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Sandra Häuplik-Meusburger
Olga Bannova

Space Architecture Education for Engineers and Architects

Designing and Planning Beyond Earth

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Douglas A. Vakoch, SETI Institute, Mountain View, CA, USA
and California Institute of Integral Studies, San Francisco, CA, USA

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Sandra Häuplik-Meusburger
Olga Bannova

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Sandra Häuplik-Meusburger
Institute for Architecture and Design
Vienna University of Technology
(TU Vienna)
Vienna
Austria

Olga Bannova
Cullen College of Engineering
University of Houston
Houston, TX
USA

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Foreword

Space Architecture as a Discipline

When author Jules Verne wrote “From the Earth to the Moon”[1] in 1865 and “Around the Moon”[2] in 1870, he conceptually designed rockets and human space habitats in order to explore the moon. His imagination was remarkable, at that time in history there were no functional rockets, satellites, or even airplanes. Yet, Jules Verne thoughtfully considered the many dimensions and variables of humans living in the extreme environment of space and applied the laws of physics known at that time. His escape velocity was remarkably close. Many of his concepts of the environment of space were prescient. Certainly he captured the imagination of many people during the following 150 years. He influenced generations with his passionate writing about science and exploration. How much did he influence the future? During the last 60 years, the United States has landed 18 men on the surface of the moon; the US, Russia, and China have launched over 400 humans into Earth's orbit; the US and Russia have built complex permanently occupied space stations; an International Space Station (ISS) with more than 20 member nations now orbits the Earth; and China is poised to build its own space station within the next decade. On the horizon, India plans to launch humans into space for the first time. As the ISS passes its 15th anniversary, the eyes of many nations are once again turned towards the moon as a permanent research base, and the next step towards landing humans on Mars. What will the spacecraft and stations look like? How will they be resupplied? What will be their primary functions? How will in situ resources be integrated? How do we support psychological needs of crews who may be away from Earth for more than 2 years? “Space” is also now a tourist destination. How will designs change for a commercial space and tourism?

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[1]Novel by Jules Verne, first published as De la Terre a la Lune (1865).

[2]Jules Verne’s sequel to “From the Earth to the Moon”, first published as Autour de la Lune (1870).

This is no longer science fiction, but is science and engineering fact. We have also learned that space exploration is complex and very unforgiving of error. Designing spacecraft and space and planetary habitats for humans requires knowledge spanning a range of disciplines: engineering, medical sciences, psychology, human factors, life support systems, radiation protection/space weather, and other extreme space environments, at a minimum. These disciplines must result in an integrated human-centered system, which should also be reliable, safe, and sustainable. This is space architecture.

In the first 50 years of spaceflight, "Space Architecture" evolved within the organizations and companies tasked with implementing the missions. Engineers and scientists trained and educated themselves. As the next generation of humans assumes its place in the inevitable pursuit of new exploration horizons, it is time to provide a textbook for students that captures the collective experience, knowledge, and wisdom of those who have paved the way, step by step. This book does just that—addressing all steps of the design process from mission planning, to design validation, demonstration and testing, to operations. Who knows what the future will hold? Perhaps, in the next 150 years, Space Architecture will be a degree offered at most universities, with its own certificated licensing requirements.

Dr. Bonnie J. Dunbar
Former NASA Astronaut, PhD NAE FRSE (corr)
UH Cullen College of Engineering

M.D. Anderson
Professor of Mechanical Engineering
Director, UH STEM Center (Science Engineering Fair Houston (SEFH))
Director, Aerospace Engineering Graduate Program
and Sasakawa International Center for Space Architecture
University of Houston

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Chris Welch on 'The Essence of Interdisciplinarity' in Chap. 1 Introduction.
Brand N. Griffin on 'The Role of the Space Architect' in Chap. 2, Chap. 4 and the Appendix.
Brent Sherwood on 'Space Architecture Education—Site, Program, and Meaning' in Chap. 2.
Marc M. Cohen on 'Mockups 101: Technology Readiness Levels for Mockups and Simulator' in Chap. 3.
Madhu Thangavelu on 'The Moon or Mars: Where might we settle first?' in Chap. 3.
Theodore W. Hall on 'Artificial Gravity and Implications for Space Architecture' in Chap. 4.
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Sandra Häuplik-Meusburger
Olga Bannova

Contents

Chapter 1
Introduction

Abstract Space Architecture is interdisciplinary and connects diverse fields such as aerospace engineering, architecture and design, human factors design, space sciences, medicine, psychology, and art. It therefore combines the accuracy of technical systems, human needs for working and living, the interface design for the relationship between humans, and the built and natural environments. This book is structured around basic learning processes for the design of a space mission, structure, or vehicle. The chapters on the design principles are related to the Technology Readiness and Habitation Readiness Levels—TRLs and HRLs (refer to Chap. 3: Comprehensive Planning) and include examples, discussions, and tasks. Examples are given to students for further individual research and assessments. Although the authors offer multiple examples in some chapters, there are many more to research and evaluate.

1.1 The Field of Space Architecture

> Space Architecture is the theory and practice of designing and building inhabited environments in outer space (SATC 2002, p.1).

This mission statement for space architecture was developed at the World Space Congress in Houston in 2002 by members of the Technical Aerospace Architecture Subcommittee of the American Institute of Aeronautics and Astronautics (AIAA).[1]

Following the quotation above, *Space Architecture* as a discipline comprises the design of living and working environments in space and on planetary bodies, such as the Moon and Mars, and other celestial bodies. This includes space vehicles and space stations, planetary habitats, and required infrastructure. Earth analogs for space applications, simulation and test facilities are also included in the field of Space Architecture. Earth analogs may include Antarctic, airborne, desert, high altitude, underground, undersea environments, and closed ecological systems.

[1]The authors were among the attendees/signatories of the Millennium Charter which was drafted by 46 architects, engineers, industrial designers, managers, and researchers; The entire text of the Millennium Charter document can be downloaded via spacearchitect.org.

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Space Architecture, as a discipline, is not new but has been emerging for at least 40 years. When NASA and the former Soviet Union turned their views towards long-term human missions, space architects and designers were involved. There is an abundant history of early design contributions to space projects.

In 1967, architect Maynard Dalton was among eight people from the 'Advanced Spacecraft Technology Division' who received an award for "Preliminary Technical Data for Earth Orbit in Space Stations". (NASA [Issues] 1967, p.4) In 1968, Dalton and Raymond Loewy, a world-renowned industrial designer, worked on the Saturn-Apollo and Skylab projects. Loewy suggested a number of improvements to the existing layout, such as the implementation of a wardroom, where the crew could eat and work together, the wardroom window, the dining table, and the color design among other additions (cf. Compton and Benson 1983). Dalton prepared the Skylab Experience Bulletins. Later he was project engineer for the Space Station module (1971). From 1965 to the 1980's Soviet Union's space systems, the Barmin Design Bureau produced a complex research and planning project designing structures and mobile systems for a long-term lunar base. Architectural and structural design aspects were recognized as key elements of the project and thoroughly defined in the project. Lunar base "Zvezda" was part of that work (1960–1980). Perhaps the first female space architect was Galina Andrejewna Balaschowa.[2] She started at 57 at the Experimental Office OKB-1 as an architect and moved a few years later to the space architecture department, where she worked closely with Korolev. She designed Sojuz spacecraft, and Salyut and Mir stations.

Space Architecture is interdisciplinary and connects diverse fields such as aerospace engineering, architecture and design, human factors design, space sciences, medicine, psychology, and art. It therefore combines the accuracy of technical systems, human needs for working and living, the interface design for the relationship between humans, and the built and natural environments. It is simultaneously technical, humanistic, and artistic and deals with the design process from a "big picture" perspective down to every detail of each component. In addition to traditional knowledge of planning and building processes, special knowledge is needed regarding how to design for humans in extreme environment and how to do so creatively.

Sources for Further Research on the History of Space Architecture:

- Book "Space Stations—base camps to the stars" by Roger D. Launius (Konecky and Konecky 2003)
- Book "Architecture for Astronauts—An Activity based Approach" by Sandra Häuplik- Meusburger (Springer, 2011)
- Book "Living in Space: From Science-fiction to the International Space Station" by Giovanni Caprara (Firefly, 1998)
- Book "Living and Working in Space: A History of Skylab" (Compton and Benson 1983)

[2]Галина Андреевна Балашова (Rus).

- Book "Galina Balaschowa—Architektin des sowjetischen Raumfahrt programms" by Philipp Meuser (in German, with many illustrations of original drawings on Salyut and Mir space station interior; DOM Publishers, 2015)
- Book "Moon—a step towards technologies for Solar system exploration" editors Victor Legostaev and Vitaliy Lopota (in Russian, Луна – шаг к технологиям освоения Солнечной системы; 2011)

1.2 Structure of the Book

This book is structured around basic learning processes for the design of a space mission, structure, or vehicle. The chapters on the design principles are related to the Technology Readiness and Habitation Readiness Levels—TRLs and HRLs (refer to Chap. 3: Comprehensive Planning) and include examples, discussions, and tasks. Examples are given to students for further individual research and assessments. Although the authors offer multiple examples in some chapters, there are many more to research and evaluate.

This chapter briefly describes the history and field of space architecture with additional sources for further reading. This chapter introduces the reader with the structure of the book and how to use it in a class environment or for personal education.

Chapter 2, discusses differences in educational practices in architecture and engineering disciplines and addresses them through a space architecture philosophy. The purpose of this is to help educators and students who come from different backgrounds to understand each other and the multidisciplinary nature of space flight design and planning processes. The chapter includes descriptions and analyses of architectural and engineering educational approaches, comparing research and design processes, and providing examples of each.

Following the Approaches and Methods is Chap. 3, which addresses mission planning and building an exploration strategy. Mission types, requirements, and constraints, as well as current and future missions' goals and objectives are given as references for students and teachers to use in class and class projects. This chapter introduces students to the practice of applying Technology Readiness Levels (TRLs) and Habitability Readiness Levels (HRLs) to assess any technology or a habitation system.

Chapters 4–6 correlate with the structure of Technology Readiness Levels (TRLs) and Habitation Readiness Levels (HRLs) described in Chap. 3.

Chapter 4, covers design research fundamentals and prerequisites including human factors, environmental characteristics, and influences on design and human activities. This chapter also talks about Technology Readiness Level 1 and Habitation System Research Level 1.

Chapter 5, discusses site selection procedures, habitat concepts, and their structural and construction characteristics, plus habitability support systems principals. This chapter relates to Habitation System Research and TRLs and HRLs 2-3.

Chapter 6, describes functional allocation strategies along with development of verification methods. The chapter also introduces technology and technology operations. Examples are drawn from reduced and full-scale models and low and high fidelity mock-ups, including the International Space Station. This chapter relates to Habitation System Research and TRL and HRL 4–9.

Appendix includes glossary with common aerospace and space architecture abbreviations listed and explained; hints for students who want to know more about the Space Architecture discipline, schools that offer related programs, and index of names and organizations used in the book.

1.3 Benefits for the Reader

Based on the authors' experiences in teaching, this book was prepared with the intention to help students quickly overcome the first challenges in their learning experience. This book is also to help space architecture, architecture, and engineering educators understand a multi-disciplinary approach and to cross-introduce architectural and engineering objectives into their curricula. The authors recommend that the field of Space Architecture should become integrated into Aerospace curricula and should become part of architectural schools as well. It will greatly contribute to the ability of students to think critically.

The book takes on the mission of teaching students to design a space habitat and evaluate it at an HRL level 3. This means that the book should furnish lessons that will enable the student/reader to research, do task analysis, develop an operational concept and mission timeline, decide on areas, volumes, and adjacencies for activities and equipment, and to design lighting and other habitation systems using CAD, scale models, and drawings as appropriate.

This book is reaching out to future mission planners, engineers and architects, and all professionals involved in the design for manned spaceflight to enable them to:

- Learn about space systems and human factors as equal elements of a spacecraft and mission design;
- Acknowledge connectivity and relationships between all design elements and overall mission planning;
- Operate at all scales from the '*overall picture'* down to smallest details;
- Provide directed intention and judgment—not just analysis—towards design opportunities;
- Address relationships between human behavior and built environment;
- Interact successfully with diverse fields and disciplines throughout the project's lifecycle.

In summary, this book addresses problems and challenges of academic training that include (cf. Robinson et al. 2008):

- Students and professionals who are trained in space engineering but lack expertise in human factor derived requirements;
- Students and professionals in fields of architecture and design who are not adequately prepared with respect to engineering requirements and evaluation criteria;
- Interdisciplinary interaction that is challenged by different research and working methods, different glossary used for the identification of design problems and requirements, and evaluation criteria that are often inconsistent.

This book will assist students to achieve or master the following skills:

- Thinking and working in multi-disciplinary processes that stimulate team leadership skills—and can be applied in other aerospace fields;
- Understanding connectivity between different levels of interaction between human beings and machinery;
- Simultaneous mission planning approach and critical thinking;
- Reflections and correlations between disciplines involved in planning and executing space exploration missions;
- Knowledge gained from different disciplines through cross-applying and re-applying design approaches between *various* space-related fields of study and research.

1.4 How to Use This Book

This book is written to help students at every stage of the learning process. It can be read from the beginning to the end, but also can be used as a lexicon to look up principles and get more inspiration for personal achievements.

> Experienced space architects realize that rarely does the first mark or decision remain unaltered throughout the entire process. Therefore, it doesn't matter what the first step is, as long as the process is flexible enough to permit change. The process is cyclical so there are multiple entry points around the loop. The key to overcoming the terror of the blank page is to begin anywhere, with anything (an estimate, a trial mark, a guess) and then react to that initial decision (Griffin 2014, p. 4).

Class instructors and students can find in this book reference materials, historical examples, ideas for projects, and seminar discussions. The authors present *Discussions and Tasks* sections in Comprehensive Planning and Design Principles for the evaluation of students' understanding of the material and to stimulate creative and critical thinking in the class.

1.5 Guest Statement: The Essence of Interdiscliplinarity (Chris Welch)

At its crux, space architecture is a manifestation of humanity's desire to explore, to journey out into the universe, and to change the new spaces that we find there into new places for us to be. As for any journey, there is a departure from the well known and familiar; a movement into new and potentially challenging areas, combined with a willingness to engage with change.

Journeys can be physical, but they can also be mental. As we move forward into the 21st century, our understanding of the universe continues to evolve: our need to engage with the significant issues of our time requires us to transform our approach to dealing with complex problems. Since complexity implies many parts interacting in many ways and involving many disciplines, researchers and practitioners must be prepared to move away from the traditional disciplinary territories in which they have grown. They must start to explore new places, new languages and new ideas; engage with them, and discover what emerges from this dialogue.

This is not necessarily an easy undertaking. Modern academic and educational life revolves around research, practice, and teaching. The organizations that support these are, in the vast majority of cases, framed in terms of quasi-monolithic academic disciplines—areas of knowledge and expertise, branches of learning or similar, taken by their adherents to be in some way clearly distinct from other disciplines.

Historically, it is arguable that it was the Greek philosopher Aristotle who first created this separation between disciplines, at least as far as Western thought is concerned. Aristotle placed different types of knowledge into one of three categories, depending on their purpose.

At the highest level were the 'theoretical' disciplines such as theology and mathematics. These were to be pursued for their own sake. Aristotle then placed 'practical' disciplines such philosophy and ethics, to be undertaken in order to promote good judgment and decisions, in second place. In the lowest category were the 'productive' disciplines such as engineering and art.

Although not as rigid as might be supposed, implicit in this approach to classification is the idea that some disciplines are more 'useful' than others and that this may be used to establish comparative merit. Despite being a very culturally dependent artifact, the effect of Aristotle's system has lasted many centuries, creating a taxonomically-based approach to knowledge and the systems underpinning it. In particular, towards the end of the Renaissance and into the 17th and 18th centuries, European society became ever complex. As ever-increasing amounts of knowledge were developed, systems were needed to structure and organize it in ways that would allow it to be transmitted to the next generation as effectively as was possible at the time. Since it was no longer possible for a single individual to know everything (even if only in theory), individuals had to focus on subsets of 'total knowledge'. Inevitably, individuals with common interests formed discipline-based communities, which focused their attentions more inwards than outwards, with particular modes of enquiry and working being developed and codified.

This was perhaps most obvious in the sciences. The development of the scientific method encouraged practitioners to focus very narrowly on the subject of experiments in order to minimize outside influences that could make the results too complex to evaluate. At the same juncture, the outcomes of these experiments were applied to the development of new techniques and capabilities, which in turn stimulated new economic developments. In the form of the Industrial Revolution, this then reinforced the perceived value of the different disciplines.

Simultaneously, the view of the world—and, by extension, the universe—that science was apparently revealing to humanity was one, not only of a great mechanism, but one which was governed by and operated on the basis of a relatively limited number of physical principles which it was thought might be fully discovered and apprehended in due course. In such a situation, it is perhaps not surprising that discipline communities saw little need to communicate outside of their own groups—an attitude that has taken—and is, arguably, still taking—a long time to dissolve.

However, in due course this narrow-focus disciplinarity itself, revealed through quantum mechanics, molecular biology, and similar fields, that the universe is not as easily understandable as was thought and that it features not only complexity, and subtle interactions between its different elements, but also the potential for a variety of forms of emergent behavior that humans are only at the start of being able to comprehend.

At the same time, the rapid (in geological terms), and frequently anthropogenic, changes to the world and its environment, combined with the accelerating impact of human beings on the world, their society, and themselves, means that we are faced with increasingly complicated issues that cannot be engaged with or addressed in purely disciplinary ways. These issues require us to deploy additional knowledge that, as yet, we do not have and will not be able to discover using disciplinary techniques alone. This is why interdisciplinarity is so very important.

The essence of interdisciplinarity is that it must not only cross the borders between disciplines and their respective cultures but that—at its core—it must be transformational and change those disciplines that it links together. At the same time, unlike multidisciplinarity, it must aim to produce new ways of approaching problems and new forms of knowledge that lie outside our existing disciplines and their knowledge. As humanity faces the challenges of the 21st-century, interdisciplinarity is undoubtedly going to become increasingly important. The dialogue between different and hitherto unconnected disciplines is going to be essential in order to address the current issues that face us and also address new ones. Humans may be drawn to disciplinarity but the universe clearly is not. This approach has already been more than adequately demonstrated by the emergence of new 'interdisciplinary disciplines' such as bioinformatics which brings together the biological sciences, computing, and mathematics and without which our research into genetics and related disciplines would not be effective.

Another ‘interdisciplinary discipline’ is, as the authors of this book clearly state, space architecture. By its very definition space architecture fulfills the requirements of interdisciplinarity. Space architecture has a clear and pragmatic focus in that it seeks to advance our understanding of how to create places in space in which humans will thrive. Space architecture addresses complex issues and yet ones that, as presented in this book as approaches and methods, are clearly describable and which draw on the expertise and knowledge of many other disciplines. At the same time, the outcomes of space architecture require its findings to be re-integrated into the different disciplines involved in order to provide new solutions.

Consequently, all users of this book must anticipate both new insights and new understanding from outside their immediate backgrounds. They must also expect their prior knowledge to be put into sharper perspective by an interdisciplinary engagement with space architecture.

New possibilities await. The journey starts here!

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Chapter 2
Approaches and Methods

Abstract Space architecture as a discipline is relatively new, but it fills a gap between the engineering approach to design habitats and other space facilities for humans, and the complexity of human factors oriented design—including personal psychology, creativity, and non-work related activities. In order to successfully fill that gap, space architecture needs to be taught academically. This chapter talks about known and potential approaches and methods, drawing examples from current space architecture programs and classes, and representative projects. The authors consider that space architecture approaches to design and planning are important to be introduced to students who are coming from the diverse backgrounds of engineering and architecture. Other disciplines may benefit as well.

2.1 Introduction and Chapter Structure

This chapter addresses architectural and engineering approaches in educational practices. The two can be quite different and cause confusion. This chapter aims to enable students, faculty members, and other interested parties to acknowledge different approaches and therefore to help them better integrate their knowledge in interdisciplinary spaceflight related design and planning processes. A guest statement at the end of the chapter from Brand Griffin[1] talks about key positions of space architecture as a discipline.

Many universities around the world offer aerospace engineering undergraduate and graduate programs, but only a few relate to the field of Space Architecture.[2] This chapter presents examples of educational practices illustrated with student projects from European and American academic institutions that offer space architecture as a mainstream or major component in their curriculum.

[1]Advanced Concepts Office at NASA's Marshall Space Flight Center, Space Architect.

[2]A selection of schools and universities offering courses on Space Architecture are listed in the Appendix.

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The chapter concludes with a guest statement from Brent Sherwood[3] where he talks about Space Architecture Education—Site, Program, and Meaning.

2.2 Future Tasks and Upcoming Challenges

Unlike early space missions, future spacecraft design concepts will not be based mainly upon engineering and structural requirements (cf. Brown 2002). Humans in future long-duration spaceflight and exploration endeavors will be assigned vital roles in the system. Therefore human needs and requirements must be addressed in overall mission architecture and spacecraft design. Human factors need to be taken into account at every stage of the design process—considering people to be more than an 'element' of the system but its modifier and innovator. Today's students and future spacecraft designers need to be prepared for the challenge of planning human missions and designing appropriate artifacts.

Table 2.1 illustrates that design considerations for many mission aspects change significantly in relation to missions' lengths and destinations. It is evident, that all mission aspects have influences on the design and vice versa:

- The longer and more isolated the mission, the more important will be the qualitative design of the habitat, including layout and integration of its structures, systems, and utilities.
- The longer and farther away from Earth, the more sustainable the habitat has to be and the more facilities will be needed for personalized activities, etc.

The importance of integration of human factors and other human-related aspects into the design process has been recognized by institutional parties.

The US Department of Transportation states the following concerning the modernization of the National Airspace System (NAS): "*The integration of human factors into the development and procurement of ... new systems is vital to the success of the future NAS. Although the Human Factors Design Guide* (HFDG 1996) *has been available for a number of years and provided vital information, it did not have the weight and impact of a design standard. Instead, the Military Standard* (MIL-STD 1989) *was commonly cited in Federal Aviation Administration (FAA) system specifications.*" (Ahlstrom et al. 2003, pp. 1–1)

Although the statement above refers to current Federal Aviation Administration FAA practices (Wagner et al. 1996, pp.1-1–1-3), an analogy can be drawn for current space systems' and facilities' design approaches with more weight given to human factors and human activities-oriented design. Broader understanding of human-related physical and psychological impacts on design solutions and understanding how design can be used for mitigation purposes are critical for success of future exploration missions.

[3]Strategic Planning & Project Formulation, NASA Jet Propulsion Laboratory, Space Architect.

Table 2.1 Comparison of mission aspects and design considerations of short missions (orbital) and long missions (Moon and Mars)

Missions aspects	Short missions (e.g. Orbital)	Medium missions (e.g. Lunar)	Long-term missions (e.g. to Mars)	Change of design considerations
Duration (months)	<6	6–12	>12	Habitat mass and volume
Distance to Earth (km)	300–400	350–400 K	60–400 M	Logistics mass and volume, increase of sustainability
Crew size	3–6	4≤	6≤	Size of habitat and logistics modules, privacy and social space
Degree of isolation and social monotony	Low to high	High	Very high	Interior design including privacy and social space (territorial issues)
Crew autonomy level	Low	Medium	Very high	Interior design with a certain flexibility to adjust to the crew needs
Emergency evacuation	Yes	Limited	No	Mission architecture and base/vehicle configuration
Availability of mission support				Mission architecture and habitat design, communication technology
Outside monitoring	Yes	Yes	Very limited	
Two-way communications	Yes	Yes	Very constrained	
Email up/down link	Yes	Yes	Yes	
Internet access	Yes	Yes	No	
Entertainment	Yes	Yes	Yes	
Re-supply	Yes	Very limited	No	
Visitors	Yes	No	No	
Earth visibility	Yes	Yes	No	Viewports

Modified from the source: Kanas and Manzey (2003)

When aiming to create an optimized design that is compatible with mission goals, technological, scientific, design, and human factors requirements, there is added complexity because of interdisciplinary design processes. Designing a crew habitat for outer space, surface of Mars, or any other extra-terrestrial body is one of the biggest challenges for space architects and engineers. Interdisciplinary communication is vital for successful and efficient design and interactions between all parties involved in design and planning activities.

Difficulties in understanding each other can arise between professions. Often disciplines and practices use different terminology and acronyms identifying

Table 2.2 Engineering and architectural approaches throughout processes

Task	Engineering approach	Architectural approach
Problem definition	Product-oriented	Process-oriented
Approach	Linear (analysis) start at the beginning of the process	Nonlinear and iterative (synthesis), start at critical points, then adjust
Workflow	Workflow from the start to the end, done with numbers (quantitative methodology)	Workflow anywhere in the project, done with models (qualitative methodology)
Solution	There is one ideal solution, most decisions are quantifiable	There are many solutions, some decisions are quantifiable

Adapted from Table 2.10 by Brand N. Griffin

entities, objects, and functions. Even the meaning of 'design' differs between engineers and architects.[4] That can create confusion and misunderstanding which may lead to significant design flaws and errors affecting overall planning and mission success. Table 2.2 shows examples of how different tasks can be understood by architects and engineers. In general: ways of identifying a problem, perceiving it, and finding design solutions can be quite different (cf. Cross 1993).

2.3 Educational Practices

Different disciplines have different approaches for finding a solution. Although there are no canonical definitions of space-architecture and aerospace engineering practices, they have different educational approaches and often different tasks assigned. The same can be observed in other disciplines such as medicine, industrial design, and physical sciences, etc. This chapter discusses engineering and architectural approaches in order to achieve better integration of space architecture subjects into both curricula.[5]

2.3.1 The Engineering Approach to Habitation Design

> An engineer starts his design from a problem, i.e. from ignorance as non-knowledge. This corresponds to a question and indicates a direction towards an aim. Therefore the engineer needs knowledge concerning means as a functional compliance for an aim, knowledge of

[4]Major terms that are used throughout this book are listed in the Appendix, in the Glossary section of the Appendix.

[5]Note: The authors highly recommend the inclusion of interdisciplinary team-oriented working processes at the university level.

how to gain and to use such a means, knowledge concerning values behind the aim, and knowledge of how to modify the aim in the light of values, if necessary. (Michelfelder et al. 2013, p. 3)

Several specialized disciplines share an engineering approach. Two branches of aerospace engineering deal with a craft's design and all the components required for its successful implementation: aeronautical engineering concerns aircraft design for operations in Earth atmosphere; astronautical engineering relates to vehicles operating in space and on celestial bodies; others include civil, industrial, and maritime engineering.

Historically, space mission and craft design is based on an engineering approach that is called Systems Engineering. The International Council on Systems Engineering (INCOSE) defines it as follows:

Systems Engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. …Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. (INCOSE 2015[6])

A goal of a system, as a group of elements that interact with each other, is to achieve specific common goals and to make the overall functionality better than the result of each element acting individually. According to Maier and Rechtin (2000, p. 8), "*systems are collections of different things which together produce results unachievable by the elements alone.*" Each system has its boundaries that separate it from the surrounding environment or from other systems. Elements and units inside the system are its basic components and if two or more of them have relationships they can be combined into sets based on the character of those relationships and become a subsystem of the main system. The description of a system as a whole leads to the three most important common characteristics that are present in all systems: *organization, generalization, and integration* (Chang 2011 p. 13).

2.3.1.1 Engineering Classes

Aerospace engineering students have to understand at least the principles of mathematics, physics, science, and engineering in order to design, construct, and test various types of aircraft and spacecraft. Engineering classes are focused on learning about systems, subsystems, elements, and parts. Students understand connections between them in order to perform a particular function for which those systems or units are designed. The engineering approach, illustrated in Fig. 2.1 uses

[6]INCOSE—International Council on System Engineering. http://www.incose.org/AboutSE/WhatIsSE.

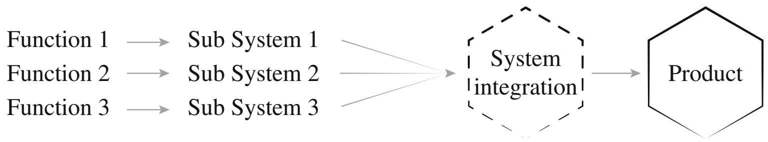

Fig. 2.1 Example of a common engineering design approach

system and sub-system requirements as constraints for the system. Each function is determined by a trade-off process. The organizational stage includes function determination and prerequisites. It is followed by generalized requirements, and the integration stage usually becomes a part of the process in professional system engineering practice. System engineering is dealing with a system as a whole and connects the traditional engineering disciplines. It also includes the evolutionary process of maturity levels (David 2013; Kossiakoff et al. 2011; Kesseler and Guenov 2010).

A drawback of this approach may be the neglected human factor if it is treated as only an equal system element. The International Space Station is an example of an engineering design approach. Important human factors and habitability elements have either been discarded in an early stage (eg. crew module) or have been added lately to the station (eg. personal crewquarters).

2.3.2 The Architectural Approach

> As a professional discipline, architecture spans the arts, engineering, and the sciences. Students must have an understanding of the arts and humanities, as well as a basic technical understanding of structures and construction. Skills in communication, both visual and verbal, are essential. While knowledge and skills must be developed, design is ultimately a process of critical thinking, analysis, and creative activity. The best way to face the global challenges of the 21st century is with a well-rounded education that establishes a foundation for lifelong learning.
>
> (ACSA [Goals] 2015[7])

The architectural discipline is multidisciplinary by its nature. It builds upon a basic understanding of engineering, esthetics, and social sciences. The level of such understanding depends on the complexity of the design problems and proposed architectural solutions. Architectural understanding of a design process includes problem examination, synthesis, and innovative pursuit. Developing skills in communication—both visual and verbal, is an essential part of architectural educational practice.

[7]ACSA—Association of Collegiate Schools of Architecture. http://www.acsa-arch.org/about/about-acsa.

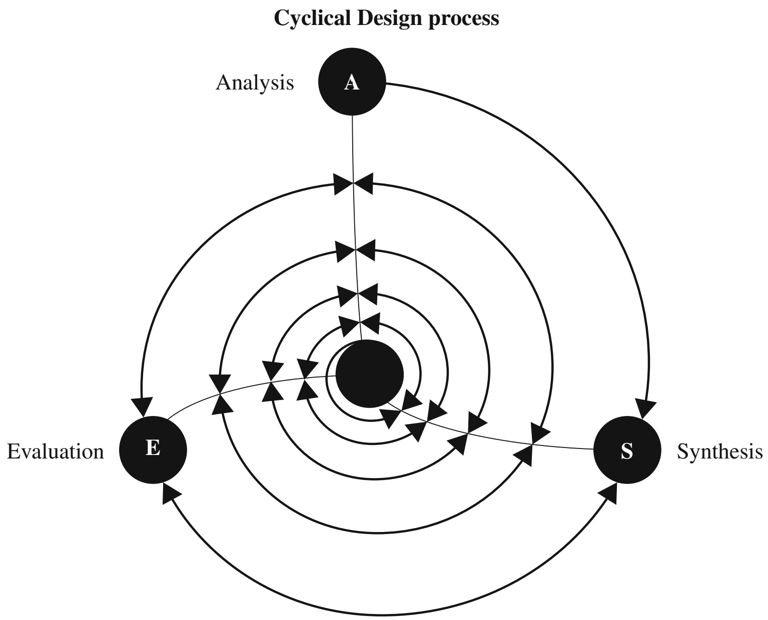

Fig. 2.2 Cyclical design process (original model by Donna P. Duerk, adapted by the authors)

2.3.2.1 Architectural and Design Studios

The architectural studio approach is based on a project-oriented strategy where students have to be creative in identifying required information and knowledge, analyzing it, and synthesizing the results into a final architectural design. The architectural approach to project development is basically non-linear and based on the synthesis of multiple disciplines.

Cycles of design process will evolve through time and levels of development. Figure 2.2 shows a diagram of a cyclical design process. “The design process is often seen as a serendipitous, cyclical process covering much ground at ever-increasing levels of detail at each sweep.” (Duerk 1993, p. 10)

Brand Griffin also refers to a model for spiral evolution in his guest statement in Sect. 4.6, which originally comes from software engineering.[8] In terms of Space Architecture, it corresponds to the idea that at every design level all elements are considered, roughly at the beginning and more detailed at a later stage.

“Design is a cyclical process in which the designer or the design organization iterates a sequence of conception, representation, and evaluation until arriving at a satisfactory solution”. (Cohen 1996, p. 2)

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[8]The original spiral model was developed by the software engineer Barry Boehm in 1986. Since then a number of variations do exist. (Boehm Barry. 1986. A Spiral Model of Software Development and Enhancement.)

Architectural training teaches students to operate at all scales from the "overall picture" down to the smallest details; to provide directive intention—not just analysis—to design opportunities, to address the relationship between human behavior and the built environment, and to interact with many diverse fields and disciplines throughout the project lifecycle.

2.3.3 The Space Architecture Approach

> Engineers think architects make things prettier, difficult to build, and more expensive. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect. (Griffin 2014, p. 2)

The space architecture approach combines engineering thinking with criteria related to habitability and human factors, such as considered in architecture and industrial design, plus including other disciplines such medicine and science.

During a space architecture studio, students advance and complete their individual projects for manned systems and habitat facilities aimed at optimizing human safety, performance, and comfort under extreme and confined conditions of space habitation.

When introducing architecture students to a design studio in Space Architecture, Marc M. Cohen states that "…. *it is always a challenge to orient them to the unique and peculiar characteristics of designing human habitation in vacuum and reduced gravity regimes. Typically, the faculty presents a broad overview of the Space Architecture discipline, and to introduce the students to leading concepts and accomplishments. The challenge is a difficult one, given the shortness of time for a quarter or semester, and the variety of the students' backgrounds, with some stronger or weaker in engineering, human factors, materials science, and physics. Also, the students often start from differing levels of professional preparation and training, so it is inevitable that each one interprets the information differently and takes an individual and often idiosyncratic approach.*" (Häuplik-Meusburger and Lu 2012, p. 4)

Depending upon the overall topic (manned systems design, space structures and applications, lunar and planetary exploration, and terrestrial analogues) students usually start with extended research of relevant topics that include mission architecture, human factors, ergonomic influences, extreme environments, constraints and influences, and psycho-social factors. They will attain a good understanding of the system and associated structures through design, research, and analysis of specific projects. Certain creativity and the development of 'out-of-the-box options' can be helpful at the beginning.

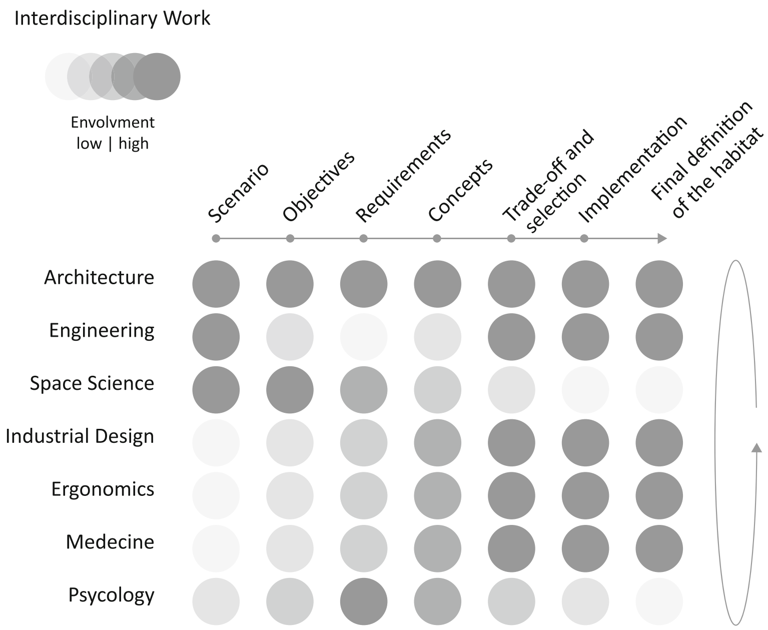

Fig. 2.3 Scheme of a disciplines relationships synthesized approach diagram

The design process is interdisciplinary (Fig. 2.3) and also related to:

- Systems' and elements' Technology Readiness Levels (TRLs) and Habitability Readiness Levels (HRLs)
- Availability of resources (physical and intellectual)
- Timeframe
- Societal and political support
- Economic and environmental impacts. (Testing and feedback)

Interrelationships between design stages with involvement of different disciplines should be established throughout the design and production development (Fig. 2.4).

Many diagrams (e.g. 2.1 and 2.2) address similar reciprocal design processes but depict it from different perspectives: the spiral process reflects an architectural synthetically enhanced approach and is based on system engineering process. The multi-linear diagram reflects engineering and architectural team efforts in pursuing integrated design solutions. There are many more variations of these models and other ways of representation exist.

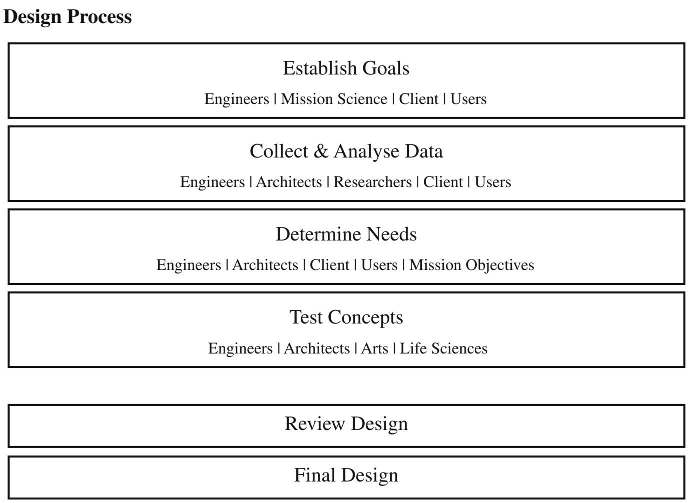

Fig. 2.4 Design process diagram (position paper on the role of space architecture, IAA 2013, p. 3)

2.4 Educational Examples

Although there is still a need for an appropriate educational approach to enumerate space architectural objectives in related disciplines, recent examples of academic courses, programs, and workshops show the benefits of integration to expand the potential of future space exploration mission planning and spacecraft and structures design.

2.4.1 Master of Science in Space Architecture Program (SICSA,[9] University of Houston)

MS-Space Architecture degree at the University of Houston was accredited by the Texas Higher Education Coordinating Board in 2003 after the first class of NASA professionals conducted their studies at the Sasakawa International Center for Space Architecture in 2001–2002 academic year (Table 2.3).

SICSA's central mission is to plan and implement programs that will advance peaceful and beneficial uses of space and space technology on Earth and beyond. Many of these activities address extreme terrestrial environments. The center offers two types of MS-Space Architecture curriculum, one for full-time students

[9]Sasakawa International Center for Space Architecture, Cullen College of Engineering, University of Houston, Houston, Texas, USA.

Table 2.3 Program/course summary ‘SICSA Master of Science in Space Architecture Program’

University/Host	SICSA
Length/Disciplines	Three semesters (full-time students), architecture and engineering students; five semesters (part-time industrial students)
Curriculum	Consistent with degree plan and program syllabi
Special features	Regular program

(3 semesters) and another for part-time local industry employees (5 semesters). Students with various degrees and backgrounds work on projects in teams or individually. All projects are related to current trends in the industry and national space exploration programs. Projects also include government and corporate aerospace organizations grants and proposals (Fig. 2.5).

Curriculum includes: project oriented studio classes, seminars, special problems—elective classes and invited lectures. Seminar classes provide students with basic knowledge about man-systems integration, mission planning and analysis, and spacecraft and habitat design (Fig. 2.6).

During the course, students learn the theory, requirements, and design concepts for spacecraft and habitat design. Topics of focus include human factors, ergonomic influences, extreme environments constrains/influences, and psycho-social factors. The goal of the program for students is to attain a good understanding of these structures and systems through design, research, and analysis of specific projects. Projects topics include: manned systems design, space structures and applications, and Mars and Moon exploration (Bannova and Bell 2011).

During the class, students perform detailed investigations and conduct individual research on manned space systems aimed at optimizing human safety, performance

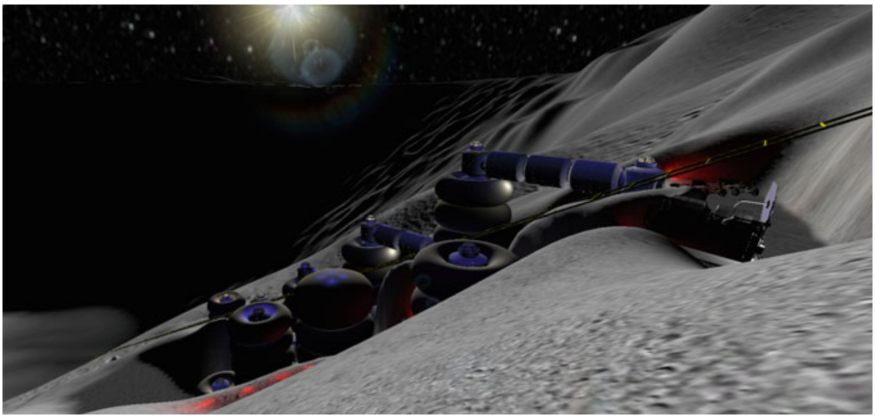

Fig. 2.5 Sustainable Moon settlement for 80 people; Project developed for Houston Museum of Natural Science’s Planetarium by graduate students Thomas Hockenberry, Stacy Henze, Nima Cheraghpour (2012 MS-SA student project)

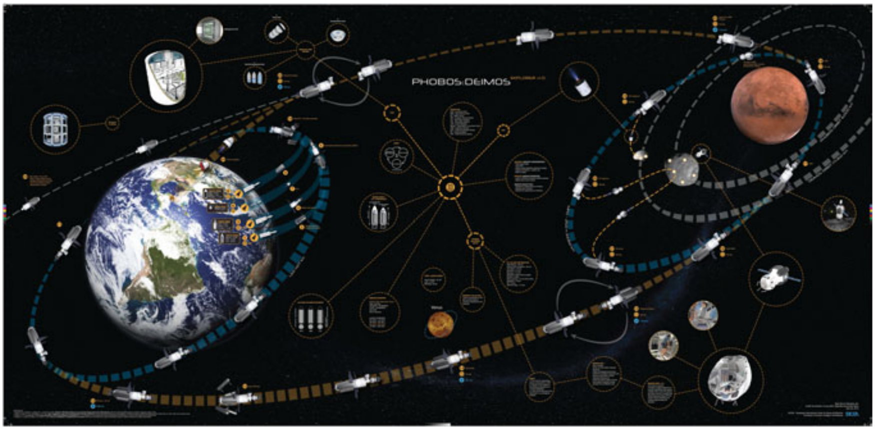

Fig. 2.6 Phobos/Deimos Mission Architecture by graduate students Nejc Trost and Abhishek Jain. (2013 MS-SA student project)

and comfort under extreme conditions. Habitability and human factors lessons from extreme environment analogs on Earth and previous space missions are examined and analyzed.

2.4.1.1 NASA Grants and Cooperation with Industry

In September 2008, the NASA Explorations Systems Mission Directive (ESMD) awarded contracts to Boeing, ILC-Dover and the University of Maryland to conduct concept study investigations to develop requirement definitions and planning for a "Minimum Functionality Habitation Element" (MFHE) lunar habitat. The primary study purpose was to conceptualize the smallest module possible that was capable of providing barest living and work essentials for initial short-term lunar missions with virtually no emergency contingencies other than basic radiation protection countermeasures. Although NASA would never actually fly such a facility, the central intent was to examine lowest operable volumetric, mass, consumable, and equipment system functionalities to establish a foundation baseline upon which more acceptable capabilities and accommodations can then be added. Means to achieve such expanded growth features were then to be conceptualized as a secondary priority. All work was to be completed within a six-month period (Fig. 2.7).

SICSA was a member of two of the study teams, one headed by Boeing, and the other by ILC-Dover. The Boeing team involved several major corporate participants. Members included Hamilton Sunstrand, Harris, Honeywell, ILC-Dover, Oceaneering Space Systems, Orion, and the United Space Alliance. The ILC-Dover team was much smaller, with only SICSA and Hamilton Sunstrand as additional members.

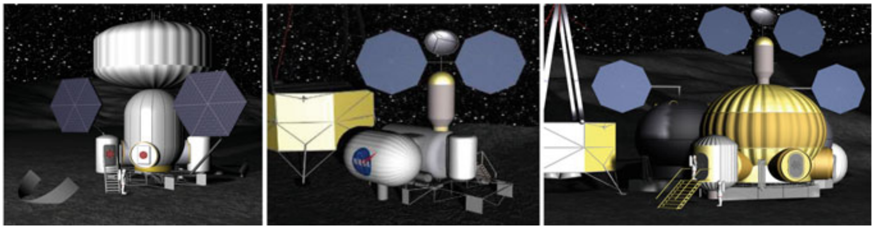

Fig. 2.7 Boeing team and ILC Dover team MFHE evolutionary growth approach proposal. (SICSA project 2009)

Table 2.4 MFHE given guidelines

Crew accommodations	Operations
The MFHE should initially support a crew of four for 28 days plus an additional 30-day contingency exception	Crew missions will be scheduled at 6-month intervals based upon a reference 4.0.0 mission campaign (Fig. 2.8)
Later expanded capacity should provide for continuous 4-person 180-day stays, with surges of an additional 4 people during crew changes	The MFHE will be landed pressurized at a polar location, and will remain on the lander for approximately 2 years prior to occupancy following offloading by a Tri-ATHLETE
Scientific workstations should be incorporated (e.g. a geosciences glove box)	EVA operations for surface exploration and maintenance will occur approximately every other day

NASA established functional support requirements to guide the study, but provided some latitude for contractors to "push back" on those they wished to challenge with logical alternatives. The original guidelines described in Table 2.4.

Students worked on two alternative habitat configuration concepts and expansion scenarios that originated with highly constrained mass/volume features consistent with earliest operational accommodations. The schemes incorporated means to commence operations while placed upon landers, to off-load the modules to the surface using a special lander-integrated crane, and to subsequently increase functional capacities using soft augmentations and additive element growth. Comprehensive team study results were presented to NASA in February, 2009, and have been publicly released to all interested parties. The final reports are available online (Bienhoff 2009; Lin 2009).

Figure 2.8 depicts comparison diagram of NASA mission campaign 4.0 outline and SICSA's mission proposal with use of designed surface elements that offer advantage of minimizing number of launches and overall mission costs.

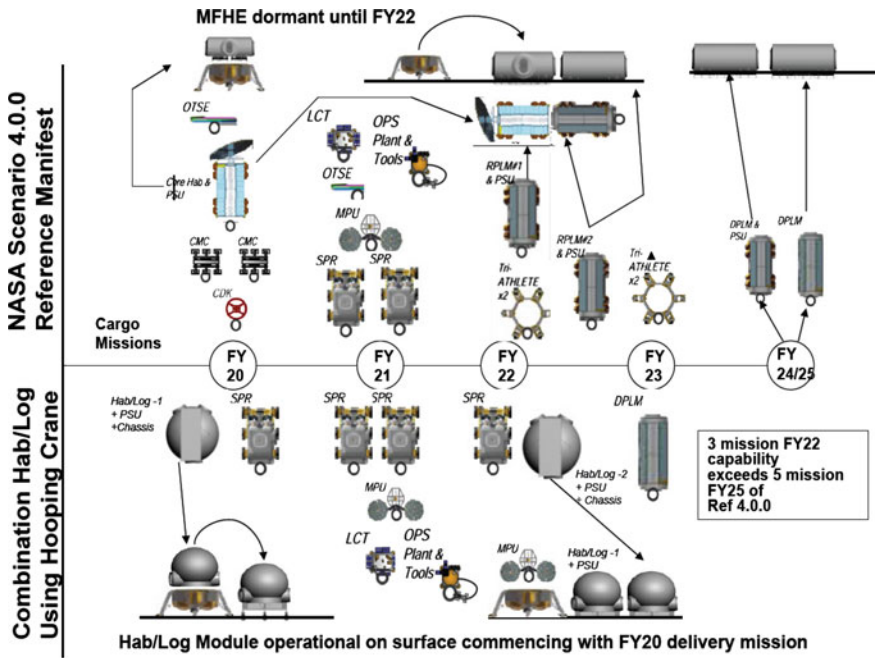

Fig. 2.8 Comparison SICSA's MFHE campaign proposal with NASA mission campaign 4.0

2.4.2 Destination Moon Design Studio (TU Vienna, Vienna University of Technology)

The design studio, 'Destination Moon', took part in the frame of the Master of Architecture program at the Vienna University of Technology (TU Vienna) in 2012. The TU Vienna is one of a few universities worldwide that offers courses in Space Architecture (see Appendix: Hints for Students). In 2012, 25 students took part in the semester program (March–June) and worked on their vision of a future research base on the Moon. All projects have been published and are available online for further research (Häuplik-Meusburger and Lu 2012) (Table 2.5).

In the first phase of the studio a settlement strategy, based on a hypothetical scenario, was developed by the students. The emphasis of the second phase of the studio was on the design and implementation of a lunar research station. Particularly relevant was the mind shift of conventional architectural design challenges required by a change of perspective. As most of the students had no previous knowledge in the field of Space Architecture, this course was accompanied by theme-specific lectures and workshops with space experts.[10]

[10]Studio directed by: Dr. Häuplik-Meusburger Sandra and DI Lu San-Hwan; External project evaluation: Dr. Marc M. Cohen; Students: Abele M., Badzak M., Benesch O., Czech M.,

Table 2.5 Program summary 'Space Architecture Classes at the Vienna University of Technology'

University/Host	Vienna University of Technology (TU Vienna)
Length/Disciplines	A course is one semester (full-time and part-time students), architecture students, guest students from other faculties (engineering)
Curriculum	Part of the Master of Architecture program
Special features	Periodic program Accompanied by a vast space lecture series
HRL	3 (internal configuration, functional definition and allocation, use of reduced scale models)

2.4.2.1 Evaluation Criteria for Student Projects

In order to assess how well the students developed solutions, two kinds of reviews were provided: an internal one in the sense of a traditional studio review and an external one from the perspective of the larger world of human spaceflight. Space Architect Marc M. Cohen was invited to assess the feasibility of the projects in the professional practice of Space Architecture. Based on the design brief by the studio directors, Cohen developed the criteria for evaluation. There were three broad domains of evaluation: Concept, Representation, and Space Architecture Features. This method can be used as an example and adapted for other design studios and projects.

The domain **Concept** encompassed the ideas that the students brought to their projects. Evaluation themes for Concept are listed in Table 2.6.

Figure 2.9 shows a visualization of the student project titled 'Twist', which was evaluated highly in the Concept category. The project 'Twist' creates a linear array of units that begins at the upper edge of a crater wall and follows the slope down towards the center. The form of these habitation units derives from the structure, which consist of a spiral spring. The crew will deploy this spiral inside the inflatable, giving it a form that provides volumes of varying shapes and sizes that can accommodate the living and working environment functions. The spiral will initially be flexible but its foam filling will harden into a rigid shape. This project got a good score in the domain Concept. Areas that need further attention include the construction of the spiral to be further articulated, particularly the outer inflatable layer that would be filled with foam that solidifies (Häuplik-Meusburger 2012, p. 115).

Representation covered the way students presented their ideas as a metric to skill and craft. Evaluation themes for Representation of the Design Concept are

(Footnote 10 continued)

Demirtas T., Galonja D., Hengl K., Heshmatpour C., Khouni A., Klaus J., Kolaritsch A., Krljes D., Küpeli B., Lang E., Lazarova Y., Lukacs D., Milchram T., Mörtl C., Mulic A., Nagy P., Nanu A., Pluch K., Rossetti V., Shi Y., Siedler D., Stefan K., Steinschifter M.; Invited Space Experts: M. Aguzzi, W. Balogh, W. Bein, M. Cohen, S. Fairburn, N. Frischauf, B. Foing, M. Gitsch, G. Grömer, M. Hajek, J. Huber, Kabru, O. Lamborelle, R. Peldszus, T. Rousek, D. Schubert, M. Schultes, U. Schmitzer, G. Thiele, F. Viehböck, A. Vogler.

Table 2.6 Evaluation themes for the criteria CONCEPT for the design studio 'Destination Moon' (Marc M. Cohen)

CONCEPT: definitions of descriptive criteria	
Evaluation themes	Explanation
Analogy, including Backstory	The use of analogy is a time-honored and widespread practice in architecture. Some students use analogy, but that is not a requirement in any sense. However it can add a story line and a degree of richness to the narrative
Formal concept	Developing such a concept as a discrete physical and visual form is an essential step in architecture
Imported philosophy	It has become fashionable in recent decades to start an architecture project from a philosophical—instead of a formal—parti (Point of Departure). Although the use of imported and possibly irrelevant philosophy sometimes provokes controversy, the recording here addresses only whether it is present in the project
Structural concept	Because Space Architecture occurs in the extreme environment of vacuum and reduced or microgravity, the structure must not only support conventional live and dead loads, but also the pneumatic pressure of the atmosphere
Geometric construct	As part of the structural concept or the formal concept, a geometric concomitant often becomes a prominent organizing principle
Science of physics concept	Some Space Architecture concepts invoke innovative applications of science, most often physics, in developing a habitat project. However, often as much peril can accrue to the project as benefit unless the architect brings a solid grasp of the science to the effort

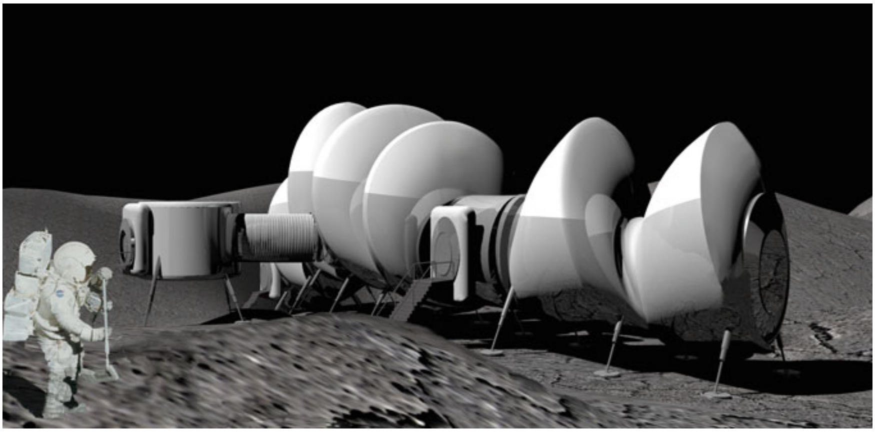

Fig. 2.9 Rendering of the project Twist by Daniela Siedler, Vienna University of Technology, Institute for Architecture and Design, Design Studio Destination Moon 2012 (TU Vienna, HB2, Siedler)

Table 2.7 Evaluation themes for the criteria REPRESENTATION for the design studio 'Destination Moon' (Marc M. Cohen)

REPRESENTATION of the design concept	
Sub themes	Explanation
Storyboard/Preliminary sketches/study model	The early steps in the creative process serve as a tremendously important viewport into the architect's design process, and can offer strong first order predictions of how well the project direction will turn out. The point in this criteria is not whether the architect went through these steps or not, but only whether she or he uses them in the review presentation to explain and illuminate the final project
Functional diagram or matrix	Mature and serious architectural design usually demands a symbolic representation of the relationship between functional areas or spaces. This representation can take the form of a table, a matrix, or a diagram that explains the decisions about adjacency, separation, parallel elements, and other supra-design features that shape the entire project, such as the modularization of living quarters, working areas, or agriculture
Adjacency matrix	An adjacency matrix is a special case of a functional matrix that explicates the importance of connecting or separating individual spaces
Site planning	The base or habitat sits on or under the surface of the extra-terrestrial body. Where the project intersects the surface, the need arises to elaborate that intersection and the relationship between the habitat and the surrounding terrain
Architectural plan	The plan drawing acts as the heart of an architectural project and probably the most time-honored representation of a building. It provides the shorthand for everything else in the project
Architectural building section and elevations	The buildings section and elevation articulates the plan's realization in three dimensions
Architectural 3D CAD	Computer Aided Design (CAD) has become the standard means of representation in most architectural projects
Structural detail or other detail	Because Space Architecture projects are often innovative, the architects often need to explain how they will make their structural concept or other feature feasible and realizable. The detail conveys understanding of the craft of building
Scale model	Presenting a project with a 3D scale model helps the reviewer and the public understand the concept. Scale models are particularly helpful for people who are not trained design professionals and so may encounter difficulty in visualizing a 3D concept from 2D drawing
Working scale model	Where a Space Architecture project involves changes in form or structure as part of installation, deployment, or inflation, a working model offers significant help to demonstrate the concept

listed in Table 2.7. The architect of the project 'Luna Monte' presented her concept with a storyboard, at least partially hand drawn, that was extremely helpful in expressing both the architectural concept and the beginnings of a concept of

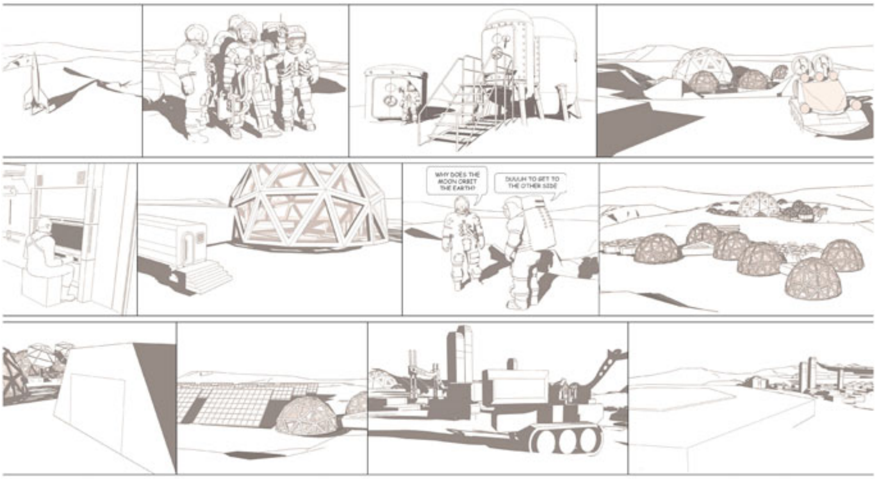

Fig. 2.10 Clipping of the storyboard for the project Luna Monte by Aida Mulic, VUT Vienna, Institute for Architecture and Design, Design Studio Destination Moon 2012 (TU Vienna, HB2, Mulic)

operations. The architect provides a complete functional diagram drawn at a habitable house/human scale. The project conveyed the functional relationships (Häuplik-Meusburger 2012, p. 89) (Fig. 2.10).

The domain **Space Architecture Features** encompassed the specific knowledge that the students gained and applied in the studio. Evaluation themes for Space Architecture Features are listed in Table 2.8.

The 'Balloon in a bowl' habitat, featured in Fig. 2.11 consists of a deployable, hexagonal plan inflatable. It has an inner deployable/ expandable framework. The functional modules include the Habitat, Greenhouses, and Regolith Processing. The Resistance/Residence pursues a philosophy of "environmental adaptation". The concept for an integrated inflatable and rigid structure that all deploys together is quite clever and the model explains it very well (Häuplik-Meusburger 2012, p. 105).

2.4.3 MASH—Deployable Emergency Shelter Study (TU Vienna, Vienna University of Technology)

In 2013, the design studios at the TU Vienna challenged the students to develop, build, and simulate an emergency shelter for Mars. The design brief requested an additional crew support element, with regards to potential EVA/science activities to be performed on Mars and related safety issues. The primary feature had to be a

Table 2.8 Evaluation themes for the criteria REPRESENTATION for the design studio 'Destination Moon' (Marc M. Cohen)

SPACE ARCHITECTURE ELEMENTS	
Sub themes	Explanation
Multiple access	Multiple accesses reflect a design that provides two or more means of entry to important areas, rooms, or spaces. There are many functional and safety reasons for why multiple accesses can be an asset
Dual remote egress	Two or more remotely separated exits from a given room or volume is a hallmark of the earliest life safety and fire codes on Earth. It deserves equal or greater attention in a space habitat
Multiple circulation loops	A circulation loop refers to a means of perambulating or translating around a space habitat or base. Multiple routes or loops would be beneficial for flexible and varying uses
Public space	In a space habitat with five to six or more crewmembers, there will be common living, gathering, and circulation areas in addition to shared workspaces. Common living spaces include the wardroom, galley, exercise, and entertainment areas
Vertical circulation	Nearly all the projects incorporate high ceilings or multiple levels in the habitat. [in the studio] The ways in which the crew can access these parts of the total volume serves as an important functional element
Private quarters	Providing a private living space and sleep quarter stands as one of the most widely recognized requirements since Raymond Loewy's design for the Skylab sleep quarters
Work or lab area	Most crewmembers will go to the space habitat or base to work, doing engineering, research, science, or technology development. They will need suitable accommodations to perform these tasks
Plant Growth Area	Self-sufficiency in food will emerge as a vital capability to sustain human space settlements. In addition, the partial G environment presents opportunities for agricultural research
Life support	Life support is a sine qua non of a space habitat. The issue for the studio Destination Moon is the extent to which the architects recognize the role of life support and make some accommodation or indications for it
Surface mobility	The ability to travel safely and in relative comfort over distances on the lunar surface
Use of robotics	Autonomous, robotic, and teleoperated systems are already becoming ubiquitous in the space exploration environment. Surely these capabilities will act as an integrated element of the Destination Moon base
EVA access airlock	Travel on foot to explore and work will remain essential for nearly all EVA activities on the Moon. Therefore the space habitat should include some type of airlock provisions

portable and deployable shelter that can be employed in the event of an emergency requiring immediate action and where return to the base/rover is not possible in time (Table 2.9).

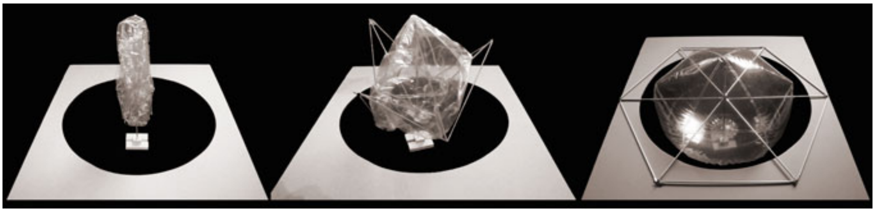

Fig. 2.11 Scale model showing the deployment process of the lunar base project Resistance/Residence undercover by Stefan Kristoffer, VUT Vienna, Institute for Architecture and Design, Design Studio Destination Moon 2012 (TU Vienna, HB2, Kristoffer)

Table 2.9 Program summary 'Space Architecture Classes at the Vienna University of Technology' (TU Vienna)

University/Host	Vienna University of Technology (TU Vienna)
Length/Disciplines	A course is one semester (full-time and part-time students), architecture students, guest students from other faculties (engineering)
Curriculum	PART of the Master of Architecture program
Special features	Periodic program Building of a prototype and Mars Field Simulation
HRL 4–5	4–5 (full scale, low fidelity mockup evaluations), human testing and occupancy evaluations

Following the selection of prospective emergency scenarios and the definition of design criteria, a series of preliminary designs for an emergency shelter was developed within the HB2 academic design studio. A 1:1 prototype was built and tested during the Morocco Mars Analog Field Simulation in February 2013 as part of an operational evaluation of this deployable and portable multipurpose shelter. All design projects and the eventual prototypes have been published and are available online for further research (Häuplik-Meusburger et al. 2013).

2.4.3.1 Prototyping and Field Simulation

The team at the TU Vienna chose a design-orientated approach along with a literature research of the state of the art and potential applications. Students were asked to work on emergency scenarios likely to happen on Mars and to develop the design criteria for the first models.

Based on the res[C]ue concept, a full scale prototype was developed and built.

In total, three prototypes were developed and tested. The second prototype was tested with the suit tester during a Dress Rehearsal Meeting in Innsbruck. The third mock-up was then tested during a field simulation in the Sahara, dealing with the three pre-defined contingency scenarios (Fig. 2.12).

Fig. 2.12 Superposition of several images: Students simulate procedure of selected emergency scenarios to get a feeling for spatial and functional requirements at the Vienna University of Technology, Institute for Architecture and Design, Design Studio Destination Moon 2012 (TU Vienna, HB2)

Between the 1st and 28th of February 2013, the Austrian Space Forum (OEWF) conducted an integrated Mars analogue field simulation in the northern Sahara near Erfoud, Morocco in the framework of the PolAres programme (Groemer et al. 2014). The emergency deployable shelter was among the experiments preparing for future human Mars missions, conducted by a small field crew. The emergency scenarios were tested by the student team and the OEWF analogue astronauts during the analogue simulation mission (Fig. 2.13).

The prototype was made to fit a number of human activities based on the most likely emergency scenarios during an EVA on Mars. Three selected emergency scenarios were tested during the simulation:

Deployment procedure

During the field tests, the handling was successfully demonstrated for the full deployment circle:

- Handling and transportation of the mock-up in packed state and transportation
- Deployment of the structure, including opening the package and inflating the floor membrane
- Deployment of the structure under different topological conditions
- Retraction of the Shelter and performance of the pneumatic system

Fig. 2.13 The Mars Deployable Shelter during the simulation at the Morocco Mars Analog Field Simulation in 2013; TU Vienna, Institute for Architecture and Design, HB2, Design Studio Deployable Emergency Shelter for MARS, 2013 (*Photo* OewF, Zanella-Kux)

Ergonomic usability and its adaptability

The ergonomic usability and its adaptability were evaluated for the following criteria:

- Interaction between the proposed structure and its users (handling and activities in the shelter)
- Off-nominal situations to test the flexibility of the prototype
- Ergonomic and spatial suitability to actions and
- Individual perception of comfort in relation to these activities

The evaluation was based upon a comparison between the shelter deployment behavior under controlled (laboratory) conditions versus the deployment in the field (to account for the influence of dust), as well as a subjective assessment of the developers, the on-site team including the analog astronauts and a post-mission inspection of the wear-and-tear patterns of the hardware. The evaluation demonstrated the expected good functionality of the mock-up. The deployment (pop up) worked as expected and took less than 1 min. Opening (unzipping) the shelter was tested a number of times. Some difficulties were detected due to the small size of the zip pull tabs. Additional ribbons were then connected to the pull tabs allowing easier use with the space suit gloves. The deployment on a slope and rocky surface worked well.

The prototype was designed to allow functional adaptability including the adoption of the sitting and lying positions for the astronauts. The change between the two positions is achieved through air shifting between two supporting pneumatic cushions, one in front and one in the back of the shelter. The change between the two positions was tested with two astronauts inside the shelter. The mechanism worked well and efficiently. The analogue astronauts reported that sitting in the shelter was very comfortable and allowed them to fully relax. The measurements of the astronauts CO_2 levels (carried out by the ÖWF) support this finding. The sitting height was sufficient. The position of the arm-supports could be increased by 5–10 cm. The ergonomic usability in the lying position, however, was not sufficient. The problem was that the life support system on the back and the antenna did not allow the analogue astronauts to lean back, leading to discomfort.

2.5 Guest Statement: The Role of the Space Architect—Part 1 (Brand N. Griffin)

2.5.1 Architectural Versus Engineering Approach

Engineers think architects make things prettier, difficult to build, and more expensive. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect. This is not an identity problem, but an asset more like being ambidextrous rather than schizophrenic. Table 2.10 provides some insight into the different approaches of engineers and architects.

The tendency to classify personal attributes leads to the assumption that they are complementary or mutually exclusive. Thus, one is either engineer or artist; not both. Most authors writing about system architecture are engineers yet they acknowledge that the role requires a combination of deductive (engineer) and inductive (architect) reasoning.

Because space flight started and remains within the engineering domain, space architects have had to masquerade as system engineers or configurators (engineering for vehicle designer). Engineering managers suspect there must be a role for architects but do not know where to place them within their organization. Part of the problem is the job title. This description uses "space architect" which can easily

Table 2.10 Engineers and architects approach problems differently

Engineering approach	Architectural approach
There is a single, ideal solution	There are many solutions
I must start at the beginning of the process	Start anywhere, then adjust
A good process will yield a good solution	Inspiration before process
Most decisions are quantifiable	Some decisions are quantifiable
You can't do that	Why not?

include system architect, space system architect, configurator, subject matter expert, and sometimes systems engineer. MIT professor Crawley (2007, p. 1) offers the following comprehensive definition for system architecture: "the embodiment of concept, and the allocation of physical/informational functions to elements of form, and definition of interfaces among the elements and with the surrounding context." It is no wonder space architects have not found a home in the engineering organization.

There is no single job title for the "space architects" scattered across international government and private organizations. Practicing space architects currently contribute to mission planning, vehicle integration, habitat design, and human factors, but are particularly attracted to the areas of design integration and concept development.

2.5.2 Waterfall

In his book **Systems Architecting**, Eberhardt Rechtin (an engineer intrigued with architectural problem solving) addresses the role of the architect within the organization. His model has less to do with the individual professions and more about establishing functional connections within an organization. He begins describing different phases of program development using a waterfall (Fig. 2.14). This logical progression defines a sequence of major programmatic steps moving from need and resource to adaptation. Because the conventional waterfall does not accurately represent today's complex systems, he provides further definition in an expanded waterfall (Fig. 2.15) adding a box for the architect and showing organizational relationships (Maier and Rechtin 2000).

What is clear by this diagram is that the architect must not only have a comprehensive view of the product and process, but must be directly connected to key decisions from beginning to end. Dr. Rechtin believes that the system architect "is not a generalist, but rather a systems-oriented specialist" (Rechtin 1991, p. 141). Furthermore, regarding the architects role, he states that "… architecting is working *for* a client and *with* a builder" (p. 36) Then he upsets the applecart by saying, "… engineering is working *with* an architect and *for* a builder. (p. 8)" Within aerospace, this relationship is disruptive, but it is consistent with the fundamental nature of "architecting" because the architect must be well positioned within the organization to be effective. In other words, you cannot "architect" from below. Considering the nature of the work and role in the organization, it is logical that the number of architects is small compared to the number of engineers. In fact, along with others, Frederick P. Brooks and Robert Spinrad believe that the greatest architectures are the product of a single architect or at least a very small, carefully structured team (Rechtin 1991, p. 47). Rechtin reinforces, "If [...] the single mind is the essence of architectural integrity, then 'the disciplined team' is the essence of engineering integrity." (1991, p. 4)

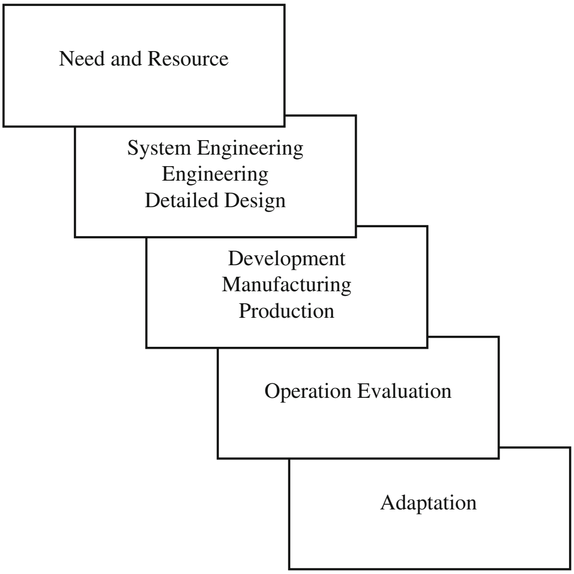

Fig. 2.14 Waterfall of major programmatic steps (Griffin B., redrawn by the Authors, based on Eberhardt Rechtin)

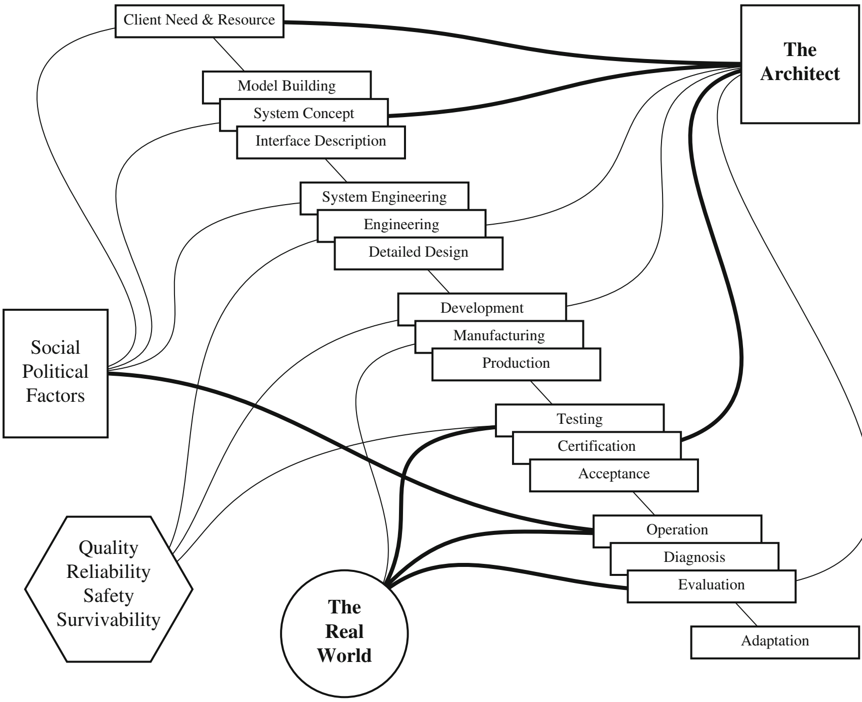

Fig. 2.15 The architect's role in the expanded waterfall (Griffin B., redrawn by the Authors, based on Maier and Rechtin 2000, p. 37)

Regarding roles, there is little purpose to debate the jurisdictional question of just how much system engineering is done by the architects (not much because there are not that many architects) or how much system architecture is done by the typical systems engineer (not much-too many cooks spoil the soup). Overlap is essential-this interface looks fuzzy from either side. The serious mistake is to leave a gap.

2.5.3 Heuristics

Why all the fuss? Just design it, get management buy-in, build it, and then send it to the launch site. This approach is partially correct, but to make a point, it over simplifies each step. In reality, the process for building complex systems relies on many decisions-making techniques, some logical, some heuristic and others a product of management decree.

Georgia Tech's, Tom McDermont states "system architecting differs from system engineering in that it relies more on heuristic reasoning and less on the use of analytics." (2011, p. 26) A similar, yet more forceful assertion is made in **Systems Architecting**. Heuristics, or experienced based reasoning, is characterized as essential to architectural problem solving. Rechtin says, "…architects have insights, lessons learned, rules of thumb and the like that consciously or unconsciously are brought to bear on complex problems." (1991, p. 43)

Heuristics are not new. Three commonly cited examples of heuristics are: (1) Murphy's Law, if anything can go wrong it will, (2) the acronym KISS or Keep It Simple, Stupid; and (3) Occam's Razor: The simplest solution is usually the correct one.

With regard to space architecture, von Tiesenhausen, one of the von Braun German "rocket scientists" who worked on the Apollo Program says, "*If you want to have a maximum effect on the design of a new engineering system, learn to draw. Engineers always wind up designing the vehicle to look like the initial artist's concept*." (Akin's Laws of Spacecraft Design, 30) Furthermore, there are many applicable heuristics in **Systems Architecting** with others collected in personal lists of "laws."

2.6 Guest Statement: Space Architecture Education—Site, Program, and Meaning (Brent Sherwood)

In 2002, the Millennium Charter (SATC 2002) crafted at the 1st International Space Architecture Symposium defined space architecture as "the theory and practice of designing and building habitable environments in outer space," by analogy with terrestrial architecture.

Space architects hunger to tackle the near-existential problem of fashioning "offworld" environments—places off Earth where the native conditions we find are quickly lethal, but in which human civilization could nonetheless someday survive, root, grow, and thrive. We are motivated by the long view that, no matter what else befalls us or what we bring upon ourselves, somehow humans inevitably must lead Earth life out into the universe.

Nothing builders have faced in the most recent ten millennia of human history—recorded in artifacts—exactly prepares us for this new challenge. In just the past half-century humans have ventured into a place where there is no weight or night, touched the Moon, and established a research outpost that skims above Earth's atmosphere. What of the next half-century?

Off Earth, we find a combination of conditions unlike any encountered before by living things: absence of weight; unfiltered, unending sunlight; cold so deep it liquefies air; lethal radiation streaming from solar storms and dying stars; distances too vast to allow direct conversation; and alien landscapes stranger than we might dare imagine.

Architects always start with Site, Program, and Meaning: the "where," "what," and "why" of a building project. But for space architecture, what are these things?

First questions about Site might be about slope, ground consistency, view-lines, and sunlight at some particular place on the lunar surface. Or, following Mars discoveries, we might think about how to keep perchlorate-laden dust from infiltrating an airlock, or about the planetary-protection implications of subsurface ice, or about engineering a scheme to access the ancient southern highlands (which we cannot yet do). However, we shall see that "typical" site topics are all second-order issues. Space is vast, and many more inner solar system destinations will be accessible to humans in this century than just the surfaces of the Moon and Mars. As space architects, we must be prepared to define and solve challenges for all the places people might go, and for what they might be doing there.

So the next issue is the architectural Program. At first, it might seem obvious: keep the "soft pink thing inside" alive (as fighter-jet engineers used to say), but far away from Earth, and for as long as it takes to land, explore, and get back to Earth. This model of an architectural program—which later we will call *Explore*—is, however, only one of four very different programs for what humans might be doing in space in this century. *Explore* is the vision promoted by government space agencies today, but as space architects we must be prepared for other models, too. What happens once exploring is done? Do we move on, or *Settle*…or retreat? How would the architecture of a settlement be different from that of an exploration outpost? And what about the vision several of today's entrepreneurs have, to make space flight accessible to ordinary people? Leisure travelers need a different kind of *Experience*, in different numbers and with quite different amenities than do highly trained, right-stuff mission crews. And finally, what about the architectural needs of technical teams in space who would support these activities, or who would construct and sustain other types of industrial mega-projects to *Exploit* the unique properties and resources we find in space? What are the space architecture implications of the four Programs?

Finally, one of the modern distinctions of today's architects is that as a community of practice, we continuously ask "why." We do not simply design solutions for programs given; we challenge underlying purpose and contextual issues to find and then express Meaning in what we design (Sherwood 2012, pp. 600–609). The built environment speaks, both presently and down through time, by embodying the aspirations and values of both builders and clients. For architecture in space, what are these aspirations? What should they be?

2.6.1 Site

We should think beyond the limited typical view of "destinations" for human space flight. We are fortunate that the universe presents us with two large worlds—the Moon and Mars—that people could explore in this century. Naturally we are drawn to these destinations because they are planet-sized and we, after all, evolved on a planet. But they are only two among myriad potential Sites where space architecture could be important. Ironically, they are also the hardest among all these destinations to reach. Space architects should understand the full range of potential destinations, because design requirements vary significantly across them.

Figure 2.16 is a conceptual map of the "human-accessible" solar system, ranging from near-Earth space out to the surface of Mars. The obvious, traditional

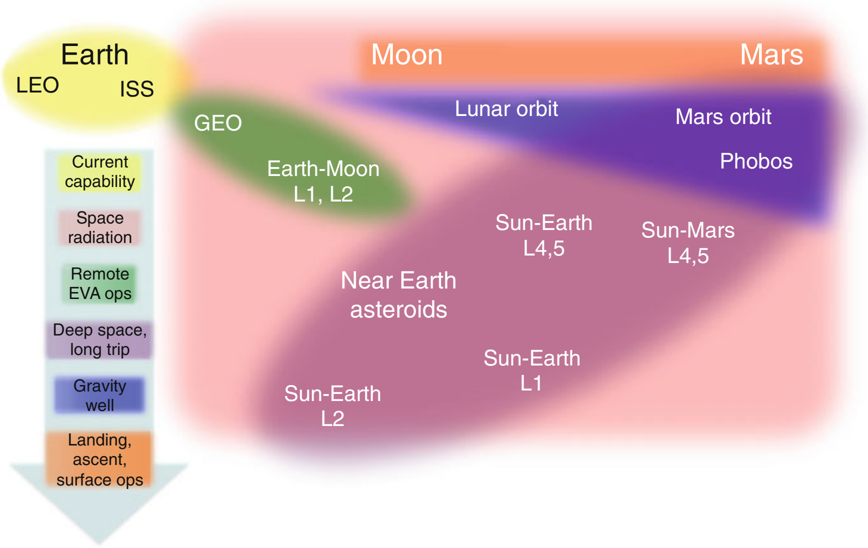

Fig. 2.16 In the foreseeable future, humans could live and work in diverse locations throughout the inner solar system—not only on the Moon or Mars. Each Site poses unique architectural challenges and opportunities (Sherwood)

destinations are across the top. The color key shows additive challenges that must be met, in increasing order of need as we move out from Earth.

Current space flight capability is in the yellow zone: low Earth orbits (LEO) that include the International Space Station. In the 1970s we could get to and from the Moon's surface, but today we cannot, and all human space flight is constrained to the yellow zone. The first challenge beyond LEO is radiation: every destination in the large pink rectangle is bathed in it: (1) transiting the van Allen belts of electrons and protons trapped by Earth's magnetic field; (2) large, episodic fluxes of energetic protons emitted by unpredictable solar storms; (3) galactic cosmic radiation fluence, comprising heavy atomic nuclei and protons accelerated to relativistic speeds by stellar explosions. On Earth's surface, inside the geomagnetosphere and beneath atmosphere, we are shielded from all this, but space voyagers will require shielding technology and biomedical mitigation. Risk tolerance during the Apollo program exceeded today's standards; astronauts flew unshielded, and one of the largest solar flares occurred on August 2, 1972, between Apollo 16 and 17.

Next, consider the green oval containing nearby destinations. GEO comprises geosynchronous orbits, a set of close-to-equatorial orbits centered on a definitive, circular equatorial orbit with 35,786 km altitude. At this special destination, orbital velocity matches Earth's rotation, so satellites "hang in the sky" as viewed from Earth. These orbits are already industrialized for telecommunications and for persistent remote sensing of Earth. The remaining undeveloped major use would be collection, conversion, and transmission to Earth of solar energy for electrical power (more on this below).

The two-body Earth-Moon system also has five Lagrange points, where the inertia of a satellite's orbital motion is in balance with the gravitational fields of both bodies. These special destinations allow spacecraft to maintain position with respect to both Earth and Moon with very little propulsive expenditure. Of the five points, EM-L1 (between Earth and Moon, 85 % of the way to the Moon) and EM-L2 (64,700 km beyond the Moon's Farside) are particularly useful. EM-L1, a gravitational high ground, could be a staging node for routine travel to and from the Moon and other destinations throughout the solar system. At EM-L2, a large "halo orbit" has the benefit of being able to see both Earth and the lunar Farside simultaneously, providing a continuous, real-time telecommunication link between them. In addition to radiation mitigation, the "price of entry" for practical human operations throughout the green zone would be the capacity for extravehicular activity (EVA), especially for maintenance or large-scale construction operations in GEO, or depot operations at EM-L1.

In 1974, Gerard K. O'Neill's concept team postulated that EM-L4 and L5 would become prime locations for space settlements, constructing power stations for GEO. Industrial-scale amounts of lunar resources would be launched to L4 and L5 from lunar mining colonies by electromagnetic catapults. The L5 Society took its name and inspiration from this destination.

The diagonal purple oval zone includes many useful destinations that, while not more challenging to reach than the EM points from an "energetic" (propulsion) standpoint, are all much farther away. All in deep space, they impose long trip times that pose diverse additional challenges for human space flight, as yet undemonstrated: long-duration, deep-space life support, medical care, psychological factors, and operational sustainability.

By far the largest class of destinations in the purple zone is NEOs (Near Earth Objects), asteroids and extinct comets in solar orbits similar to Earth's. There are well over 10,000 NEOs known so far, including about 1000 that are bigger than 1 km, of which almost 200 are classified as Potentially Hazardous Objects (PHO) that could cause large-scale destruction if they hit Earth. NEO orbits continually evolve due to complex perturbations, so PHO orbits are continually monitored and analytically propagated into the future to assess probability of impact. No means have yet been tested to deflect or disrupt such an impending impactor. Potential human activities at NEOs include scientific and geotechnical exploration, disruption experiments, relocation, resource extraction, and eventual settlement.

Other destinations in the purple zone include the five Lagrange points of the two-body Sun-Earth system (Fig. 2.17). SE-L1, between the Sun and Earth, offers a unique vantage point both for monitoring solar wind emissions just before they reach Earth, and for continuously, synoptically observing Earth's entire day-lit hemisphere. SE-L3 allows continuous robotic monitoring of the side of the sun that we cannot see from Earth. SE-L2 is a preferred location for in-space telescopes due to its benign environment, constant distance from Earth, and geometry: to a spacecraft there, both the sun (for power) and Earth (for data relay) are on the same side of the sky all the time. The James Webb Space Telescope is designed for operation at SE-L2. JWST's baseline operations scenario does not include human intervention, but servicing might be planned for future telescopes once human missions reach out into deep space. No human has yet been as far from Earth as SE-L2 (1.5 million km away, four times as far as the Moon).

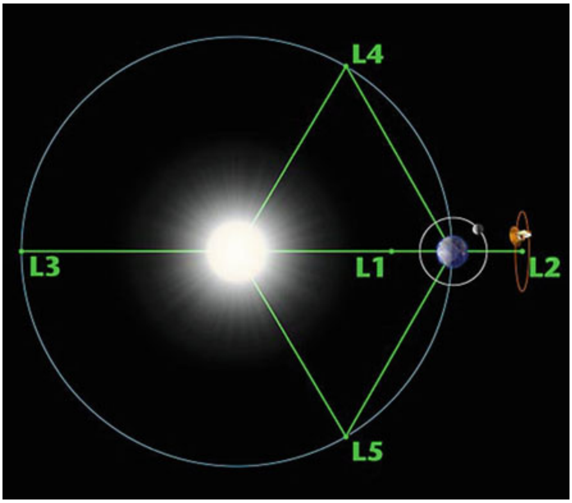

Fig. 2.17 Diagram of all five Earth-Sun lagrange points (NASA)

SE-L4 and SE-L5 are potentially key destinations for an industrial space flight future. These are the “stable” Lagrange points in the Sun-Earth system, 60° ahead of and behind Earth in its orbit (thus, 1 AU from Earth or 150 million km, 100× more distant than SE-L2; a radio signal takes more than eight minutes to travel from Earth to these destinations). Because they are dynamically similar to the Sun-Jupiter L4 and L5 points, where we know that more than 6000 Trojan asteroids orbit, they may harbor asteroids. But because they are in the day-lit sky as viewed from Earth, detecting asteroids with terrestrial telescopes is quite challenging. So far, only a single Earth Trojan asteroid has been discovered (in a highly inclined orbit). But if there are many more, they could comprise a key material resource for in-space use. These places remain among the most promising sites to host human settlements in the distant future.

Mars also has Trojan asteroids, despite its small size; seven have been discovered so far. Just as the moons of Mars can inform our understanding of the dynamical history of solar system formation, the composition of the Mars Trojans likely holds similar clues. From the standpoint of human exploration, they are comparable to voyages to the vicinity of Mars but may represent key stepping stones for increasingly challenging missions on the path to Mars, as they are not deep inside Mars’ own gravity well.

The blue triangle encompasses destinations that require large propulsion stages to get into and back out of planetary gravity wells: orbits around the Moon and Mars; and Phobos and Deimos, the two moons of Mars. Albeit deep in the lunar gravity well, low lunar orbit (LLO) can be a superior staging location for some system architectures, particularly those that use oxygen propellant mined from the Moon. Phobos is particularly interesting: scientifically because of its anomalously low bulk density and record of solar system dynamical evolution, and operationally both as a source of volatiles, and as an orbital base for teleoperating robots on Mars (it rotates synchronously, with Stickney crater always facing Mars).

Finally, the orange bar at the top contains the destinations most commonly talked about: the surface of the Moon and the surface of Mars. Getting humans to and from these destinations requires all the advanced capabilities of the other destination classes (radiation protection, EVA operations, reliability without Earth intervention, large propulsion stages), but also a significant list of additional, expensive capabilities: planetary descent and soft landing, extensive surface operations of multiple types, and planetary ascent and rendezvous. Mars has enough gravity to make landing and ascent a challenge, but barely enough atmosphere to help slow down. While landing robots on Mars may seem almost commonplace today, landing human systems weighing over ten tons would require dramatic implementation of multiple technologies not yet demonstrated. Landing on the Moon must be done using only propulsion, so large descent stages are required. Indeed, the “orange bar” destinations that govern so much of our conversation about future human space flight are the hardest to get to and from, among all the destinations shown.

While not indicated by this map, it is conceivable that after gaining experience with long-duration, even permanent, deep-space flight, humans could venture throughout the Main Asteroid Belt, a vast region of the inner solar system, ranging from about 2–3.3 AU (twice as far from the sun as Mars), that contains hundreds of thousands of asteroids and the icy dwarf planet Ceres. Sunlight in the outer Main Belt is only one tenth as strong as at Earth, but would be sufficient, along with the vast material resources found there, to eventually support a huge human population.

The inner solar system is truly a rich place, full of diverse types of destinations, conditions, and resources. Space architects need to realize that human space flight futures are not limited to just the Moon and Mars, or a specious choice between them. However, without the gravity caused by planetary-scale mass, the other destinations on the map and in the Main Belt are microgravity or milligravity environments. Human habitability exceeding ISS-type mission durations (everywhere beyond cis-lunar space) will depend on effective, sustained deconditioning countermeasures, possibly including rotating artificial gravity. Most of these destinations are too far away for real-time conversations with Earth to occur; one-way signal delays range from minutes to hours. The unique environmental and operational characteristics of specific Sites must be calculated and understood up front.

2.6.2 Program

Given the possible Sites, we can consider the range of architectural Programs for human space flight. All the purposeful activities ever envisioned for human space flight aim principally at one of four objectives:

- Explore
- Exploit
- Experience
- Settle

Table 2.11 contrasts these objectives, focusing for each on its most definitive specific activity (Option), how we might justify it in a few words (Purpose), a simple conceptual template for what each means to our culture (societal Myth it embodies), some unique Needs beyond just time and budget, its Yield after several decades, and finally the actual spacefaring population that it would create by mid-century. The four objectives are not interchangeable. Each measures success using different criteria, each hinges on different investment priorities, and each creates a different future. The differences matter greatly because we cannot really develop all four at once.[11] Even if combined coherently, the resources of all existing global and private space programs would be insufficient to create all four

[11]Further Reading: Sherwood, Brent. 2012. Technology Investment Agendas to Expand Human Space Futures, Proceedings of the AIAA Space 2012 Conference and Exposition (Pasadena), American Institute of Aeronautics and Astronautics (Reston), 2012, AIAA 2012-5131.

futures simultaneously. A choice to pursue one objective cannot avoid deferring progress toward the others, so it is vital that our society be clear about which one we want the most, or first.

2.6.3 Explore

By mid-century, a small team of intrepid humans could stand on Mars. This tiny planet (total surface area about equal to Earth's land area) has fired humanity's imagination for millennia and physically lured us for centuries.

We know its atmosphere is unbreathable, almost two hundred times thinner than Earth's. And we know that while it was once an ocean world, it is now as cold and dry as Antarctica. Still, Mars is the "least inhospitable" ready-made world within our reach. It has polar caps and night frost, wind-driven weather, and Grand Canyon-like landscapes. Plate tectonics never started there. And, far smaller than Earth, it cooled so fast that its magnetic field died billions of years ago, allowing the solar wind to strip its atmosphere and send it into a permanent, desiccated deep freeze. But flowing and standing liquid water once hosted clement conditions; did life ever arise there?

Today, we use robots for scientific exploration of the amazingly diverse remote places throughout our solar system. Back in 1961, just as the first human-launch experiments occurred, President Kennedy connected human space flight to exploration by selecting the "Moonshot" (from among a menu of barely feasible options) as a highly visible yet peaceful project to demonstrate US technological superiority over the Soviet Union.

Ever since Apollo succeeded, exploration has become the de facto raison d'etre for human space flight by space agencies around the world, even though "using people to explore planets" was not actually Apollo's core purpose. This linkage between human space flight and exploration is so strong that it is commonly taken as an equivalence: in some discussions, the astounding feat of continuous operation of an international research laboratory in Earth orbit is derided as "going nowhere, in circles."

Severe technical challenges limit direct or extensive exploration by humans of the Moon, near-Earth asteroids, the moons of Mars, and Mars itself. About ninety times farther than the Moon (as measured in travel days), Mars is cast as the prize: the "horizon goal" and "ultimate destination." Mars is the most distant surface we could reach by mid-century. This explains why, if to *Explore* is our core objective, the Moon cannot compete with Mars—it is neither novel nor distant enough. Hence Table 2.11 defines "Explore Mars" as the best proxy for the broader exploration imperative. Is the societal myth of Lewis and Clark, intrepid explorers of a new continent, as strong elsewhere as in the US? NASA's international partners tend to favor incremental steps, which feeds persistent debate about "exploring" the Moon first.

The space architecture challenge centers around sustaining, and maximizing the hour-by-hour productivity, of a small team of highly trained experts very far from

Table 2.11 Four distinct options capture the range of possible goals for human space flight

Option	Purpose	Myth	Needs (+$\$10^{11}$ over 40 year)	Yields	2050 space population
Explore Mars	Extend direct human experience as far as possible	Hero (Lewis and Clark)	Public commitment sustained over several decades	Cultural achievement: setting foot on Mars	Six international civil servants
Settle the Moon	Establish humanity as a two-planet species	Pioneer (Heinlein)	Routine heavy traffic to lunar surface	"Living off the land" in space	10^3 citizens raising families off-world
			Use of lunar resources		
Accelerate space passenger travel	Create new travel-related industries	Jet set (Branson)	"Four 9s" reliable launch and entry	Highly reliable, reusable space vehicles	10^3 crew +10^5 citizens in LEO every year
				1-h intercontinental travel	
Enable space solar power for Earth	Prepare for post-petroleum age with minimal disruption	Green	Public–private and inter-agency partnerships	Energy-abundant future	10^2 skilled workers in GEO
				Economical heavy-lift launch	

Each transforms unique investments into a unique vision of the future by mid-century (Sherwood 2011; reformatted by the Authors)

any physical help. For such professionals on such a mission, what configuration and amenities are optimal? How can we make an environment safe from natural hazards for several years? What role could the architecture play in managing, or avoiding altogether, spaceflight deconditioning? Which technologies and equipment can control the air, water, temperature, and consumables, and be maintained for such a long voyage; and how should they be integrated into the architecture? What is the relationship between habitats for deep space, for landing and ascent, for planetary surface operations, and for mobility?

The necessary investments to land people on Mars are daunting: advanced in-space propulsion, space vehicles weighing tens of tons that decelerate to a soft landing within seconds (with humans inside), extraction of propellant and breathing oxygen from the tenuous Mars atmosphere, machinery and medical means to survive three years away from Earth, isolation of human biology from the Mars environment, and many others—even small fission reactors. Most of these "stretch" technologies would yield uncountable spinoff benefits we cannot foresee today, as space flight has always done. And at the project's culmination, billions of Earthlings would pause in their quotidian concerns, awed by live video of the "first Martians."

As hard as it is to estimate the cost and date of achieving this milestone, it is impossible to anticipate its impact on humanity's existential sense of self and destiny. We also do not know whether the commitment needed to get that first small crew on Mars can be sustained over the decades of development, tests, and setbacks it would take. Nonetheless, *Explore* is the objective our space agencies are currently aiming for.

2.6.4 Exploit

Imagine a world where electricity comes from the sky, rather than from burning fossil fuels; a world where precious metals, mined on the Moon and harvested from captured asteroids, are imported from space in vast quantities. Space is almost inconceivably empty. But paradoxically it holds resources that can enable a human future without limit. Today we use various Earth orbits only for observation, telecommunications, astronomy, and research. But by mid-century, space could also provide both energy and materials for Earth at industrial scale. Exploiting these resources would almost inevitably then pull humanity naturally out into the solar system.

Space material resources are diverse. The Moon has concentrations of "rare Earth elements" essential for high-tech products ranging from smartphone screens to the magnets in wind-turbine generators. It also contains recoverable amounts of ^{3}He, a rare isotope of helium that could fuel hypothetical fusion power reactors. And a very small fraction of asteroids are almost solid metal: iron and nickel alloyed with platinum-group metals vital for electronics and chemical manufacturing. Nudging the orbits of just a few of the thousands of NEOs could bring such resources close enough to harvest, forever changing industrial economics.

Enabling industrial-scale exploitation of space material resources would require many investments—in high-power space systems, large-capacity electric and electromagnetic propulsion, autonomous extraction and processing technologies—far beyond the means of today's space entrepreneurs but suitable for government development. How important might it become to some nations to assure access to unlimited amounts of strategic materials?

The most startling space resource weighs nothing at all: photons. In high Earth orbit, sunlight is about forty percent stronger than on the surface, and the sun never sets. The fundamental technologies to convert sunlight into electricity; transmit microwaves to Earth with phased-array antennas; then collect it with dipole-antenna arrays over farmland to convert the power back into electricity for the terrestrial power grid, are all well understood. The geosynchronous orbit, already industrialized for telecommunications and remote sensing, could be developed further into an inexhaustible source of clean electrical power, for "export" anywhere on the globe independent of night, weather, or local conditions, and without blighting the landscape or damaging wildlife or the environment (Fig. 2.18).

This would be "macro-engineering" to be sure. Only a vast enterprise could supply a meaningful fraction of Earth's energy appetite: complex transnational public-private partnerships, funding a steady stream of heavy-lift cargo launches,

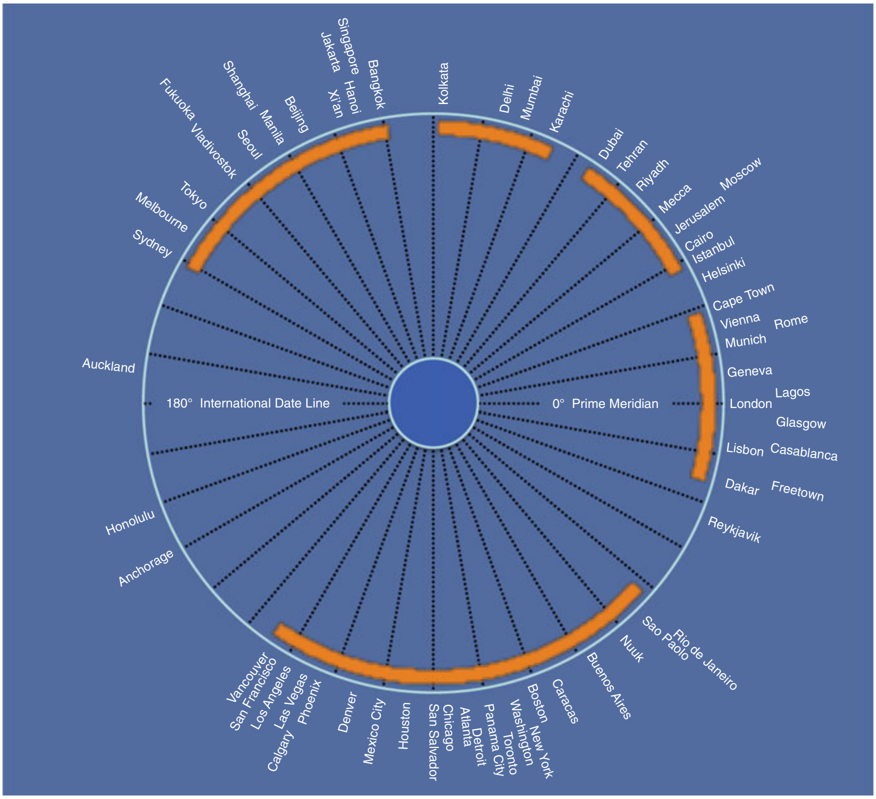

Fig. 2.18 Human geography viewed from GEO: projecting longitude of major population centers onto GEO (Earth shown to scale) shows diverse cultures becoming unlikely neighbors when Earth's electricity "comes from the sky." Today's major spacefaring powers (the US, Europe, Russia, India, China, and Japan) all have obvious regional interests (Sherwood)

fleets of robot workers, and onsite crews to construct and operate platforms in space with a total area comparable to the US National Highway System.

The space architecture challenge centers on routine and continuous access by technical work crews totaling several hundred people, throughout vast arcs of the geosynchronous belt, to a fleet of robots that build and maintain enormous power stations. Dormitories, maintenance shops, in-space shuttle "buses," and seasonal rotation of crews from Earth would all be needed—systems without precedent and not currently being developed. How far could today's ISS-based life-support subsystems and habitable modules go in supporting this scenario? How could a habitat large enough to support social assembly of such a human community be built and verified? What functions, features, and leisure facilities would be needed for hundred-person work crews? Modern shale-oil extraction encampments in the US upper Midwest offer a template for the type of accommodations appropriate for work and life on an industrial frontier, but very little design analysis has been done so far to understand how to adapt these lessons for space flight.

Space operations based on high power would quickly open additional space resources and their derivative industries: materials, tourism, and manifold service industries not yet conceived. Albeit grandiose, the vision of industrializing space for power requires no miracles. It could be done, if one or more spacefaring nations chose to lead humanity through an orderly transition to a sustainable, post-petroleum world.[12]

Today though, *Exploit* does not yet drive any nation's space flight priorities. Only Japan—with 40 % the population of the United States but just 4 % the land area, most of it mountains—and perhaps China and India appear interested in demonstrating the feasibility of power from the sky. None of the most accomplished space exploration leaders (the US, Russia, and Europe) have yet connected their capabilities in launch, human space flight, and space operations with the looming geopolitical issue of clean, sustainable energy; Earth's non-renewable energy sources are still too available, affordable, and profitable.

2.6.5 Experience

By mid-century, two-week vacations in Earth orbit could be routine. Like cruise ships today, orbital resort hotels would course silently over the planet once every ninety minutes, through eighteen sunrises and sunsets each day. Architects imagine the amenities: weightless staterooms with awesome views; gourmet meals prepared from space-grown and globally imported fresh foods; "zero-g" recreation including spherical swimming pools, weightless discotheques, and free-fall sports, games, and performing arts; guided telescope tours of the home planet below; and suited excursions into the vacuum of space.

Leisure travel in Earth orbit is a marketable *Experience*: the ride of your life (ten minutes up and forty-five down); the incomparable sensations of sustained weightlessness; and the solar system's most poignant, beautiful, ever-changing view out the window. As happened with air travel in the first half of the 20th century, demonstration of consumer-level flight safety would unleash a mass market. While today neither sufficient safety nor compelling destinations exist, both are achievable with focused investment.

The space architecture challenge includes everything needed for routine operation of resort destination complexes: spaceliners to ferry scores of passengers at a time between Earth and orbit; large-volume pressure vessels built and certified for occupancy in space; big windows to make the most of the glorious views; "kitchen science" for chefs operating in free-fall; leisure architecture of many types; space

[12]Further Reading: Sherwood, Brent. 2012. Space Architecture for Industrial-Scale Space Solar Power, AIAA 42nd International Conference on Environmental Systems (San Diego), American Institute of Aeronautics and Astronautics (Reston), 2012, AIAA 2012-3574.

surgery; perhaps rotating artificial gravity; and many others. Today no government is developing any of this; unless some do, this amazing yet feasible future will remain far off.

Without technology help, privately funded commercial orbital leisure travel will be a very slow-growing market, catering only to the hyper-rich and interrupted by the kind of spectacular accidents that teach aerospace lessons. The research and flight rate required to approach airline-like safety are far beyond the means of today's commercial space flight entrepreneurs, all of whose plans and machines adapt technology originally developed by NASA. And today's space "destination systems" also depend on technologies developed by and for government projects. One outspoken former NASA Administrator used to pound on the podium and declare, "Space tourism is not my job!" But why not? NASA's own predecessor agency (NACA, the National Advisory Council for Aeronautics), created during World War I, developed the airfoil and engine technologies inside every modern commercial and military jet. As a result, air travel enables the way we live today.

If NASA and its partners decided to transform our world again, by developing the technologies to enable hundreds of thousands of ordinary people to fly in Earth orbit every year, they could jumpstart whole new industries including orbital resorts and one-hour travel between London and Tokyo. Many secondary industries would emerge around this core market, making the *Experience* of space viscerally central to mid-century society.

2.6.6 Settle

Imagine living in a human community committed to taming a hostile frontier, putting down roots and raising families in a strange, faraway place full of unique challenges, experiences, and joys. Eventually humankind will settle space. Expansionary and adaptable, *Homo sapiens* has "built to suit" everywhere on Earth. Given territories to explore, resources to exploit, and experiences to sell, human civilization will expand, settle down and set up shop.

Settlement would bring space flight and architecture fully together in the most complete and fundamental way. Far beyond laboratories for researchers, cargo vessels and dormitories for workers, and spaceliners and cruise ships for tourists, settlers would need the thousands of big and little items and services that make human communities self-sustaining in any place. They would generate power, find and extract raw materials, grow and make food, fabricate and recycle building materials and commodity goods, import and export specialized products, raise children, create governments, establish cultures, and leave legacies—all off Earth, in circumstances without precedent. Learning to "live off the land" in space would teach us countless lessons, methods, and technologies useful back on Earth, where we see the human imprint on our natural world looming larger with each passing decade.

No space agency has yet decided to aim to *Settle* space. This may seem illogical: doesn't government investment to explore also advance the settlement purpose? It does, but only weakly. A determined focus on settlement would drive major investments in different directions. Foremost would be routine heavy traffic between Earth and the settlement site. Here especially, the Moon or SE Lagrange points would "win" due to the enormous costs of large, reusable space transportation systems and operations. Rocket systems would be optimized for economy and reusability, and they wouldn't all need to be human-rated. Then, settlers would need technologies for the large-scale extraction of volatiles, metals, ceramics, and glasses from the ground; the manufacture of end products from these resources; and civil engineering to build with them. How would usable products of all types be made; indeed, how could everyday products be re-designed so that they could be manufactured in the settlement, from local materials? What would community-scale life-support and food-production look like on the Moon—clearly it could not be based on warehouses full of finicky machinery. What would it mean to architects to re-invent the broad spectrum of capabilities to support human living, literally from the ground up? None of these questions is a focus of government research today.

Conflating a future vision to *Explore* with one to *Settle* is not optimal for either. The former is about expanding the human range of direct experience as far away as possible; the latter is about expanding human civilization as sustainably as possible. Despite persistent fantasies of Martian colonies, economics strongly favors settling the Moon first: just three days away; rich in raw materials for rocket propellant, construction, and biomass; with low but useful gravity; and with a view of the blue-marble Earth in the black sky. However practical the settlement of Mars will ever be, the Moon will always offer a simpler, safer, quicker, and less expensive way to learn how to *Settle*.

While we can imagine a space settlement slowly growing wherever there are raw materials and energy, fueled by a self-contained barter economy within its expanding population, no place in space is hospitable as found. Horses, pickaxes and grit are insufficient for this frontier, where the very means to stay alive—let alone expand—are high-tech, expensive, and all necessary immediately and continuously. The high capital cost to seed a settlement, and the ongoing challenge of maintaining and elaborating its complement of advanced equipment until it could establish indigenous high-tech production capacity, mean that someone has to invest for a long time. This scale and type of investment requires government commitment, which would in turn hinge on strategic or economic return.

Neither is remotely defensible for Mars. Lunar settlement might conceivably be motivated by competition between China and the West, at least for a time. But long-term justification would still require that the Moon export to back Earth something economically valuable: services, experiences, energy, or materials. The markets for space services and experiences so remote from Earth are precious thin; and the Moon is an impractical platform for beaming energy directly to Earth. This leaves extraction and export of strategic elements as the only foreseeable economic driver for growing a lunar settlement. This same logic drove O'Neill's vision of settling EM-L5, funded by lunar mining to construct GEO platforms to supply Earth with electrical power.

2.6.7 Architecting Our Path

Fewer than a thousand people have flown in space so far. For those who grew up with the "space program," this nonetheless amounts to an astounding total, so large it precludes household recognition of today's astronauts. But out of a human population of seven billion it is a tiny fraction. All spacefarers so far have been carefully selected and highly trained for their missions. Despite our hard-won experience accommodating these explorers and researchers in space, we know nothing at all about how to accommodate other types of potential spacefaring populations: leisure passengers, large-scale industrial crews, or settlers.

By the end of this century we could understand through experience the basics of space architecture for any of the four alternative Programs, but likely not all of them. Private investment in space flight is just beginning, and the barriers to rapid or sustained growth are many and severe. Because space technologies are so complex and expensive, global public investment via government space flight programs will continue to dominate the human space flight agenda deep into this century. So it is vital that, by our investment choices today, we decide consciously which futures to open and which to defer.

Are all big rockets the same? We could design for human-rated throw capacity to deep space, or for economical high-rate delivery to construction sites, or for passenger reliability. Which future should we enable first?

Are all life-support systems interchangeable? We could design for maintainability without resupply, or for closing the loop to minimize mass, or for scalability to large populations. What type of space travelers should we prepare for?

Is reusability important? We could design for rare expeditions to remote places, or for routine exchange of goods, services, and people with a colony. Which vision should we enable?

Figure 2.19 is a simple roadmap that shows how we could make the fastest progress opening all four futures. Everything accomplished in the first half-century of human space flight up through the International Space Station is encapsulated in the two milestones at the lower left: developing the capability to get humans into and out of space, and to sustain them there. Both resulted from government investment, which now (with the SLS and Orion) is extending NASA's human space flight domain throughout cis-lunar space.

The NASA vision then reaches for Mars, at the lower right. But optimistically, even the most skeletal architecture cannot land a tiny crew on Mars until about 2040. This is because the bottom half of the figure is "top-line constrained" since it depends on the NASA budget (and arguably, the companion budgets of cooperating agencies around the world focused on the *Explore* vision). No realistic scenario can increase the agency budget by enough to make a significant difference in the rate of progress, and no amount of exhortation can change this fact. The only way to break out of the top-line constraint is to attract private capital in addition to, and on par with, government funding, and this cannot occur for a roadmap that generates no wealth.

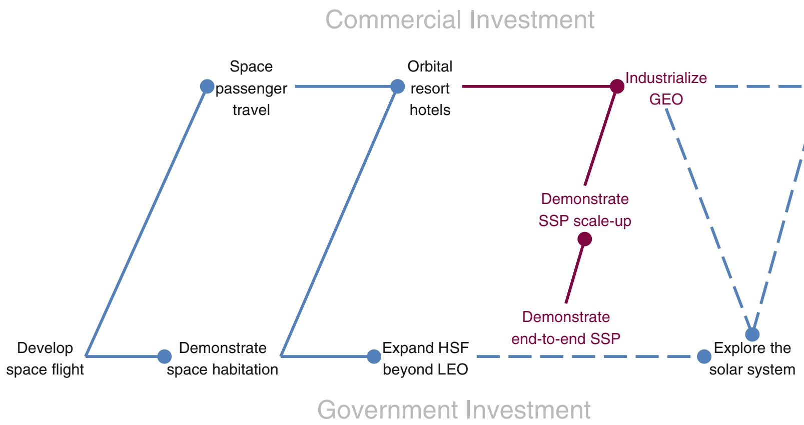

Fig. 2.19 Human travel beyond Earth orbit is too expensive for the traditional space-agency exploration model. A more robust path would first build a commercially based, high-power operations infrastructure. Industrializing GEO for clean energy has the capacity to attract the private capital needed to leverage government investment budgets (Sherwood)

Interestingly, while NASA focuses on SLS and Orion, the potential space passenger travel market is indeed beginning to attract small amounts of private capital (i.e., outside the NASA top-line budget) to develop flight systems based on technologies developed by NASA, RSA, ESA, JAXA, and CSA. Exemplified by companies like SpaceX, Blue Origin, Sierra Nevada Corporation, Bigelow Aerospace, and Virgin Galactic, this path emerges across the top half of the figure.

The large agencies now face a fork, even without realizing it. They could fixate on the bottom path, sights set on exploring Mars, and devote all their resources to making headway on that challenge. Or, they could choose to make space flight integral once again to solving one of the most pressing problems of our era. The Cold War that drove Apollo may be over, but today's world does not lack vexing problems. By investing only a few billion dollars in technology development and end-to-end tests of space solar power, we could demonstrate to the public and to energy investors how industrializing GEO could, at once, benefit Earth and generate profit.

With proof in hand (for example, signs in Times Square and Ginza lit by power from the sky), government and commercial co-investors could establish a public-private partnership to develop and demonstrate the many capabilities needed for industrial-scale implementation (cutting across the center of the roadmap to bridge the worlds of government and commercial investment). Achieving that milestone would clarify the issues, risks, and costs of a large-scale enterprise—hard information needed to attract large-scale corporate and government investment to develop and deploy operational systems.

This new, profit-making space energy sector would create large demand for transportation between Earth and space for both cargo delivery and work crew rotation, as well as crew habitation systems. Both of these expanding markets could be served completely by genuinely commercial providers, after strategic government investments in enabling technologies. Because the large-scale enterprises all occur in the top half of the roadmap, government involvement in these businesses could be limited to regulation, taxation, and security, as in most industries on Earth.

In such a future, space flight, rather than being an effete high-tech industry, would be evident throughout society: integral to the economic and environmental health of society and the Earth. Civilization's transition to a post-petroleum state might be managed with less disruption than otherwise appears to await us in this century.

If space flight became societally central again, and especially if large-scale space operations became as routine, robust, commercially based, and power-rich as they would have to be to industrialize GEO for terrestrial electricity, then human exploration and settlement would both be much smaller steps than the insurmountable cliffs they are today. Perhaps our dreams of walking on faraway sands, and of settling other worlds, are feasible, but not just yet. However, if we first become a trans-Earth civilization, these ambitions become in turn natural.

The US spends about ten billion dollars a year investing in human space flight; the other spacefaring nations altogether invest about as much. This enormous sum is more or less focused on the *Explore* path, motivated by Mars in the US, and it is proving to be very hard, with few opportunities for space architecture. If sustained through mid-century, this investment could put a few humans on an alien world more than twenty light-minutes away. Alternatively, capitalism and the strategic value of space resources might turn our space flight investment toward tangible societal benefits: we could bring the *Experience* of space flight within reach of mass markets, or we could choose to *Exploit* the inexhaustible clean energy available near Earth to transform humankind's impact on our home planet. Either of those paths would create a need for space architects to solve a broader, deeper range of design problems than getting a crew to Mars and back. By far the richest set of space architecture challenges—tabula rasa for designing our built environment and the most fundamental opportunity since our profession began—would arise if humanity set out on the path to *Settle* space.

The roadmap described here does not require us to suppress anybody's dream, or even reverse course; it uses everything already done or being built today. Its only novelties are to recognize that private capital must be attracted if progress is to accelerate; that *Exploit* is a defensible, practical, and achievable purpose that can do this while making space flight central again to a core societal challenge; that the profitable exploitation of space resources would in turn accelerate growth of the *Experience* industry; and that this commercial foundation would then significantly enable the *Explore* and *Settle* goals dreamed about for decades. If humankind threads the needle of this century's most vital terrestrial challenges, then someday we may make a second home for humankind—and take our first steps toward inhabiting the infinite.[13]

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[13]See also: Sherwood. Brent. 2011. Inhabiting the Solar System, Open Engineering, 1(1), 2011, pp 38–58, DOI: 10.2478/s13531-011-0004-y. Springer, March 2011.

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Chapter 3
Comprehensive Planning

Abstract Every exploration plan begins with determination of goals to be achieved and an outline of missions that have to be performed in order to attain selected targets. Comprehensive planning has to be applied when goals, requirements, and potential outputs are put together in one complete process for planning a space exploration mission. This chapter addresses general aspects of such a process, aiming to help students grasp a "big picture" space architecture vision. Examples of space missions that have already been performed and either completed or under way at this writing are used to illustrate the mission planning process through an overview of their statements and goals. Future exploration mission statements and goals are presented as examples of possible options.

3.1 Introduction and Chapter Structure

This chapter introduces the process to determine mission goals and requirements, from the definition of the mission statement to design concepts and their evaluation.[1] Comprehensive plans for space missions typically include a broad range of issues and cover a long-term time horizon. Although not all contributing factors can be extensively covered in this chapter, a main overview and assistance in further research is provided. Mission planning is similar to architectural programming (cf. Duerk 1993) when it is included with system engineering. Space Architecture concerns human spaceflight and creating safe and comfortable environments during space missions for the crew. A basic understanding of orbital mechanics, Kepler's and Newton's laws, propulsion requirement calculations, spacecraft systems, and operations design issues is recommended (Peters 2004).

The chapter's structure is divided in three sections:

- How to plan and where to start (Sect. 3.2)
- Types of space missions and their goals (Sect. 3.3)
- Missions requirements and constraints (Sect. 3.4)

[1]See Appendix for definitions of terms.

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Each section is divided into sub-sections to discuss issues in detail and describe particular settings. The chapter concludes with a guest statement by Marc Cohen[2] about space architecture mission planning and a statement from Madhu Thangavelu.[3]

3.2 How to Plan a Human Space Mission and Where to Start

Questions
What is the purpose of Space exploration? What are the reasons to choose a certain destination? Who is going there? What are the goals and performance related requirements? What is necessary to accomplish these goals? What is necessary for a comfortable environment for humans to live and work? What is necessary for a safe return? How to plan for future follow-up missions? Where can one begin with the design of a spacecraft or a habitat for a space exploration mission?

The point of departure for a successful planning process for any exploration mission is to identify goals based on thorough research questions and challenges to conquer. There are many restrictions and requirements driven by technology, environment, budget, timing, etc., which raise many questions and pose multiple challenges that have to be addressed. The major question out of all of them is *Why*?[4]

> The ultimate goal of human space exploration is to discover if life exists on other worlds, to understand the genesis and evolution of the universe, and to learn to live on other planets. (Cohen 1996, p. 1)

Although exploration in general is driven by the human desire to learn more about surroundings and to expand horizons for humanity, there are multiple reasons for exploring different environments that lead to specific mission goals for each destination. Table 3.1 summarizes some of the reasons for exploration missions to the Moon, Mars, and space in general for a better understanding of forming mission goals process.

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[2]Astrotecture™ Space Architect.

[3]USC University of Southern California, Department of Astronautical Engineering.

[4]Source for research: "Introduction to Space: The Science of Spaceflight" by Damon (1995, p. 217).

Table 3.1 Why do we explore? NASA [Voyages] (2012), Eckart (2006), Larson and Pranke (1999, p. 12)

General	Moon	Mars	Asteroids and comets	Space
Continue and strengthen the cooperation between the space faring partners	[Land people on the Moon and return them safely]	[Transport a human crew to Mars (and return them safely)]	Scientific knowledge about origins of the Universe and possibly life	Research laboratory in a microgravity and space environment (ISS)
Exploring the unknown—advancing science; Benefiting humanity Humanity as explorers (philosophical)	Discover the history of the Moon, Earth, Solar System, and the Universe	To gain new scientific knowledge of Mars and Earth	Potential resources collection asteroids mining	Test bed for technologies
Cultural and social	To sustain human life off Earth with in-situ resources	Perform in-situ science (signs of past and present life, solar system's origin, and history)		Gaining knowledge about Earth, Solar System, and the Universe
Economic and commercial use		To support technological and economic growth		
To inspire global achievement				

3.2.1 *Mission Goals and Objectives*

Mission goals and objectives spread much further than the destination of a space journey—they begin on Earth and come back to it in many aspects, including planning for future missions, future developments on Earth, and potential benefits that may be not very obvious at the beginning. This process includes a multi-staged progression with multiple retrievals and reviews, cross-discipline testing, and establishing relations between all components of design: physical, psychological, social, and environmental.

According to NASA, any mission[5] is achieved through strategic goals or objectives.[6] Each goal is pursued through specific performance goals that are synonymous with performance requirements. (NASA [Strategic] p. 15)

> A goal is a statement of intention, an end that one strives to attain or that toward which effort of play is directed. Goals are statements that move us to take action! They are vehicles for making design decisions. (Duerk 1993, p. 36) (Fig. 3.1)

[5]Mission = The core function(s) and primary job(s) of the Agency.

[6]Goal = Objective = A specific milestone or target level necessary to realize goals.

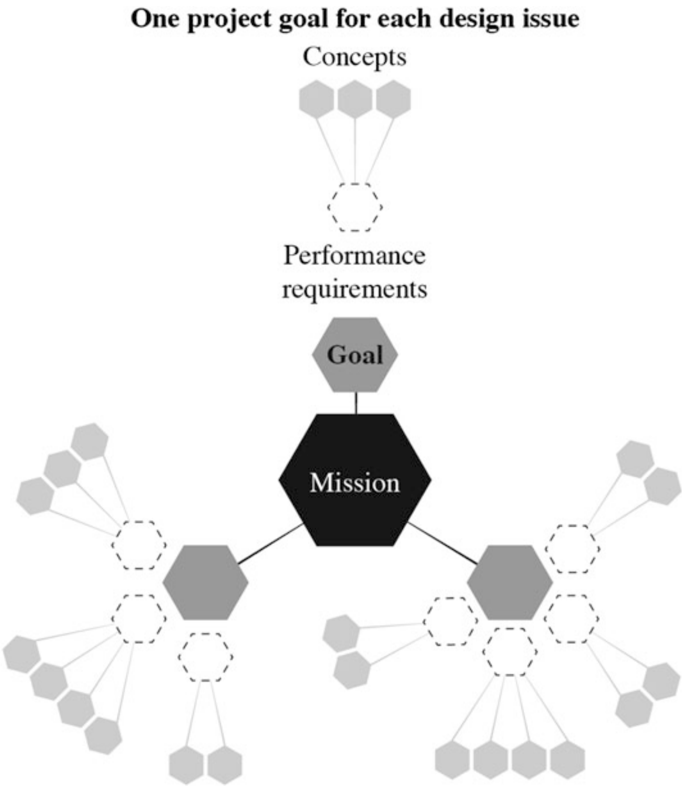

Fig. 3.1 Missions have multiple goals and requirements (Original model by Donna P. Duerk, adapted by the authors)

Planning and building future long-term space missions will challenge both technology and human endurance. According to current road maps,[7] planetary exploration missions' scenarios include short expeditions to the Moon and long-term manned missions to Mars. A human mission to Mars will include a long travel time (6–9 months) each direction and a stay on the planet's surface between 3 months and 2 years (see also Table 2.1 in Chap. 2) displays relevant mission aspects that have to be addressed beforehand in the planning and design phases.

Conditions of long-term space missions to Mars will differ significantly from conditions experienced by the crew during long time missions in Low Earth Orbit (e.g. Mir and ISS missions). During a long-term mission to Mars the degree of crew isolation, social monotony, and autonomy will be extremely high. It is documented

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[7]ISECG Global Exploration Roadmap, NASA; NASA/SP–2009-566-ADD2 Human Exploration of Mars Design Reference Architecture 5.0; ESA Roadmaps for Technologies for Exploration; Draft 2015 NASA Technology Roadmaps: http://www.nasa.gov/offices/oct/home/roadmaps/index.html.

that both isolation and the external environment in Polar Regions affect an individual's consciousness and somatic and mental health (Palinkas 1986; Barabasz 1991; Dudley-Rowley et al. 2002). Among the psychological challenges, which can be foreseen for future long-term missions, are the following: Lack of sensory variety; Total isolation and autonomy; Time factor and fatigue; and Group roles and leadership (Bannova and Jorgensen 2006).

3.2.2 Discussion and Tasks

Discuss reasons for human exploration of new worlds and space and the history of exploration on Earth. What was and is common between expeditions to new worlds on Earth in XVII, XVIII and XIX centuries and space exploration missions? Are there any correlations and lessons to learn? How may it affect space mission planning? Based on information in Tables 2.1 and 3.1, suggest three mission objectives for: transition flight to Mars, on Earth orbit (different orbits may be chosen), and near Earth asteroid mission.

3.3 Types of Space Missions and Their Goals

Each type of mission has certain goals that dictate particular requirements and constraints and result in different mission architecture and spacecraft design (Larson and Pranke 1999). Human aspects bring both more complexity and more opportunity for broader mission goals (Table 3.2).

Table 3.2 Types of current space missions

	Orbital	Flyby	Landing	Sample return
Robotic/success rate	Yes/high	Yes/medium to high	Yes/medium	Yes/high
Manned/success rate	Yes/medium to high	Destination dependable/n/a	Yes/high (Apollo)	Yes/high (Apollo)
Examples	Robotic: Cassini (Saturn orbit), Messenger (Mercury orbit) and Mariner (Mars orbit) Manned: Apollo, Skylab, Mir, ISS	Robotic: Voyager, Mariner—Venus (USA), Venera (USSR),	Robotic: Luna, Venera, Vega (USSR), Apollo, Mars Exploration rovers (USA), MIP (India), Chang'e (China), Manned: Apollo 11, 12, 14, 15, 16, 17(USA)	Robotic: Luna (USSR). Apollo (USA) Manned: Apollo (USA)

3.3.1 Performed Missions: Orbital (Manned and Robotic)

A mission is called orbital when a spacecraft orbits any celestial body, for example a planet, moon, asteroid, or star. The International Space Station is such a mission orbiting Earth. This is a very valuable type of mission. While a spacecraft is orbiting a celestial body, it can collect a large amount of useful data such as: surface observation, atmospheric and surface compositions, and other important dimensions and measurements such as a celestial body's diameter and mass.

A spacecraft requires a large amount of propellant to allow significant ΔV (see Appendix A.6: Glossary) for precisely orbiting a planet or another space object. If the spacecraft fails to do so it will either crash on the surface or miss the orbit and disappear into space. There is significant international experience in orbital missions with a high level of success.

Examples:

Apollo 8, 10, 13, Venus and Mars probes, Cassini (Saturn orbit), Messenger (Mercury orbit) and Mariner (Mars orbit) (Tables 3.3, 3.4 and 3.5).

ISS initial goals include:

The objectives established for the space station program over its lifetime include:

- demonstrating leadership in space
- forging international cooperation with Cold War allies
- conducting human biological research to benefit biology and medicine on Earth
- conducting materials research to benefit Earth
- serving as a construction platform for Lunar and Mars missions
- supporting ex-Soviet aerospace workers and institutions, and symbolizing post-Cold War US-Russian cooperation

Table 3.3 Cassini-Huygens mission: statement and goals (NASA [Missions] 2015)

Cassini-Huygens mission (Saturn and Moons 1997–2017)
Mission statement
Cassini—Saturn Orbiter and Huygens—Titan Probe (SOTP) provide information about Saturn and its rings/satellites, and collect data about Titan's atmosphere and surface
Goals
1. Determine the three-dimensional structure and dynamic behavior of the rings of Saturn 2. Determine the composition of the satellite surfaces and the geological history of each object 3. Determine the nature and origin of the dark material on Iapetus's leading hemisphere 4. Measure the three-dimensional structure and dynamic behavior of the magnetosphere 5. Study the dynamic behavior of Saturn's atmosphere at cloud level 6. Study the time variability of Titan's clouds and hazes 7. Characterize Titan's surface on a regional scale

Table 3.4 Messenger mission: statement and goals (NASA [Messenger] 1999–2015)

Messenger mission (Mercury, 2004–2015)
Mission statement
Understanding this “end member” among the terrestrial planets is crucial to developing a better understanding of how the planets in our Solar system formed and evolved. To develop this understanding, the MESSENGER mission, spacecraft, and science instruments are focused on answering six key outstanding questions that will allow us to understand Mercury as a planet
Goals
1. Acquire compositional and mineralogical information to distinguish among the current theories for why Mercury is so dense 2. Investigate the geologic history of Mercury in great detail, including the portions of the planet never seen by Mariner 10 3. Help to answer the question of why the inner planets differ in their magnetic histories 4. Determine the size of Mercury’s core and verify that Mercury’s outer core is molten 5. Find out if there are unusual materials at Mercury’s poles and what they are composed of 6. Find out if permanently shadowed areas that contain highly reflective material at radar wavelengths are ice, even though Mercury is the closest planet to the Sun 7. Discover important volatiles on Mercury 8. Measure the composition of Mercury’s thin exosphere, providing insights into the processes that are responsible for its existence

Table 3.5 International Space Station: statement and goals (NASA [ISS] 2015)

International Space Station (Earth Orbit, 1997–2024 (tentative))
Mission statement: the International Space Station combines unique possibilities for developing science, technology, and human innovations that demonstrate new technologies and make research breakthroughs not possible on Earth to benefit life on Earth
Goals
1. Develop the best strategy to plan, coordinate, and monitor the varied activities of international partner organizations 2. Develop human health support and measures for crewmembers’ protection from the space environment during long-duration space exploration flights 3. Test research and technology innovations for future exploration missions 4. Develop and validate operational procedures for long-term missions 5. Provide a platform for global education 6. Provide Earth observation to benefit disaster relief efforts

- learning how to construct large structures in space
- learning how to operate in space
- providing an engineering testbed for space equipment
- conducting human biological research to support future long-duration space missions
- pork barrel politics

There has never been a single document that listed these justifications and objectives for the program. Nevertheless, all of them have appeared in some official form or another since the creation of the space station program—in speeches, budget documents, memos, and other international records (Day 2005).

3.3.2 Performed Missions: Flyby (Robotic)

During a flyby mission, a spacecraft flies close to a celestial body, collecting maximum information about it and then continues its mission without orbiting. Currently flyby missions continue sending data and pictures of planets and rings, ring composition, composition of atmospheres, planets' diameters and mass, composition of the planet itself and planet's core, plus other valuable information. Spacecraft for such missions have to be designed with increased durability and redundancy. This type of mission beyond Mars cannot be crewed with the current technology, due to length of the flight and the associated hazards for humans. Flyby missions to the Moon and Mars or asteroid belt can be crewed if orbital trajectories allow in-flight time within human survivability requirements.

Examples:

Voyagers 1 and 2 flyby missions delivered data about the four gas giants of the Solar system: Jupiter, Saturn, Uranus, and Neptune. They are the most successful and well-known space probes. Both of the Voyager missions are unmanned and were launched in 1977. They were designed to study planetary systems of Solar system giants but continued their journey into interstellar space. In addition, the trajectories of the two spacecraft have been used to place limits on the existence of any hypothetical trans-Neptunian planets (Table 3.6).

3.3.3 Performed Missions: Surface Landing (Manned and Robotic)

Missions to the surface of a celestial body usually include goals related to sample collection, surface observation and imaging, analysis of atmosphere and soil, water tracing, and temperature records. Advanced missions may also include measuring radiation levels on and under the soil surface.

Table 3.6 Voyager mission: statement and goals (NASA [Missions] 2015)

Voyager mission (Outer Solar System, 1977–current)
Mission statement
Extend the NASA exploration of the solar system beyond the neighborhood of the outer planets to the outer limits of the Sun's sphere of influence, and possibly beyond
Goals
Primary mission was the exploration of Jupiter and Saturn and was extended to include 1. Explore Uranus and Neptune. Voyager is the only spacecraft to have visited those outer planets 2. The Voyager Interstellar Mission (VIM) will explore the outermost edge of the Sun's domain 3. Continue to characterize the outer solar system environment 4. Search for the heliopause boundary, the outer limits of the Sun's magnetic field and outward flow of the solar wind 5. Penetration of the heliopause boundary between the solar wind and the interstellar medium to measure the interstellar fields, particles and waves unaffected by the solar wind

Robotic landing missions include only descending stage and do not plan for probes or rovers to be returned to Earth. Future landing missions will be precursor missions and dedicated to deliver surface modules for extended surface stays for humans or to establish surface settlements for long-term human presence on the planet. Surface landing missions demand the design of advanced systems that can provide a soft surface landing, which usually includes propulsive landing to avoid the crash of fragile equipment on unpredictable terrain of foreign worlds. The hostile environment of Venus required extra thermal protection for the spacecraft to survive, which lead to a significant increase of the lander's and overall spacecraft mass.

Examples:

Apollo 11, 12, 14, 15, 16 and 17 missions were manned and sample return missions. Most successful robotic landing missions up to date are: Moon—Luna 16, 17, 20, 21 and 24, Indian MIP, Chinese Chang'e; Mars—Spirit, Opportunity, and Curiosity. Venus—Venera 5–14 landers survived between 23 min (Venera 7) and 127 min (Venera 13). Vega 1 and 2 also landed on the surface of Venus and transmitted data for about an hour each (Table 3.7).

3.3.4 Performed Missions: Sample Return (Manned and Robotic)

Sample return missions can be robotic and manned or a combination of both. A major goal of such missions is to collect the maximum number of surface samples from diverse locations on a celestial body for future thorough analysis on Earth. This type of mission is essential and is required prior to establishing any type of permanent or long-term human presence on a planet's surface.

Table 3.7 Apollo 11 Mission: Statement and Goals (NASA [Missions] 2015)

Apollo 11 mission (The Moon, 1969)
Mission statement
Complete a national goal set by President John F. Kennedy on May 25, 1961: perform a crewed lunar landing and safe return to Earth
Goals
1. Scientific exploration by the lunar module, or LM, crew 2. Deployment of a television camera to transmit signals to Earth 3. Deployment of a solar wind composition experiment, seismic experiment package and a Laser Ranging Retroreflector 4. Gather samples of lunar-surface materials for return to Earth 5. Extensively photograph the lunar terrain, the deployed scientific equipment, the LM spacecraft, and each other, both with still and motion picture cameras

Examples:

Apollo 11, 12, 14, 15, 16 and 17 missions were manned and planned as sample return missions. Multiple robotic sample return missions have been accomplished by NASA, the Soviet Union, and Russia. Successes of recently emerging space nations such as China and India demonstrate their capabilities to perform further exploration, including sample return missions (Table 3.8).

Table 3.8 Apollo 17 mission: statement and goals (NASA [Missions] 2015)

Apollo 17 Mission (The Moon, 1972)
Mission statement
To expand geological knowledge of the Moon, land in the Taurus-Littrow highlands and valley area where older and younger rocks than previously returned from other Apollo missions could be found and researched
Goals
1. Geological survey and sample materials and surface features in a preselected area of the Taurus-Littrow region 2. Deploy and activate surface experiments 3. Conduct in-flight experiments and photographic tasks during lunar orbit and trans earth coast 4. Apollo Lunar Surface Experiments Package, or ALSEP, with a heat flow experiment 5. Lunar seismic profile, or LSP 6. Lunar surface gravimeter, or LSG 7. Lunar atmospheric composition experiment, or LACE 8. Lunar ejecta and meteorites, or LEAM 9. Lunar sample and lunar orbital experiments 10. Biomedical experiments included the Biostack II experiment and the BIOCORE experiment

Table 3.9 Future space mission aspects and characteristics

	Orbital	Landing/sample return	Sortie	Outpost	Long-term
Precursor —robotic missions	Fuel depot, assembly operations, logistic support	Rovers, landers, and ascent stages (sample return)	Rovers, landers, and ascent stages	Habitat, support elements, surface transportation	Habitat, support structures, and mechanisms, ISRU
Manned	Scientific labs and production facilities, space hotels	Limited EVAs, manned rovers, landers, and ascent stages	Minimal habitat, landers, and ascent stages	Habitat, logistics, landers, and ascent stages	Multiple habitats, extended logistics, landers, and ascent stages
References	ISS as a prototype, Bigelow aerospace	Asteroid mining	Constellation program, MFHE study	Constellation program, MFHE study	NASA's global exploration roadmap, Moon and Mars surface missions

Destinations include: asteroids, cis-lunar, Moon, Mars, Phobos and Deimos, and Earth orbit

3.3.5 Future Exploration Missions

Future manned missions revealed in NASA's global exploration roadmap (ISECG 2013) will require extensive preparation and a number of precursor robotic missions, while maximizing "synergy between human and robotic missions" (ISECG 2013, p. 14). Although robotic and manned flights are often parts of common mission architecture, their goals should be coordinated in order to reach overall mission success (Table 3.9).

The document "Main outlines of fundamentals of state policy of Russian Federation in the sphere of space activity for the period until 2030 and further perspective"[8] proposes a manned mission to research the Sun, Mars, Venus, the system of Jupiter, the planets and small bodies of Solar System, and asteroids with the assistance of automatic spacecraft and international cooperation. It is planned to conduct new projects, such as space electric power stations, storing nuclear waste, and industrial manufacturing of various materials in space (Bannova and Mayorova 2014).

Analog (and/or test-bed) missions are a necessary step in preparation for any space endeavor and have to be planned and executed in accordance with anticipated space mission goals. Analog missions are discussed in the Chap. 6.

[8] http://federalbook.ru/files/OPK/Soderjanie/OPK-11/V/Osnovnie%20pologeniya.pdf (in Russian).

3.3.5.1 Precursor Robotic Missions

Precursor robotic missions do not involve humans during spaceflight and deployment operations. Still, they have to be planned to integrate human factor design aspects. For example: Orbital assembly missions must be planned in accordance with the crew arrival point and their integration into mission operations. Pre-deployed habitats and support structures on the surface of the Moon or Mars have to be located in close proximity to the crew landing site but a safe distance from it to avoid possible damage from ejecta during landing operations. Offloading systems and transportation paths from landing sites to final destinations should be fully developed and operational.

Special attention has to be given to systems that the crew will be monitoring and maintaining routinely throughout the flight and operations related to EVAs (Extra Vehicular Activities). For example, life support and power systems, EVA support devices inside habitat, and the means for surface exploration should be coordinated.

3.3.5.2 Following Manned Missions

All orbital manned missions' goals comprise scientific data collection with possible development of technology transfer initiatives, and crew safe return and/or deployment for further destinations. Scientific data includes surface observations, atmospheric measurements, possible landing sites observations, and evaluations.

Sortie missions usually follow robotic precursor missions when some surface elements are already placed on the surface. Sortie missions aim to collect maximum data during a short surface stay, possibly to leave assets on the surface for follow-up missions, and safe return.

Landing and sample return missions' goals are similar to sortie missions. In addition, the crew performs sample collection and basic scientific research, leaving assets on the surface, and safe return.

Outpost missions require a significant number and value of precursor missions with multiple surface elements pre-deployed. Establishing an outpost on the surface of a planet has to have long-term perspectives and goals. They include developing and testing ISRU procedures and techniques, assembling or constructing basic infrastructure elements for outpost evolutionary growth, and providing means for crew safe return.

Settlement missions usually follow outpost missions and are the next step of an outpost's evolutionary growth. Settlement missions require establishing continuous ISRU operations and habitation with increasing level of sustainability and autonomy from Earth support. These missions should provide support for multiple operations for ascent and return to Earth.

3.3.6 Discussion and Tasks

Analyze and compare requirements and constraints for surface missions to the Moon, Mars, and Venus based on an historic overview. What objectives and goals were outlined for these missions? What had to be done to meet their requirements and fulfill the goals?

What is the major determination driver for a precursor robotic mission? What is it for a manned mission? What is the same and what is different? (e.g. Mass reduction versus crew safety.)

3.4 From Goals to Requirements to Constraints

Questions for Exploration
What do people need during a space flight? What systems and/or subsystems are required and safe to use? Why is a systematic approach needed? How can human systems and habitability be validated?

3.4.1 Human Spaceflight Requirements

> The requirements and constraints for any mission depend on the mission itself and how we implement it. (Larson and Pranke 1999, p. 21)

Having defined a mission and its goals, requirements and constraints have to be examined. Often things can be learned from previously completed missions. Different kinds of definitions for requirements exist. "*Functional requirements define how well the system must perform to meet its objectives. Operational requirements determine how the system operates and how users interact with it to achieve its broad objectives. Constraints limit cost, schedule, and techniques for carrying out the mission*." (Larson and Pranke 1999, p. 21).

Missions can have hundreds of requirements. The more in detail we look at missions, the more challenging it gets to define the criteria. Standards have been developed to address those criteria (NASA [Standards] 2014). Current approaches to designing human missions are greatly based on the **Human-in-the-loop approach** (NASA [Guidelines] 2003, p. 11) that include the following requirements:

- *Requirement 13: The vehicle shall provide the flight crew on board the vehicle with proper insight, intervention capability, control over vehicle automation, authority to enable irreversible actions, and critical autonomy from the ground.*

- *Requirement 14: The flight crew shall be capable of taking manual control of the vehicle during all phases of flight. The vehicle shall exhibit Level I handling qualities as defined by the Cooper-Harper Rating Scale (a scale used to determine how effective aeronautical modifications are).*
- *Requirement 15: The spacecraft displays and controls design shall be based on a detailed function and task analysis performed by an integrated team of human factors engineers with spacecraft displays and controls design experience, vehicle engineers, and crewmembers. Solutions in this design area shall not be limited to those solutions derived from experience with Shuttle if newer or alternative concepts are applicable.*
- *Requirement 16: Mission design, including task design and scheduling, shall not adversely impact the ability of the crew to operate the vehicle.*

The only requirement related to mission planning is requirement 16, which is referring to people as vehicle operators. As such they are not allowed to interact with or adapt the environment they live and work within to their needs. This can become an issue contributing to psychological repercussions during a spaceflight. Personalizing a private place is one of the important contributing factors for mitigating extreme feelings of isolation and loneliness (cf. Kanas 2011; Kanas and Manzey 2003).

The space architecture approach enables mission planners and spacecraft designers to incorporate human aspects into the whole design process to provide stimulating and optimized living and working environments for the crew along with helping to establish effective relationships between humans and their environment. Mission statements' examples can be found in the following sub-chapter 'Overview of types of current space missions'.

The NASA Space Flight Human Systems Standards (NASA-STD-3001) applies to all present and future systems with a human crew. It covers the requirements for system design needed to support astronaut health, safety, and performance.[9]

Table 3.10 gives examples of some human space flight requirements along with their rationale.

3.4.2 Technology Readiness and Habitation Readiness Levels

Systems, subsystems, or elements of a future spacecraft, habitat, or any other structure have to be appropriate to mission goals and a space mission planner and designer has to understand how reliable the spacecraft is Technology Readiness

[9]Further Resource: NASA Developed Technical Standards can be found at: https://standards.nasa.gov/documents/nasa.

Table 3.10 Human space flight requirements and their rationale (NASA [STD 3001-2] 2011, Authors)

Requirement	Rationale	Discussed in chapter
Windows	Integral part of space flight operations [psychological reasons?]	Sections 4.3 and 5.4
Lighting	Integrated into space module structure and/or personal crew quarter elements	Sections 4.2 and 4.3
Standardization	Rack systems, utilities runs and packaging have to comply with allowable area and volume	Sections 5.3 and 5.4
Food and Nutrition	Combination of dry and frozen food. Growing supplementary food is desirable but optional. Growing food is mandatory for long missions	Section 4.3
Recycling	Maximize sustainability and minimize launch mass and volume requirements for consumables	Section 5.5

Levels (TRLs) have been established for that purpose. Technology Readiness Levels describe the maturity of a technology with respect to TRL development stages. They are used to assess a certain technology or system, in order to identify its 'readiness', and how well it performs and meets the established goals, as well as identifying the associated risks. They are widely used by different agencies and industries for system and element evaluation and validation. Table 3.11 introduces the TRLs' definitions according to NASA (NASA [TLR] 2012) and ESA.

According to the ESA (2008, pp. 33–34) TRL Handbook, the TRL philosophy is as follows:

The first 4 levels are used to increase the level of functionality of the tool, from the mathematical formulation through prototyping up to incremental enhancement at the level of an 'alpha' (preliminary) version.

The next two are used to improve the tool up to the level of a (commercial or otherwise) released product.

The last three levels cover the deployment of the tool in a space project, starting with a pilot application up to a fully operational project.

Besides the TRLs, there are many other approaches to assessment. Other system assessment processes and tools include System Readiness Levels (SRL), Integration Readiness Levels (IRL), Software Readiness Level (SRL), Operational Readiness Level (ORL), Programmatic Readiness Level (PRL), Design Readiness Levels (DRLs) and the Habitation Readiness Levels (HRLs). All these assessment tools evaluate the level of performance for a particular set of requirements.

Table 3.11 Listing of technology readiness levels in respect to common engineering terms, and explanation and examples (Mankins 1995; European Space Agency [TRL] 2008; Cohen 2012)

TRL	TRL definition (commonly used engineering/R&D terms)	Explanation and examples
TRL 1	Basic principles observed and reported (scientific research)	At this level, basic scientific research has resulted in the observation and reporting of basic principles. Example: scientific research of basic properties of materials, such as nanotechnology applied to generate more efficient solar cells, thermo-regulating materials, radiation shielding
TRL 2	Technology concept and/or application formulated (systems analyses, pre-phase a studies)	Identification or 'invention' of practical applications for observed physical principals. Example: potential applications of a new superconducting material for thin film devices and in instruments
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept (laboratory experiments)	Initiation of active research and development of the concept elements. This includes both analytical and experimental approaches to proving a particular concept. (Elements of a fabrication device for thin film silicon solar cells development on the Moon: proof-of-concept lab research)
TRL 4	Component and/or breadboard validation in a laboratory environment (component, breadboard)	Active research and development of the concept as a system. Example: fabrication of thin film silicon solar cells on the Moon project
TRL 5	Component and/or breadboard validation in a relevant environment (high-fidelity breadboard, engineering breadboard, function-oriented model)	Validation of the total applications (component-level, sub-system level, or system-level) in a 'simulated' or somewhat realistic environment. Example: VASIMR propulsion system elements vacuum chamber testing
TRL 6	System/subsystem model or prototype demonstration in a relevant environment—ground or space (high-fidelity laboratory prototype, engineering qualification model. subsystem model, system model)	The innovative approach is demonstrated by an actual system prototype in a space environment. The demonstration might represent an actual system application, or it might only be similar to the planned application, but using the same technologies. Example: All-Terrain Hex-Limbed Extra-Terrestrial Explorer, (ATHLETE) demonstration; Desert RATS Field Tests on the Black Point Lava Flow in Arizona; model of a system tested with a scale model

(continued)

Table 3.11 (continued)

TRL	TRL definition (commonly used engineering/R&D terms)	Explanation and examples
TRL 7	System prototype demonstration in a space environment (system demonstration)	An actual system prototype is demonstrated in a space environment. TRL 7 would normally only be performed in cases where the technology and/or subsystem application is mission critical and relatively high risk. Example: Mars rovers: Spirit, Opportunity, Curiosity; unmanned Orion test flight
TRL 8	Actual system completed and “flight qualified” through test and demonstration—ground or space (theoretical first unit, flight unit, flight spare)	In almost all cases, this level is the end of true ‘system development’ for most technology elements. Example: sky-crane soft landing technique delivered curiosity rover to Mars and crashed in a safe distance from the rover
TRL 9	Actual system “flight proven” through successful mission operations (mission operations, flight qualified hardware)	In almost all cases, the end of last ‘bug fixing’ aspects of true ‘system development’. Example: loading and testing new control algorithms and software updates of curiosity rover computer system

Because of their relevance to habitation, ‘Habitation readiness Levels’ were formed by a group of NASA engineers (Connolly et al. 2006). They have been created to address habitability requirements and design aspects in correlation with already established and widely used standards by different agencies, including NASA TRLs (Table 3.12).

3.4.3 *Discussion and Tasks*

Discuss characteristics and requirements of TRL 1 and 2. What about known or emerging technologies can be considered to satisfy them? Consider using HRLs for justification of habitability of an artificial environment for the crew. Where and how it can be tested? Find and discuss examples.

Table 3.12 Habitation readiness levels and its relation to technology readiness levels (Connolly et al. 2006)

Habitation systems research	Research and design levels	Habitat subsystem technologies should have the following TRL
Habitation systems research (Level 1)	Level 1: human factors, crew systems, and life support research related to habitation systems	Any TRL
Conceptual and functional feasibility of the technology (Level 1–4)	Level 2: habitation design and concepts, functional and task analysis	Any TRL
	Level 3: internal configuration, functional definition and allocation, use of reduced scale models	TRL 6 or higher
	Level 4: full-scale, low-fidelity mockup evaluations	TRL 6 or higher
Demonstration of the technology (Level 5–6)	Level 5: full-scale, high-fidelity mockups, human testing and occupancy evaluations	TRL 6 or higher
	Level 6: habitat and deployment field testing	TRL 7 or higher
Testing of the technology and technology operations (Level 7–8)	Level 7: pressurized habitat prototype testing	TRL 8 or higher
	Level 8: actual systems completed and "flight qualified" through test and demonstration	TRL 8 or higher
	Level 9: actual system "flight proven" through successful mission operations	TRL 8 or higher

3.5 Guest Statement: Mockups 101: Technology Readiness Levels for Mockups and Simulators (Marc M. Cohen)

NASA and other agencies have adopted the taxonomic approach of classifying technology development projects by *technology readiness levels*. This system is useful for understanding where a technology or project stands in the development process. It is relevant to mockups and simulators, which can prove useful at nearly every level (except—for now—at the in-space TRLs). At each TRL, the mockup displays particular attributes. Table 3.13 explains these correlations. Nolte and Kruse (2011) warn against the proliferation of readiness levels, that is, the creation of new definitions for technology readiness to match specialized circumstances. Indeed, in the 2003–2005 period, there was an effort within NASA (Connolly, Daues, Howard, Toups) to create a new "habitation readiness scale," but this paper heeds the Nolte and Kruse warning and so adheres to NASA's established TRL

Table 3.13 Technology readiness levels (TRLs) in relation to mockup attributes

TRL	General description	Mockup-specific attributes	Typical materials	Remarks
1	Basic principles observed	Conceptual design to show that X can exist with attributes Y and Z	Foamcore, cardboard, sintra board	Scale models usually work as well as full-scale mockups
2	Concept formulation, modeling, and simulation	Control design variables for dimensions	Plywood, sintra board, wood	Architectural experiments
3	Proof of concept	Form, fit, function, mechanical operations	Metal, plastic, wood	Engineering integration phase
4	Component/subsystem test in a laboratory environment	Functional and operational research	Electronics, mechanical systems	Includes part task flight simulator
5	Subsystem test in a relevant environment	Partial habitable living and working environment simulation	Electronics, mechanical systems, atmospheric system	Includes motion-base flight simulator
6	System test in a relevant environment	Full habitable living and working environment simulation	Electronics, mechanical systems, hypobaric atmosphere	Includes high fidelity mission simulator

scale, adjusting instead the ways and means of achieving those clearly defined levels.

The TRLs correlate *explicitly* to the mockup/simulator attributes. At a deeper level, the mockup/simulator attributes correlate i*mplicitly* to the fidelity of the analogue. *Degrees of fidelity* would be a separate discussion that is beyond the scope of the present essay.

This section presents examples of mockups and simulators that display the characteristics and properties described in Table 3.13. This series of examples is not intended to be comprehensive to show all possible types of solutions. Mohanty et al. (2008) present such a wide-ranging survey. Rather, it illustrates the level of development, refinement, and integration that occurs in analogue research. This section is organized into two parts. The first part addresses the early TRLs 1–3 that do not rise to the level of a complete "environment." The second part addresses the mid-range TRLs 4–6 that all reference a test in a "laboratory" or "relevant" environment. The higher TRLs 7–9 all involve testing or operation in the space environment, which up to this writing have never involved a habitability mockup or other analogue except insofar as Stuster (1986) suggests one space station as an analogue for a future space station.

The ESA (2008, p. 33) TRL Handbook states a *TRL philosophy* that offers a somewhat different overview:

- The first 4 levels are used to increase the level of functionality of the tool, from the mathematical formulation and through prototyping and incremental enhancement up to the level of an "alpha" version.
- The next two are used to improve the tool up to the level of a (commercial or otherwise) released product.
- The last three levels cover the deployment of the tool in a project, starting with a pilot application (an IOD) and up to a fully operational project.

A caveat about this section is that most of the TRL literature focuses upon the validation to certify that a technology has achieved a particular TRL. The following summary uses TRLs to describe the whole effort to bring a technology from the earlier level to the one by which it is labeled.

3.5.1 TRL-1 Basic Principles Observed and Reported

TRL-1 is basic scientific research that the investigators can turn into an application or a concept under a research and development program. The imperative of TRL-1 is that it must suggest a path to future development. TRL-1 marks the point where scientific research begins to provide the basis for a new technology, whether it is a material, a process, a machine, or something else. Basic research and physical or computational models help to substantiate the basic principles observed. Scale models also play an important role and can be very cost-effective for representing three-dimensional relationships, but they are part of a different discussion.

1. **Altair Lunar Lander Ascent Module Basic Mockup—Chamber Class A**[10]

Kriss Kennedy and Larry Toups at NASA-JSC designed the mockup shown in Fig. 3.2a, b. Its purpose primarily was to understand the rough volume that would become available in the Altair Ascent Module. It is made entirely of Foamcore board except for the plywood representation of the engine head in the floor. Behind the engine head is the "EVA hatch," modeled upon the Apollo Lunar Module EVA hatch.

2. **Altair Ascent Module and Airlock Sizing Mockups—Chamber Class A**

Robert Howard at NASA-JSC oversaw the development and operation of this low fidelity simulator to understand the constraints and possibilities in cylindrical ascent modules of varying diameters. Each of the two cylinders is made of Foamcore and suspended from a wooden "A-frame." The cylindrical forms of the cabin consist of overlapping, curved sheets of Foamcore that can expand and contract over the range of likely diameters. The research staff can install Foamcore boxes to represent various outfitting and stowage, and install bunks to estimate crew living conditions.

[10]Chamber Classes are explained in Appendix A.5, Table A.2.

This sizing mockup is probably the most successful and useful TRL-1 apparatus of its kind that the author has found. Figure 3.3a shows the two cylinders with the bungee cords that constrained the outer diameter. Figure 3.3b shows the interior of the Ascent Module with four bunks installed in front of the pilot station/flight deck and piloting windows.

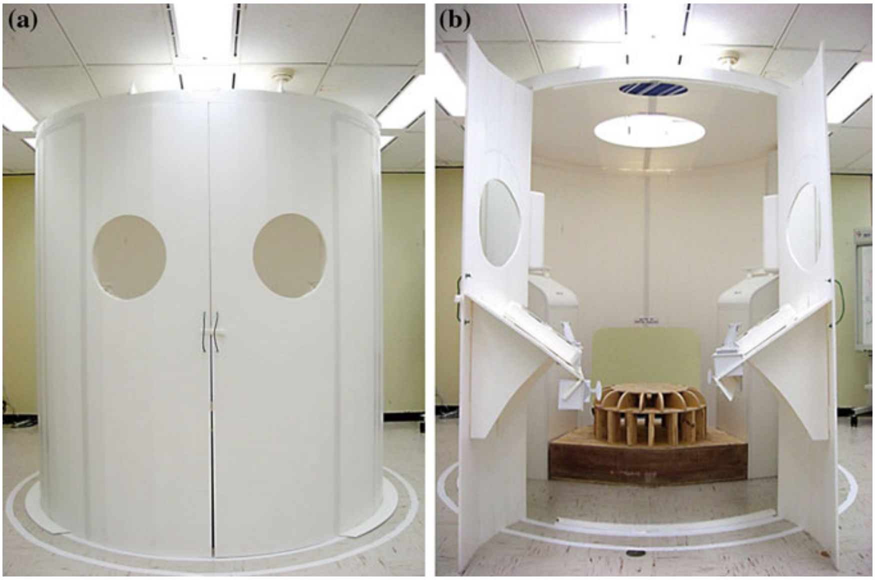

Fig. 3.2 **a** Exterior view of the Altair Ascent Module Mockup, showing the pilot windows (Cohen 2006). **b** View of the Ascent Module interior with the engine head represented on the floor and the "EVA Hatch" behind it (Cohen 2006)

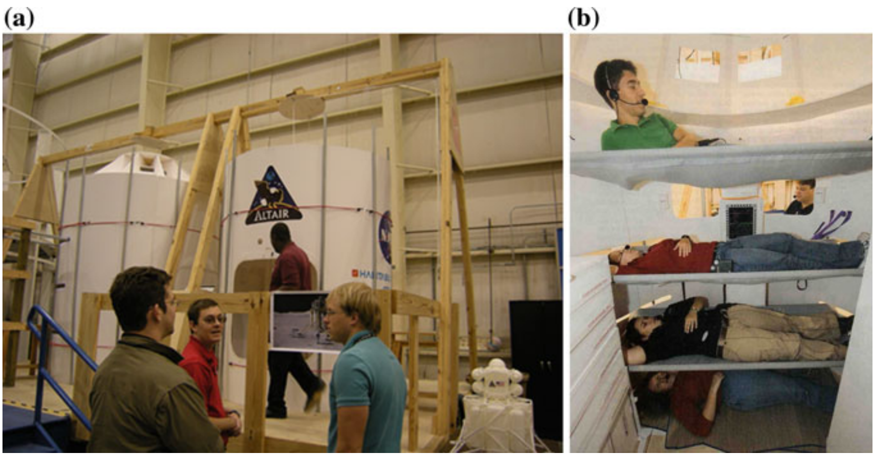

Fig. 3.3 **a** Altair Sizing Mockups: Ascent Module to the *left* and the Airlock Module to the *right* (Cohen 2006). **b.** Crew bunks in the Ascent Module Mockup (Cohen 2006)

3.5.2 TRL-2 Concept or Application Formulation

TRL-2 is when invention begins. In the case of space habitats, TRL-2 involves the schematic design of hardware and habitat configurations. The concepts begin to use fixed dimensions and to integrate with practical pressure vessel shapes and sizes. For the mockup to succeed, it must prepare to accept all the engineering systems: architectural, electrical, fire protection, lighting, mechanical, and structural. That does not mean that the concept formulation must incorporate or represent those engineering functions and interfaces, but it must demonstrate a cognizance of them and preparation to accommodate them at higher levels of development. This characteristic becomes increasingly important when planning to meet the code and standard requirements for the crew in a potentially closed environment. Often it is possible to achieve TRL-2 for Space Habitats with drawings or scale models, but full-scale mockups carry a special power of empirical knowledge through experience.

1. **Spacelab/Space Station CELSS Plant Growth Chambers—Chamber Class B**

At the time of the design of these Controlled Ecological Life Support System (CELSS) chambers in 1984, the Spacelab module was flying on the Space Shuttle, and it provided the functional cross section of the module in which to integrate these research "racks." Space Station modules were still quite speculative, so the project followed the Spacelab template. The module shell conformed to the dimensions of the Spacelab module, with the floor deck at about the same height, and the hung ceiling unit coming down to the height of the Spacelab module. The project plan called for eventual integration with the electrical, data, and life support systems (Figs. 3.4 and 3.5).

2. **TransHab Mockup—Chamber Class A**

The TransHab project at NASA JSC developed a concept for a large "fat tire" inflatable toroid around a rigid Endoskeletal core (the "axle"). The architects were Constance Adams and Kriss Kennedy. Because of the difficulties in attaching equipment or outfitting to the pressure bladder of an inflatable, the architects

Fig. 3.4 Spacelab module in use during the Shuttle Flight STS-51B (NASA)

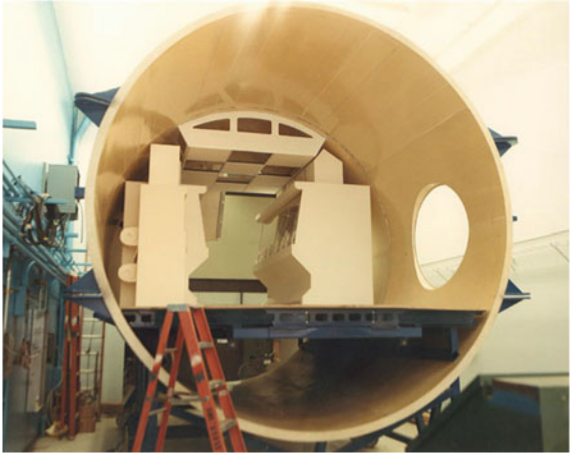

Fig. 3.5 Mockups of plant growth chambers for CELSS experiments for Robert McElroy in a Spacelab-type configuration (NASA)

developed a full-scale mockup in which to portray and evaluate their design concepts. Figure 3.6a, b shows views of the TransHab mockup, built from traditional flat and rigid materials to convey the rigid structural endoskeleton (axle) of the TransHab Concept. The TransHab mockup was a landmark of TRL-2 concept formulation because it displayed credibly how the interior of this toroid could be made useful.

The mockup represented portions of different floor deck levels with typical outfitting such as the crew sleep quarters surrounded by 10 cm water tanks for radiation protection. The spatial division incorporated vertical triangle grid walls for mounting equipment in the tradition of Skylab (Skylab Program Office 1974). The galley/dining area included an oval table with foot and leg restraints.

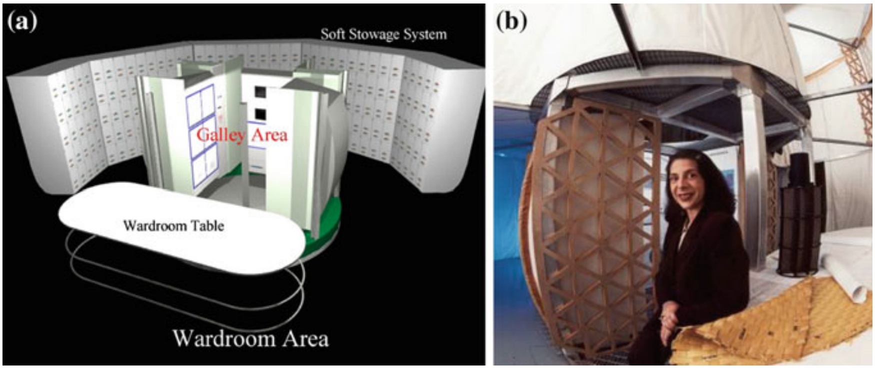

Fig. 3.6 **a** CAD rendering of the galley and wardroom area, showing the wardroom table with leg and foot restraints (Lockheed/NASA rendering). **b** Constance Adams in front of the Endoskeletal core of the TransHab Mockup (Marc M. Cohen)

The TransHab mockup was highly successful insofar as it led to developing the complete inflatable TransHab module that NASA licensed the technology to Bigelow Aerospace for a future space hotel.

3.5.3 TRL-3 Proof of Concept

The TRL-3 Proof of Concept means demonstrating one or more critical functions or characteristics of the new technology. In Space Architecture, Proof of Concept requires a full-scale, physical representation, although it may not require a complete habitat environment. This human-scale mockup must make it possible for the crew or human subjects to operate the critical functions (Fig. 3.7).

1. **Space Station Wardroom Table—Chamber Class Not Applicable**

The Space Station Wardroom Table was a joint project between the Southern California Institute of Architecture (SCI-Arc) and NASA Ames Research Center. Prof. David Nixon was the principal investigator on the NASA cooperative agreement, and the co-inventors were Jan Kaplicky of Future Systems, London, and the author. The team achieved Proof of Concept by demonstrating that crewmembers could use the table to support a variety of tasks and deployed its several segments to accommodate a variety of crew activities.

2. **Suitport in the HazMat Vehicle—Chamber Class C for the Vehicle, Suitport, and Suit**

The Suitport is a concept for rapid suit donning and doffing, egress from a space cabin atmosphere and ingress back into it, while conserving atmosphere, electrical power, cooling, and crew time. It also offers potential advantages for contaminant control, particularly to prevent the intrusion into the crew cabin of contaminants such as dust or hazardous chemicals, with the assistance of air conditioning over-pressure. The Proof of Concept for the Suitport occurred by building two Suitport mockups into the aft bulkhead of an armored personnel carrier called the HazMat Vehicle.[11] Validating the Suitport at TRL-3 involved demonstrating the crewmember could don the suit through the Suitport, egress the Suitport in the bulkhead, and return to the Suitport, doff the suit and reenter the cabin (Fig. 3.8).

3.5.4 TRL-4 Validation in a Laboratory Environment

TRL-4 constitutes a Component/Breadboard Validation in a Laboratory Environment. The laboratory environment can take a number of different forms. It can consist of a laboratory benchtop, a simulation in an environmental chamber, or a naturalistic test in a “field laboratory,” among many other options.

[11] Philip Culbertson, Jr. was the industrial designer who produced this Suitport demonstrator/mockup.

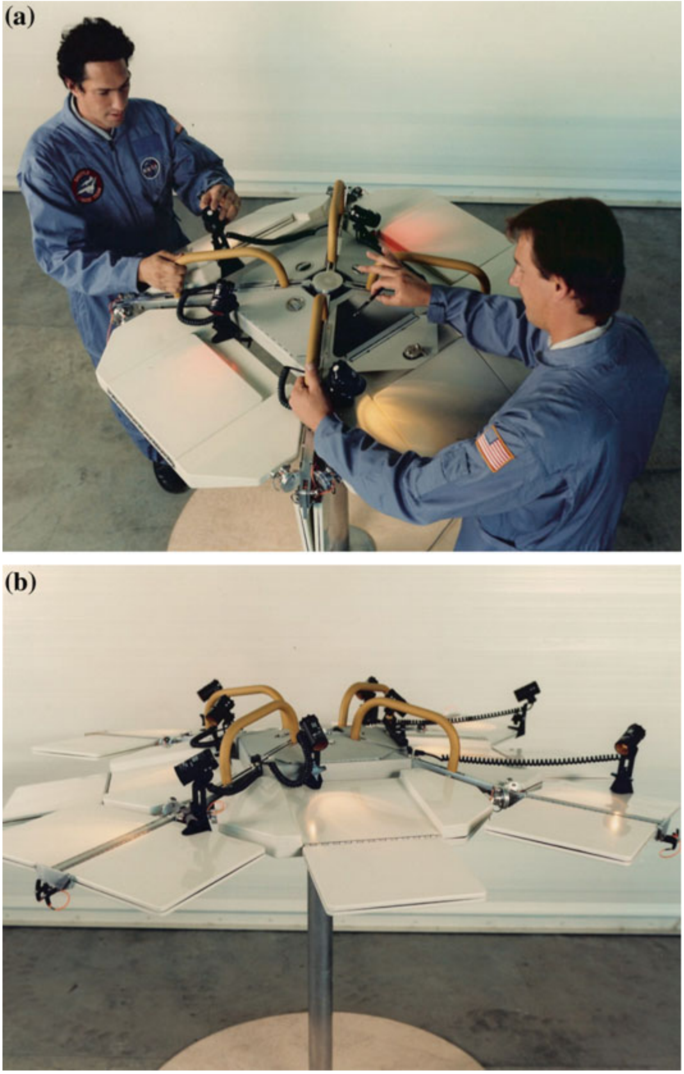

Fig. 3.7 **a** The author and Christopher R. Miller demonstrating the Space Station Wardroom Table in its compacted configuration (NASA 1991). **b** Close-up view of the Space Station Wardroom Table in fully unfolded and deployed configuration (NASA 1991)

1. **Space Station Proximity Operations Simulator—Chamber Class B to C**[12]

The Space Station Proximity Operations Simulator was a project to build and operate a simulator that would be capable of world-class research in orbital

[12]Chamber Classes are explained in Appendix A.5, Table A.2.

operations. It offered the capability to "fly" spacecraft in a virtual out the window environment, to simulate rendezvous and docking, and navigational maneuvers. The Prox Ops included the first voice recognition/voice synthesis display in a space simulator, a 3D color "God's eye" navigation display, and video display of scale model operation of spacecraft. The operator could select a spacecraft in the three-screen out the window display and fly it using the standard Shuttle side-arm controller. The Prox Ops Simulator appears in Figs. 3.9 and 3.10. Richard Haines managed the project to achieve TRL-4 by validating component and breadboard operation within several "integrated mission simulations" and by supporting research that was published in more than 20 peer-reviewed articles.

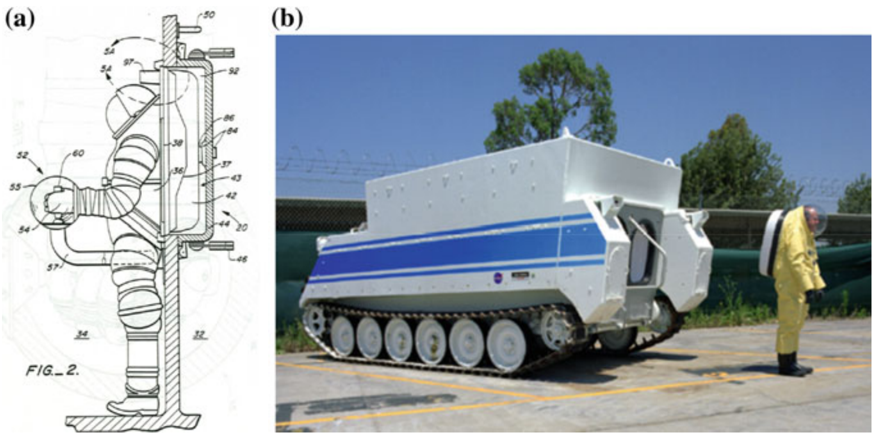

Fig. 3.8 **a** Cross-section through the Suitport (US Patent 4,842,224). **b** The Ames Hazmat Vehicle with two Suitports in the aft bulkhead. Jerry James demonstrates the Suitport-compatible backpack on the HazMat suit (NASA)

Fig. 3.9 Space Station Proximity Operations Simulator at NASA Ames. Richard Haines sits at the controls (NASA, courtesy Marc Cohen)

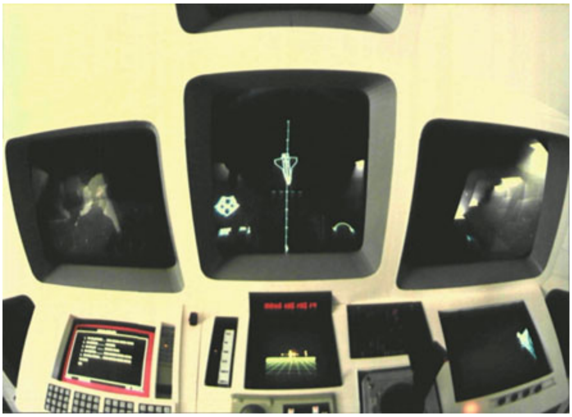

Fig. 3.10 Close-up view of the Space Station Prox Ops Simulator Controls and displays (NASA)

2. **Lunar Electric Rover Test at Desert RATS with Suitports—Chamber Class C to D**[13]

Perhaps the most widely known field laboratory test involved the NASA Lunar Electric Rover (LER), which includes two Suitports, mounted in the "rear" driver positions. Michael Gernhardt, the Astronaut Office representative for Exploration EVA is leading this project. The LER team has conducted field tests at the NASA Desert Research and Technology Studies (D-RATS)[14] field exercises for several years as shown in Fig. 3.11, and have made progress in improving the mechanisms and reducing the parts count by half.[15] On January 20, 2009, the LER served as the NASA float in President Obama's inaugural parade in Fig. 3.12.

3. **ISIS Lab—Orion Control and Display Simulator—Chamber Class Not Applicable**

The Orion Control and Display Simulator in the Intelligent Spacecraft Integrated Systems Lab (ISIS) follows the traditional concept of a laboratory more closely than the other examples. Robert McCann and Brent Beutter developed several crew station simulators for the ISIS Lab.[16] Figures 3.13 and 3.14 show two aspects of the Orion pilot station. Figure 3.13 shows the ergonomic crew couch and Fig. 3.14 shows a detail of the piloting and navigation display. ISIS showed its worth and

[13]Chamber Classes are explained in Appendix A.5, Table A.2.

[14]Further information: http://www.nasa.gov/exploration/analogs/desertrats/index.html.

[15]Personal conversation with Mike Gernhardt, May 2012.

[16]Further information: http://www.nasa.gov/centers/ames/research/technology-onepagers/human_factors_ISHM.html.

Fig. 3.11 Lunar Electric Rover at the 2010 Desert RATS field test in the Arizona desert (NASA)

Fig. 3.12 Two astronauts driving the Lunar Electric Rover while situated in the Suitports as the NASA float in President Obama's inauguration parade (News 8)

Fig. 3.13 Intelligent Spacecraft Integrated Systems Lab, NASA Ames. Brent Beutter demonstrates the crew couch and pilot display positions (Cohen 2006)

Fig. 3.14 Intelligent Spacecraft Integrated Systems Lab, NASA Ames. Robert McCann explains the pilot display screens, icons, and procedures (Cohen 2006)

achieved validation along the way by solving the extreme vibration problem for the Orion when mounted on top of the ill-conceived Ares-1 "stick." The vibration would have been so high that it was impossible for the crew to read more than a few digits or characters at any time. The ISIS team solved the problem by tuning a strobe light to the vibration frequencies, enabling the crew to see the letters and numbers "blinking" in the same place the whole time, even though everything was shaking wildly.

4. **Habitat Demonstration Unit/Deep Space Habitat—Chamber Class C**[17]

The Habitat Demonstration Unit (HDU) served as a part of the 2011 Desert RATS. It is a generic habitat intended to simulate a deep space habitat in zero-G or on a lunar, planetary, or small body surface. In 2012, NASA JSC conducted TRL-4 tests in a highbay laboratory environment in Houston. These tests involved the following components, breadboards, and subsystems (Fig. 3.15)[18]:

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[17]Chamber Classes are explained in Appendix A.5, Table A.2.

[18]Personal communication, Kriss J. Kennedy.

1. Autonomous mission ops	19. Wireless Comm and RFID
2. "Intelligent" habitat system management software	20. RFID temperature sensors
3. iHab digital double (D^2) augmented reality	21. Evolved structures (ES) and attachment H
4. Common avionics architecture Hab computing	22. Smart rail multi-functional structure (SRMS)
5. Common displays and controls	23. Smart palettes for crew quarters (SPCQ)
6. Advancements in human interfaces for spacecraft	24. Telerobotic/IVA workstation
7. Advanced caution and warning system (ACAWS)	25. Geo-Science Lab Glovebox/Workstation
8. Failure consequence assessment system (FCAS)	26. General maintenance/EVA Workstation
9. HDU core computing, wireless communication and RFID	27. Medical Ops/Life Science Workstation
10. Communications service assembly (CSA)	28. Food production: atrium concept
11. Standards-based modular instrumentation system: wireless sensor nodes	29. LED lighting: solid state lighting assembly
12. Power generation and PM&D systems	30. Inflatable X-Loft (X-Hab challenge)
13. Current sensor implementation	31. Habitability/habitation: advanced crew systems
14. iPad induction charging system	32. Hygiene—logistics module
15. Radiation environment monitor detector (REM)	33. Logistics-to-living cargo transfer bags
16. Fourier transform infrared spectrometer (FTIR)	34. Radiation protection technologies
17. Avionics integrated flat surface damage detection system (FSDDS) a. Stand-alone multi-panels, b. Flat surface damage detection system (FSDDS)	35. Operational demonstration of cargo transfer bags to deployable blankets for radiation protection and ECLS water purification demo
18. Avionics integrated MMOD Hab impact monitoring system	36. X-Hab challenge: 4 universities 37. Material handling

3.5.5 *TRL-4/5 Transition from Validation in a Laboratory Environment to a Relevant Environment*

The ESA-Russian collaboration on the EuroMars105 and EuroMars500 simulation experiments mark a pivotal transition from testing in a *laboratory* environment to testing in a *relevant* environment. Figure 3.16 illustrates the constituent modules of

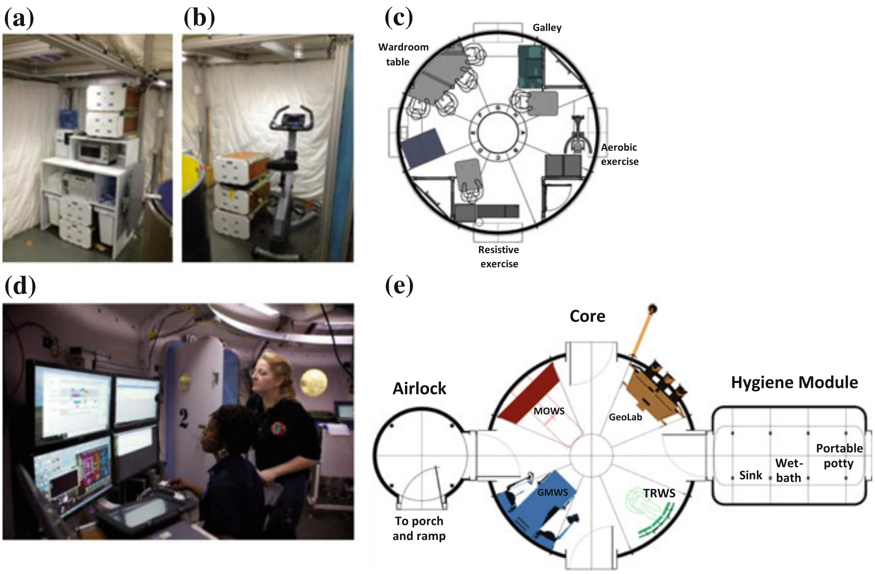

Fig. 3.15 a–e 2012 Activities at the Habitat Demonstration Unit—Deep Space Habitat (HDU-DSH) in the Research and Technology Studies at Johnson Space Center. **a** View of upper level galley; **b** view of upper level exercise station; **c** HDU-DSH upper level plan; **d** view of HDU-DSH lower level; **e** HDU-DSH lower level plan (All images courtesy of Kriss Kennedy)

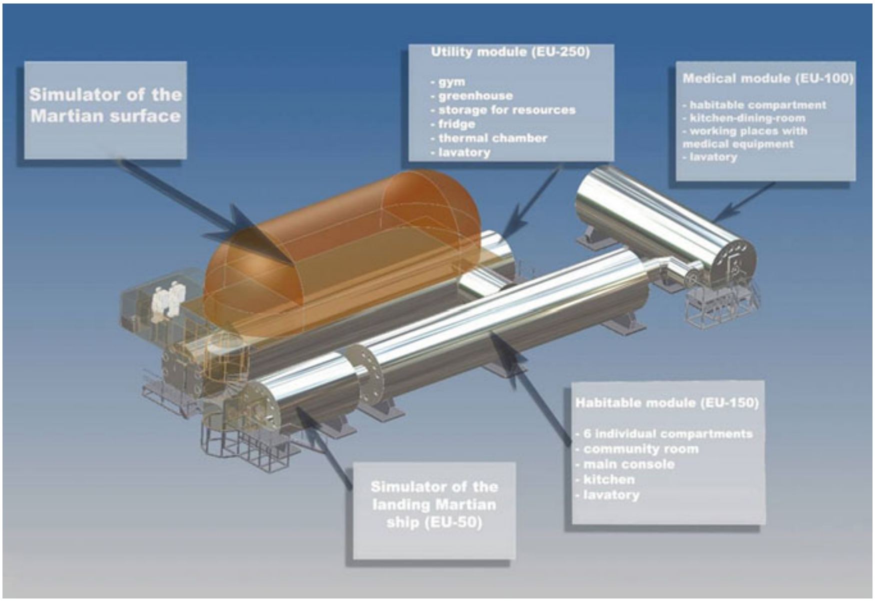

Fig. 3.16 Isometric view of the EuroMars 500 Simulator configuration at the Institute for Biomedical Problems (IBMP), Moscow (ESA)

the simulator configuration at the Institute for Biomedical Problems (IBMP) in Moscow, where the simulations occurred.[19] These chambers are Class C since the protocol involves closing and sealing the hatches, then supporting the crew with mechanical ventilation and potentially with life support. In many of the photos, the crew wears tank-top type shirts, suggesting that it is very warm inside the habitat. Figure 3.17a, b shows some of the crew and activities.

The EuroMars objective was to simulate the long duration mission for a crew voyaging to Mars. The first experimental run of 105 days was a kind of a shakedown cruise. The second run took 520 days, which would replicate the crew time on the surface of Mars during a conjunction class mission. The IBMP simulator is largely a laboratory for a wide range of observations and experiments. Despite the purpose of simulating a space habitat in which non-flammable materials would be all pervasive, the IBMP chose to outfit their simulator with a wood paneled interior. This choice of materials to create a warm and home-like environment seems contradictory with the whole purpose, but perhaps it reflects a lingering social-realist aesthetic in which people bring their complete material and environmental conditions of their society with them.

What makes the EuroMars Simulations in the IBMP facility a "relevant environment" is the long-duration isolation and confinement that will be the *sine qua non* of a human mission to Mars. In addition, the closed atmosphere and life support aspect of the simulation offers another potential kind of subsystem test and validation. ESA has released a substantial amount of documentation and photographs of the simulations. However, the Space Community is still waiting for peer reviewed or refereed papers that present the research results.

3.5.6 TRL-5 Component/Breadboard Validation in a Relevant Environment

TRL-5 initiates the technology maturation phase of testing in a relevant environment, which means some aspect of the space environment. What constitutes a relevant environment can vary widely. For life support systems, a relevant environment may mean an environmental or pressure chamber in which the gas mix is controlled and varied for an experiment; it may involve human subjects in that chamber. For a spacecraft, it may mean subjecting components or subsystems to vibration on a shake table or a thermal/vacuum test in which the radiant temperature varies from hot to cold. The possibilities are almost endless for what testing in which attribute of environment will be vital to achieve TRL-5 validation for each critical function.

1. **Ames Vertical Motion Simulator (VMS)—Chamber Class C**[20]

The Vertical Motion Simulator is a state of the art facility that with offers the largest vertical range of travel of any flight simulator in the world. Researchers use the

[19]Further information: http://www.esa.int/esaMI/Mars500/SEM7W9XX3RF_0.html.

[20]Chamber Classes are explained in Appendix A.5, Table A.2.

Fig. 3.17 **a** Crew of the EuroMars 105 simulation in the habitat (ESA). **b** EuroMars 105 crewmember Oliver Knickel with equipment to measure his night-time brain activity (ESA 2009)

Fig. 3.18 Vertical Motion Simulator, NASA Ames. The cab sits on a three-degree of freedom motion base that provides roll, pitch, and yaw. This motion base is on a bridge track with 12 m lateral motions. The bridge affords 24 m of vertical motion (NASA)

VMS to experiment with a wide range of aircraft, particularly rotorcraft. The Shuttle pilots trained for landing on the VMS. Figure 3.18 shows a typical VMS cab mounted on the motion base. The VMS operates with about five to six cabs that the staff can configure to represent a variety of cockpits. Figure 3.19 shows the basic

Fig. 3.19 Vertical Motion Simulator cab configured as the Altair flight deck and pilot station. James Berry, Northrop Grumman Chief Engineer for Exploration stands at the controls (Cohen 2006)

Fig. 3.20 Sleep quarters accessibility test in the University of Maryland Neutral Buoyancy Facility (Courtesy of Prof. Dave Akin)

configuration for the Altair lunar lander ascent module. This cab achieved TRL-5 validation on the lunar lander flight algorithms for the controls and operations.

2. **Neutral Buoyancy Testing—Chamber Class E for the Suit—Not Applicable for the Water Tank**

Neutral buoyancy testing enjoys the status of the "gold standard" of relevant environment testing for space hardware.[21] Because it offers the opportunity to put crew and hardware in an environment that can simulate zero gravity, researchers and engineers test a wide range of equipment including airlocks, docking systems, habitation outfitting, space suits, tools, and even the walking gait on a treadmill. The NASA Human Integration Design Handbook ([HIDH] 2010) states that neutral buoyancy testing has been used successfully for IVA foot, handhold, and waist restraints (p. 63, 70), and EVA suit design and range of motion testing (p. 957). Figures 3.20 and 3.21 show examples of neutral buoyancy testing for both EVA construction and habitability at the University of Maryland Space Studies Lab's Neutral Buoyancy facility.

3. **TransHab Prototype in Thermal-Vacuum Test—Chamber Class D**[22]

The thermal-vacuum test is the flagship TRL-5 test of nearly all spacecraft components and subsystems, and even applies to complete spacecraft or modules. This test was conducted in the large thermal-vacuum chamber at Johnson Space Center. The test involved inflating the TransHab to full size, without any people in it, and then subjecting it to space environmental exposure, a relevant environment. The test protocol was to evacuate the air from the chamber down to a vacuum, then expose the TransHab module to extremes of heat and cold. Figure 3.22a, b shows a TransHab prototype undergoing testing in the thermal vacuum chamber.

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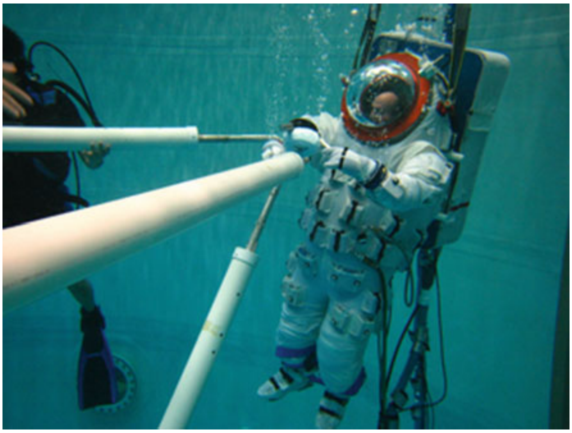
[21]Personal conversation with Prof. Ted Krueger, Rensselaer Polytechnic Institute, Rensselaer NY, May 2005.

[22]Chamber Classes are explained in Appendix A.5, Table A.2.

Fig. 3.21 EVA truss assembly experiment in the University of Maryland Neutral Buoyancy Facility (Courtesy of Prof. Dave Akin)



3.5.7 *TRL-6 System/Subsystem Model or Prototype Demonstration in a Relevant Environment (Ground or Space)*

1. **Human Exploration Demonstration Project (HEDP)—Chamber Class C, D, E, and potentially F**[23]

There are few examples of Space Habitat mockup or simulator projects that go all the way to TRL-6. What few system demonstrations in a relevant environment did occur provided little available published documentation (e.g., the 1971 McDonnell-Douglas 90-Day Life Support Test, and the 1997 JSC 91-Day Lunar-Mars Life Support Test Project.) The HEDP stands as a rare case study insofar as it is well documented and may have been the only serious attempt to achieve a full TRL-6 Space Habitation validation capability.

The HEDP example in this section (Cohen 2002) was a project to make a multidisciplinary simulation of "a day in the life of a planetary habitat." The context involved the renovation and renewal of the S-18 Altitude Chamber to simulate crewed space missions. The irony of this plan was that when NASA built the S-18 and the nearby 50-G Centrifuge in the Building 243 rotunda, their purpose was to simulate the human mission to Mars that NASA expected to launch by 1985. Figure 3.23 shows the S-18 chamber when it was new. The sphere to the right of the horizontal airlock cylinder was a pressurizable capsule. After spending six months in the S-18, the Mars crew would enter the capsule to be transferred to the 50-G Centrifuge to simulate Mars atmospheric entry and landing.

The HEDP strategy was to test multiple subsystems together over a relatively short time of one to two days in a confined environment. The four disciplines were

[23]Chamber Classes are explained in Appendix A.5, Table A.2.

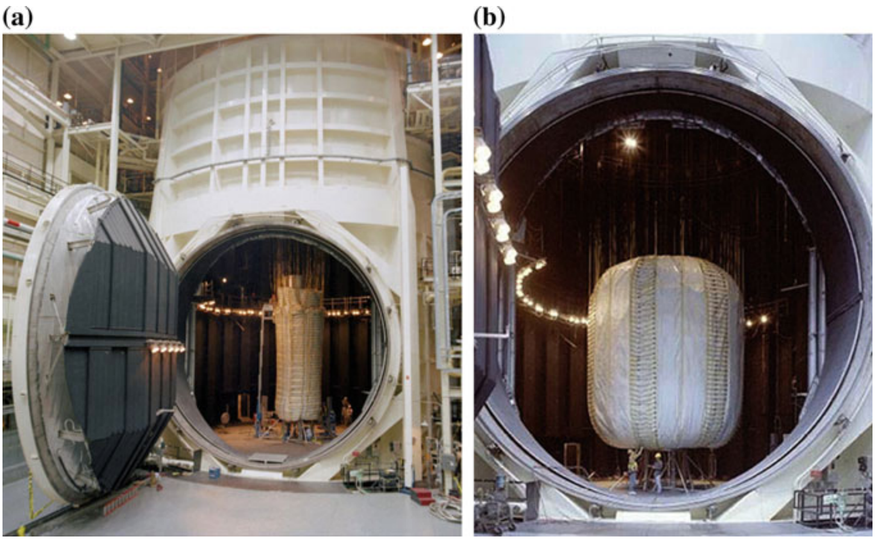


Fig. 3.22 **a** The TransHab Shell Development Unit 3 with MMOD layer before inflation in the thermal-vacuum "Chamber A" at NASA Johnson Space Center (NASA December 1999). **b** TransHab Shell Development Unit (SDU) 3 fully inflated in the thermal-vacuum "Chamber A" at NASA Johnson Space Center, Dec 1999–Jan 2000 (Courtesy of Synthesis-International)

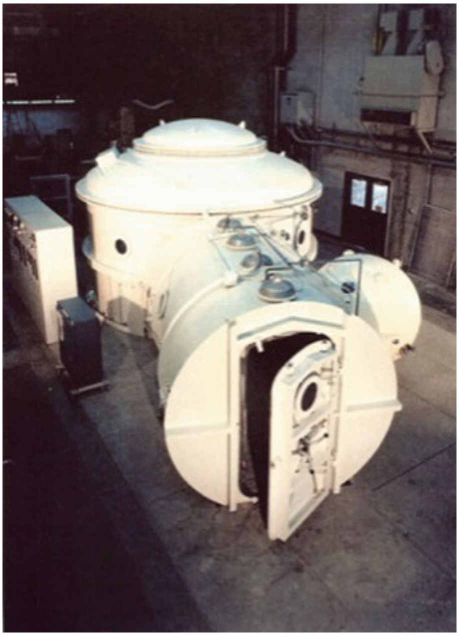


Fig. 3.23 The S-18 Altitude Chamber circa 1965 when it was completed to simulate a human mission to Mars and other scenarios (NASA)

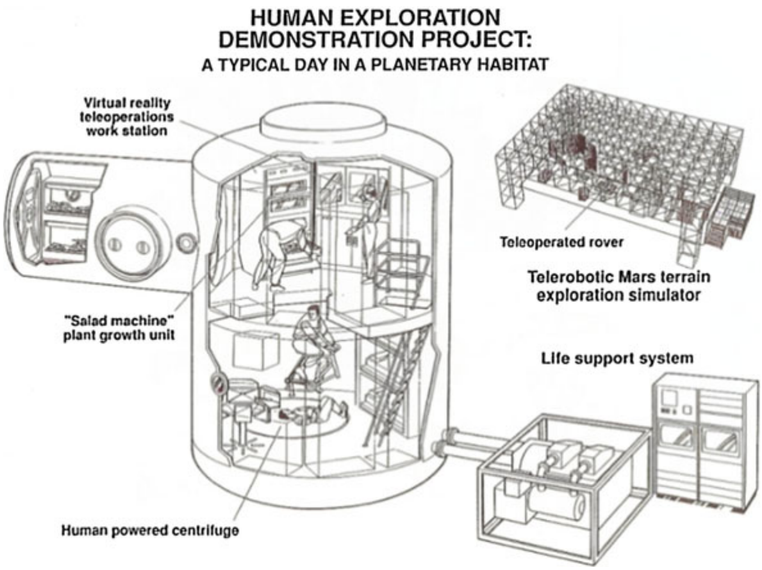


Fig. 3.24 Concept rendering for the Human Exploration Demonstration Project emphasizing the multi-disciplinary nature of the short-term simulation (Niche Wallace for NASA)

Human Factors, Information Science, Life Science, and Life Support. The Human Factors Research Division provided habitability outfitting on the upper deck shown in Figs. 3.23 and 3.24, including the ship ladder to the lower level, plus a virtual reality system with capability to operate a rover in a remote building. The Information Science Division provided the rover on a Mars landscape in the other building for the crew subjects to operate. Information Science provided also the

Fig. 3.25 Upper level of the S-18 Altitude Chamber during renovation to serve as the Controlled Environment Research Chamber (CERC) (NASA)

data system that afforded the central system integration to HEDP. The Life Science Division provided the Human Powered Centrifuge (HPC) and the biomedical monitoring for the HPC subjects and potentially other crew. The Advanced Life Support Division provided the renovation and outfitting of the S-18 Altitude Chamber as a hypobaric chamber to serve as the Controlled Environment Research Chamber. The Advanced Life Support Division committed also to provide a "plug and play," externally mounted life support system that they called a "life support microscope." The HEDP accomplished its first major milestone of subsystem validation of all the elements except the life support microscope. However, NASA

Fig. 3.26 Interior of the CERC upper level with outfitting installed (NASA)

Fig. 3.27 Lower level of the CERC showing the ship-ladder and the Human-Powered Centrifuge (NASA)

Fig. 3.28 Lower level of the CERC with the Human Powered Centrifuge in operation (NASA)

politics and management attention spans being what they are, no funding was available for the next phase of two years (Figs. 3.25, 3.26, 3.27 and 3.28).

3.6 Guest Statement: The Moon or Mars: Where Might We Settle First? (Madhu Thangavelu)

The Moon or Mars debate continues despite every single report or recommendation from NASA, NRC or other independent study that point to the Moon as the next logical destination for human space exploration and settlement. Once we hone the technologies to live there, "this time to stay" as the Bush administration of yore put it, we would have all the tools to live on Mars, return resources from the asteroids, homestead on Ceres or even the much prettier outer gems in our solar system like the satellites of Jupiter or Saturn, where the vistas are far more spectacular and seasonal changes more dynamic than anything that Mars or Venus can offer.

The physical facts are right above us in the skies every night, right in front of our eyes, for those doubting Thomases. The Moon is our closest celestial neighbour, a lifeless and barren continent that orbits the Earth, just a quarter million miles away. Whereas planet Mars is at least five hundred times more distant, depending on orbital alignments. Literally and symbolically the Moon is a highly visible orb in our skies, compared to a peach pale dot that planet Mars is, that many who advocate cannot even locate in the empyrean.

Current technology allows us to ply rocket ships in cislunar space, i.e., between the Earth and the Moon every day, while there are only very limited windows of opportunity to depart Earth to go to Mars. Rocket ships to the Moon are much smaller, ten to hundred times smaller, depending on what and how many crew you wish to carry on expeditions, especially propellant, food, and potable water. And mission control can keep check almost instantaneously round the clock. We can even mount rescue or emergency missions in short order, should the need arise. We cannot do this for Mars missions using current technology. The communications time lag during most of the Mars expedition is such that mission control on Earth can do nothing to help in an emergency. Even prayers can take 30 min or more to reach a transiting Mars crew in trouble. We can resupply Moon missions every day, if we so wish, but Mars crews are stuck with what they have on board for the length of their journey that may last five to six months. And imagine this: floating around in weightlessness for five or six months, and then all of a sudden, crew are subject to gravity forces upon landing on the Martian surface. Even crews returning from much shorter trips to the ISS need a lot of time to regain their muscle and bone strength once back on Earth.

The saving grace about Mars is that the crew will experience less than half their body weight on Earth and be able to adjust to a similar diurnal rhythm of approximately 12 h of night and day. But what use is that when you need to be fully suited and are unable to breathe the almost pure CO_2 atmosphere, and that too, at such a low pressure as to be of no use at all, not to mention the dust storms that can mask the sun for months at a time. Solar photovoltaic arrays that power the ISS today have been the mainstay for space systems and satellites since the dawn of the space age and this technology will not suffice for Mars habitats because dust storms in the thin atmosphere block out sunlight, and nuclear power and propulsion systems are decades away from certification by NASA. We could use mature and reliable space qualified photovoltaics in those polar regions of the Moon almost perpetually while we learn to deploy, operate, and service nuclear reactors that could be commissioned later on as these systems are proven on the lunar surface, on Mars, and other destinations further out in the solar system, where the sunlight gets progressively dimmer and solar power becomes untenable.

The emerging robotic construction technology has huge ramifications for planetary infrastructure establishment, and that is especially true for the Moon. It is now possible to erect or build entire habitable structures, certify, and commission them before humans arrive at the destination to occupy them. Lunar settlements and associated infrastructure elements like landing pads, roads, storage hangars, and even component manufacturing factories and their supply chains may all be built and serviced from Earth. Robotic technologies have advanced so far that robots landed on the Moon may be controlled from Earth, using advanced telerobotic systems and technologies that are already playing a vital role here on Earth. It is much more challenging to build infrastructure on Mars this way, let alone steer a rover that is hundreds of millions of miles away because of time delay associated with command and control signals.

Why is NASA's Mars plan always thirty years away? This is a question often asked in policy meetings but never even brought up in any technical gatherings. The reason is simple. We do not have the technologies currently to keep people alive and well for the long duration missions through the deadly radiation environment that pervades interplanetary space, especially in our neighborhood close to the sun, where life evolved and we live happily, thanks to the protection offered by Earth's magnetic field and the thick blanket that is the Earth's atmosphere.

Even the International Space Station is protected by the Earth's magnetic field, blanketed by the Van Allen belts where the often lethal solar storms are moderated and much of the fury of our sun is quenched. Neither Mars nor our Moon have such a protective field which is responsible for planet Earth holding an atmosphere, and that is very troubling for permanent extra-terrestrial settlements. Artists' impressions of people flying around in low gravity with magnificent vistas in the background may need serious revision. Space architects think that all extra-terrestrial settlements may be deep underground with few observation towers and habitable facilities on the lunar or Martian surface which may be human tended only for very short periods in order to avoid excessive exposure and consequent radiation damage to human tissue.

Now, compounding this natural phenomenon is yet another. It is called galactic cosmic radiation, abbreviated as GCR Particles, mostly made of iron ions, some that pack energies comparable to baseball fast pitches. They are constantly zooming through interplanetary space. Thought to originate at the death knell of stars or supernovae, their energies are several orders of magnitude more than what we can generate here on Earth, even in the most advanced accelerators ever built. These particles are so powerful that they go right through spacecraft and human tissue alike, but they also generate secondary particles upon collision with spacecraft material, and these much slower secondary particles, especially neutrons, are the real culprits that can be lethal to astronauts. Ways exist to deflect charged particles like high energy protons and solar alpha particles through active shielding technologies i.e., creating electromagnetic fields around the spacecraft artificially that can deflect them, but we have yet to devise ways protect us from neutral particles created by spallation, those energetic neutrons that are generated by secondary radiation from GCRs.

Most talented engineers who build spacecraft are reticent about this show stopper, because they want to fly missions, like all of us, but NASA flight surgeons who have the final say and have to sign off on human missions, know that the risk is real. They know that state-of-the art technologies do not allow us, and it is futile to put our brave crew who are chomping at the bit to go, because they know exactly what will happen to them. They can even predict when their bodies will start to fall apart during transit, the point at which they will exceed the doses that humans can withstand without harm! Radiation doctors and professionals know that crew will perish during transit to Mars, and that we do not yet have the technology to protect them against GCRs or anomalously large solar particle radiation storms, especially the dangerous, energetic secondary particle radiation that can cause a range of effects, from immediate crew impairment to slow and painful death.

We know full well the effects of radiation sickness and how systems shut down in death from our long and varied terrestrial experience with nuclear weapons development mishaps as well as nuclear reactor accidents like Chernobyl, and more recently from the crew who were exposed to deadly radiation from Fukushima reactor collapse and containment.

NASA has an active radiation monitoring and countermeasures program. For those wishing to dig a bit deeper, a quick look through their Man Systems Integration Standards (MSIS) will reveal enough gory and precise details of how the human physiology reacts to radiation and when the body starts to fail. Space radiation is the issue that pulled the plug on the daring Inspiration Mars mission, which recently proposed to put a crew on a free return trajectory on a flyby mission to Mars and back. The buck stopped at the NASA Astronaut Office, at the flight surgeon's desk, to be precise.

Experiments are underway on the international space station to ascertain what doses humans can handle. But once outside the Van Allen belts, the radiation environment is much more severe, as seen from the recent Curiosity rover that carries an active radiation monitor. It is clear we need better radiation protection for long expeditions, especially during transit, and we also need better data from deep space missions using biological samples (not crew!), yet to be manifest. We also know that radiation exposure during transit has a different pattern than on an extraterrestrial surface that blocks much of the GCRs, due to the sheer mass of the planet. Again, the Moon, lacking a magnetic field blanket, offers the best site in our proximity to gauge the risk of long-term solar particle radiation exposure as well as GCRs, and the effects of deep isolation on crew, and is the ideal location to hone measures to combat these crucial issues.

All is not lost, though. We know that we can shield from this deadly radiation if our transit vehicles have thick enough shields of water. We also know that the tons of food and consumables for the expeditions as well as the large propellant tanks of Hydrogen could be configured as radiation shields around the crew compartment on these months long transits. Some engineers even think that water tanks would be the compact way the carry the propulsion reactants that could be manufactured as needed, en route, both for outbound and inbound legs of such a long expedition. But once we get to Mars surface, how to survive the solar particle radiation that is quite high even there, on the surface? Unfortunately, we do not have an answer to this lethal issue yet!

Adding to all the controversy to the exploration and settlement of Mars, is the issue of contamination and quarantine. Some scientists believe human activity on extra-terrestrial bodies will endanger potential life forms that may exist there. And the search for life on Mars has only just begun. It may be decades before we know if there are life forms there or not. Until then, human activity may have to wait, if we are to follow their advice. There has not been much debate about this issue with regard to the "magnificent desolation" that is the surface of our Moon.

But all this begs the question: do we have to wait for technologies to develop, or are there worthwhile missions to do and gain invaluable experience while we get all these "good to have"technologies certified and commissioned for a Mars expedition?

To be specific, are there space missions that can speed up technology evolution and inspire the public simultaneously while helping to fire up our STEM education and groom the next generation of explorers and engineers; missions that could also use space activity as sheer inspiration for our youth? The lure of the international space station seems to have run out of steam, at least among the public and the media. Space tourism may have some answers, perhaps? And the US president's plan to send crews off to some unnamed asteroid for a nebulous and uninspiring mission seems to have weak and uninspiring support in Congress.

The Moon, on the other hand, offers all the excitement, now, as opposed to the next decade or the one after. A highly literally visible celestial neighbor is just three days away, and a dozen of our best and bravest have left their footprints there, not to mention their roving vehicles, some half century ago. NASA's orbiting missions right now are providing the sharpest resolution imagery of the Moon as well as all the data, including radiation, for crew to quickly transit cislunar space and arrive at the destination. There are several nations at work right now, planning the next lunar missions. China has already landed a rover on the Moon. India was instrumental in locating water ice at the poles, that, along with constant sunlight and mild surface temperatures all year round in the polar regions, could provide a stable setting for astronauts to learn to live and evolve systems for permanent settlements anywhere in the solar system.

And just for those scientists aiming for the next few decades of Nobel prizes, some of the finest scientific discoveries of great and immediate import to our species anywhere on the solar system is waiting for us on the Moon. The Moon, while we struggle to quilt solar activity information of the past few thousand years together, holds an unperturbed record of solar activity over the last few billion years, almost back to the genesis of our solar system and the formation of the Earth-Moon system, and this precious, nay priceless, repository of information could tell us more about solar behavior over geologic time than any other body in our solar system. This data could be the defining element of the puzzle as we shape our climate change policies. To be explicit, Mars exploration cannot tell us that.

New technologies allow us to go back to the Moon at a fraction the cost of Apollo, and now, even private efforts like the Google X Prize contestants are underway to land and execute exploration missions there. There is even a private venture to establish a lunar observatory called the International Lunar Observatory Association (ILOA). NASA has not turned a blind eye to these activities. The Pacific International Space Center for Exploration Systems (PISCES) and their International Lunar Research Park initiative have been executing some ground breaking simulations here on Earth, and NASA is looking at ways to integrate all these activities under a synergetic program umbrella at the Space Portal, a program developed at NASA Ames Research Center to facilitate such innovation and commercial interaction.

Now that NASA's Orion spacecraft is nearing commission and the large Space Launch System is nearly built, all eyes will be on building a lander that can service extra-terrestrial surfaces. Rather than build it from scratch, NASA might do well to look at the effort well under way at SpaceX and at Blue Origin, that has proven it can do wonders with small business budgets and is about to land and reuse the first stage of its Falcon and New Shepard launchers. This technology lies the foundation for both lunar and Mars landers and can greatly speed up development.

Though scientific thought and religious inquiry seem to be at odds today in a world that seeks secular governance, humanity is still deeply rooted in spirituality and religions continue to offer great organizing frameworks for modern societies. All great civilizations were founded and organized upon great religions and all cherished institutions of intellectual inquiry and education have places of worship in them. While two generations of engineers have been piling study upon study of how to build labs and accelerators and telescopes and other observatories on the Moon, thought leaders among civil architects and designers have been drawing plans for what they think we should do on the Moon for all humanity.

They propose time capsules, repositories including DNA banks, spiritual facilities and churches, temples, and mosques. All of them are wary of economic development as we see it on Earth, bulldozers permanently scarring large swaths of land, and pollution everywhere. They are aware that the Moon, though desolate and barren, is even more fragile since it has no atmosphere or seasons or climate variations. Even the constant operation of rockets would be sufficient to forever alter the lunar landscape as we know it. So, we expect the pioneering lunar settlers to become far more sensitive in preserving the lunar environment than we do here on Earth, and develop and evolve the technologies to use resources accordingly.

Sound space policy is built up from hard facts on the ground, and not grand visions. The current US administration clearly sees the value of our space program as an instrument for both domestic and international policy. The Obama administration sees the International Space Station as a golden goose that keeps on laying. Even though Russia seems at odds with current developments around the world, it seems unlikely that any of the partners will bail out of the agreements in place. There is a long waiting line of nations, chomping at the bit, to enter agreements and memoranda of understandings to participate in the ISS program, even as the State Department courts capable nations like India and Brazil to extend the reach and influence of the US space program in international affairs.

So, in the prevailing global economic climate, there is no need at all for the current US administration to expand the effort to include any other visionary, new, and ambitious projects like return to the Moon or Mars.

Two generations of our best and brightest engineers, now bordering on three, since Apollo, have spent their lives waiting to execute ambitious missions beyond low Earth orbit. Can we continue to postpone missions till we get all the right "good to have" technologies in place, as is the case for Mars, or do we execute missions that we can right now with existing technologies, as is the case for the Moon? It is important to remember that leading edge technologies tend to evaporate, if they are not put to good use in a timely manner.

Is the space program about STEM, or is STEM just a by-product of visionary space missions that strive to push the envelope of our skills using state of the art technologies? These are the questions that our leaders need to be asking.

Unless governmental policy is articulated clearly, we will continue to vacillate about the visions and missions of our space program. Is this just about science, or technology, or STEM,[24] or something much, much bigger? Every visionary report has clearly suggested that human space activity at its core is about humans moving out into the solar system. It is really about extending civilization beyond Earth.

There will be false starts. The Panama Canal or the Euro Chunnel tunnel are examples of large endeavors that had to wait for generations for the right mix of technologies and politics. Starting a new, extra-terrestrial branch of civilization will be much harder. Fall-back options are surely much better and political failure backlash fewer if we start this endeavor closer to home, on the Moon.

"Outta sight is outta mind" is still a powerful heuristic in human affairs. Mars is a speck in the night sky that is discernable to the experienced viewer, but the Moon is a very visible celestial disc that graces our skies every day, showing dynamic phases, with clear landmarks that are visible to all of humanity. As da Vinci so eloquently said about flight, so since we have been there, we yearn to go back.

If our wish is to learn to live on an extra-terrestrial body, to establish an extra-terrestrial permanent settlement now, as opposed to two decades and another lost generation of engineers, then we should be lining up our ducks and executing lunar missions aimed at settlement, starting right now. We should leverage the current excitement among spacefaring nations of the world and those who are willing partners to seize the opportunity quickly and make an international lunar settlement a priority and a reality.

It is very hard to predict the future. Logic had it that we would first establish an Earth orbiting station, and from there, go to the Moon. It turned out differently. The visionary idea of going back to the Moon, by helping other nations to do it is championed by astronauts like Buzz Aldrin. This is a unique arena of endeavor in which the US can reap a lot of good will quickly, globally. NASA is already supporting projects like PISCES here on Hawaii to this end.

The US can take the lead to establish a 21st century United Nations on the Moon, at a location from where the whole world can truly appreciate the fragile beauty of our biosphere. Or, as an Islamic student in my graduate studio proposed, we might help that great religion, for which the Moon is a symbol of worship, to build the ultimate mosque there. While scientists and astronomers contemplate large observatories, experiments, and hazardous experiment laboratories on the Moon, recent architectural competitions have proposed spiritual facilities like monasteries and cathedrals, or even cemeteries and memorial monuments. Or perhaps, as some think, the Moon might be the best platform from which to launch and intercept an asteroid or cometary fragment that is headed for Earth impact with cataclysmic potential.

From that vantage point, with our eyes on the Moon, Earthlings could be the real stewards of planet Earth, keeping guard, literally, round the planet, round the clock, from the heavens.

To sum up, civil architects use heuristics, or rules of thumb, to categorize complex and seemingly intractable problems, and often grapple with conflicting

[24]Science, Technology, Engineering, Mathematics.

needs and requirements to create useful constructs. This is true for buildings and environments that shape our routines, or for cities and farms that support and nourish millions of lives. For space architects, those engineers who grapple with complex problems associated with human space missions and extra-terrestrial development, there are six "P"s that need to be clearly articulated before any mission can be undertaken to Mars. Clarity in the Policy of the administration and Protection of crew from space radiation are in the top rung of priority. Reliable Power (nuclear) and Propulsion for quick transit, landing, and liftoff are key to any mission to the Moon or Mars. Unlike the past, the Private sector will play a backbone role in all space activity. Since Mars transit times are many months long and radiation damage to crew is cumulative, unless and until we find innovative ways to protect crew, or get to destinations quickly, Proximity is an overriding factor, and our destination is currently limited to the Moon, where we can get to the safety of the surface quickly and settle underground, keeping space radiation in check.

Dangling the Mars carrot at the space community has had a retarding effect on progress because the technologies for sustaining a Mars mission cannot be achieved in a timely manner without hard data gleaned from extended Moon missions. By driving a wedge within the space community, it becomes harder to create consensus and focus efforts and budgets, when, in fact we should be pursuing a vibrant series of missions, well planned and in sequence, that allows us to close all the strategic knowledge gaps with hard data from extended and ever more complex lunar missions that we can accomplish today.

More than five centuries ago, some brave explorers set sail across the ocean, in their most advanced technology wielding ships of their day, to discover and settle the American continent and eventually to lay the foundations and build up our great society. In this 21st century, the site for a truly biplantary civilization lies just three days away by rocket ship. The Moon is about the size of Africa, a celestial continent with visible landmarks, waiting for settlement. We left our footprints and vehicles there some five decades ago. Many nations have on going missions or are currently charting plans and have ambitions to go there. Humanity can start to lay the building blocks for Planet Moon now, and the United States can play a shepherding role like we did with the ISS, but in an even grander scale, if we choose to. And in so doing, we can help the rest of the world aspire to a better future for all humanity, and also bring solar system resources into our sphere of influence and better prepare to settle the rest of the solar system.

There is a growing band of thought leaders who think we live in the Anthropocene era where human activities directly impact the fragile biosphere in irreversible ways and a chorus who think the carrying capacity of the Earth has been reached. They feel that our species is contributing to rapid changes in climate patterns and sustainable growth. Rather than continue to fix and seek tweaks to economic activity, more and more people think we should move out into the solar system. With the human space program, perhaps this diaspora has already begun, and the Moon beckons us all to step out of the cradle of humanity and break free from what is otherwise a zero sum game for resources here on planet Earth, as we see today with our struggle for energy among the oil producing economic community.

If it were just about flags and footprints, yes, we have been to the Moon, and yes, we should plant another flag on Mars. But this is not about just flexing a nation's technologic prowess anymore. It is truly about extending our species outward into the cosmos and about building serviceable pathways to celestial destinations for all humanity to settle and thrive, to live long and prosper, as the recently departed Mr. Spock might say. So, is it the Moon or Mars? Those economic bean counters argue it is all about money. But there is also a well-known counterpoint that when all the talk is about money, it is really not about money. Could it be that we, as a species, are running bankrupt on the imagination front? There is a less known heuristic that architects employ with great effect. When offered a choice, take both. And it has served them well.

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Chapter 4
Habitation Systems Research

Abstract Habitation is "*the act of living in a place*" or "*a place where someone lives*" (Webster Dictionary). While the origin of the word dates back to the 14th century, its use for Space habitation is fairly new. In fact, "*early spacecraft had to be designed to be operated and not lived in*" (Compton and Benson 1983, p. 130). The effects of impaired habitability can be inconvenient or even life threatening. The integration of human factors into habitation system "*will make mission success more likely*" (Larson, p. 134).

This chapter introduces design and planning research principles including habitability requirements, life support, environmental influences, behavioral, and other human interaction impacts that affect design solutions. The following design issues and aspects are addressed:

- Basic habitability principles (Sect. 4.2)
- Humans and environment interactions (Sect. 4.3)
- Human activities and social interaction design (Sect. 4.4)

4.1 Introduction and Chapter Structure

This chapter introduces design and planning principles that are important to consider at all stages of manned space mission planning. It is related to all Technology Readiness Levels (TRLs). With regard to Habitation Readiness Level 1 (HRL 1) definition, this chapter covers design, human factors, crew systems, and life support research associated with habitation systems (Life support systems are discussed in Chap. 5). Design and planning principles are listed following the basic design process (Fig. 4.1).

However, since the design process is not linear, students are invited to cross-read the chapter in relation to the design and planning stage of the project (See more about engineering and architectural design approaches and process in Chap. 2).

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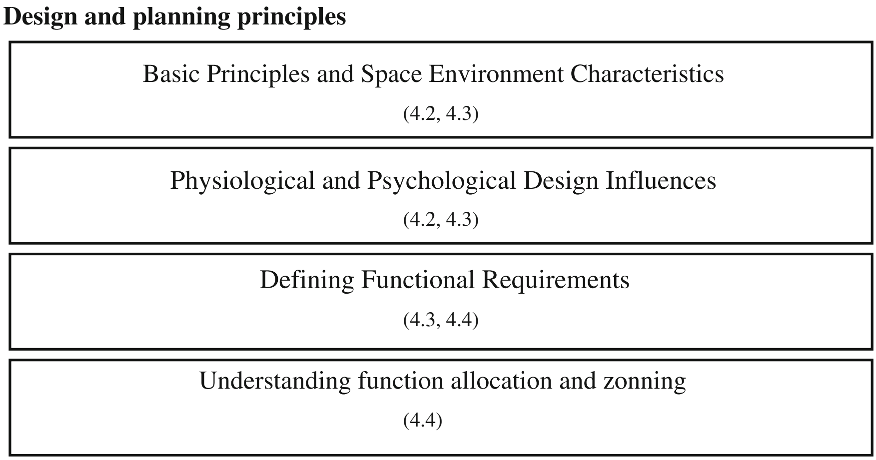


Fig. 4.1 Basic design process for design and planning principles

The chapter concludes with two guest statements. The guest statement from Theodore W. Hall[1] discusses artificial gravity design fundamentals and implications. The statement from Brand N. Griffin[2] discusses integration issues in space projects.

4.1.1 The Habitation System and Habitability

Habitation is "*the act of living in a place*" or "*a place where someone lives*" (Webster Dictionary). Historically habitability has been considered to be a low priority and architects and engineers still discuss its importance. When the effects of impaired habitability are understood as potentially life threatening, then understanding habitability and Human Factors "*will make mission success more likely*" (Larson, p. 134).

Currently various definitions for the term habitability exist (cf. Glossary section in the Appendix). Connors, Harrison, Akins, and Faren stated in their book 'Living Aloft—Human Requirements for Extended Spaceflight' (1985), that "*Habitability is a general term that connotes a level of environmental acceptability"* (p. 59). In Architecture for Astronauts the term 'habitability' is used as *"a general term to describe the suitability and value of a built habitat (house or spacecraft) for its inhabitants in a specific environment (Earth or Space) and over a certain period of time. Set into the space context, habitability can be understood as the measure of how well the (built) environment supports human health, safety and well-being to*

[1]UM3D Lab, Digital Media Commons, University of Michigan, Space Architect.

[2]Advanced Concepts Office at NASA's Marshall Space Flight Center, Space Architect.

Table 4.1 Definition of the habitation readiness level 1 in relation to the respective technical readiness level (Connolly et al. 2006, p. 3–4; ESA (TRL) 2008)

HRL	Definition of the habitation readiness level 1	TRL
Demonstration of the technology	Human factors, crew systems, and life support research related to habitation systems	Any TRL
	An HRL Level 1 Habitation System is a system in a preliminary conceptual stage where interior and exterior designs, functions, and subsystem suites are still being researched. The requirements for the habitation system and its associated crew operations may also be in a very preliminary stage with many TBDs remaining to be resolved. A focus on crew-related factors such as life support, crew accommodations, and human factors requirements is emphasized. An HRL 1 habitation system includes a preliminary list of functions, the number of crew needed to complete the function, the basic equipment the crew will use, a basic idea of the volume required, and rationale for the allocation decisions	

enable productive and reliable mission operation and success." (Häuplik-Meusburger 2011, p. XI, cf. Cohen 2011)

This chapter refers to the Habitation Readiness Levels defined by Connolly et al. (2006). For them a (Lunar Surface) Habitation System is ", *the integrated set of habitation assets to support a crewed mission and ensure a safe, productive, pressurized environment for human habitation.*" (p. 2)

All these definitions imply that it is the job of the space architect to create an environment that is safe and comfortable for people to live and work within.

Table 4.1 provides an overview of relevant Technical Readiness and Habitation Readiness Levels that this chapter references.

4.2 Basic Habitability Principles: An Introduction

Questions for Exploration
What are the basic requirements for space habitats? Which conditions are different compared to Earth? Which food systems are available? How does the environment affect physiology, anthropometry, and operations?

Knowledge of basic design requirements for a human mission is already required at an early stage of the design process. Several key requirements for human missions drive habitation design. The most important issues and design drivers are introduced in this chapter. It forms a guideline rather than a complete list, to assist further research and provides additional references and links. Many of the considered issues and their implications for habitat design will be discussed in later chapters as well. In addition, planners should remember that human needs vary individually, from time to time, and from mission to mission.

4.2.1 Life Support and Habitability Challenges

Space habitats are pressurized structures. Suitable environmental conditions have to be provided and maintained for crew health and safety. In addition, the crew needs consumables and waste products have to be discarded or recycled.

4.2.1.1 Atmosphere

A breathable atmosphere has to be provided within the habitat. Vacuum conditions in outer space, absence of atmosphere on the Moon surface, and hazardous atmospheric conditions on Mars and other planetary bodies cannot support human survival. NASA's standard for long-term habitation reflects sea-level conditions (Nitrogen 78 %, Oxygen 21 %, Argon 0.9 %, carbon dioxide 0.03 %), but atmosphere composition and total pressure values may vary somewhat due to specific operational and equipment requirements (e.g. EVAs, greenhouse, bio and technical labs etc.).

Students should have a principal understanding of the composition of Earth's breathable atmosphere, and what dangers arise if oxygen or nitrogen levels are not in balance.

Sources for Further Research:

- Book "Human Spaceflight Mission Analysis and Design" by Larson and Pranke (1999, pp. 105–111) about: Typical Design Ranges for Key Atmospheric Variables and Basic trade-offs for high and low atmospheric pressure levels
- Book "Spacecraft Systems Design and Operations" by Peters (2004, p. 477)
- Website "NASA Science News": Article about how the ISS provides the crew with breathable atmosphere (2011)

4.2.1.2 Thermal Environment and Humidity

Structures in outer space experience high temperature fluctuations from extreme cold to extreme heat. Temperatures on the Moon, Mars, asteroids, or other celestial bodies are not suitable for human survival without proper protection. The habitat should provide a 'shirt-sleeve environment'[3] in order for the crew to operate instruments and conduct experiments comfortably.

[3] See Glossary in the Appendix for further information.

Students should know that structures have to be designed in accordance with environmental temperature conditions. They should know about environmental influences upon their designs.

Sources for Further Research:

- Book "Human Spaceflight Mission Analysis and Design" by Larson and Pranke (1999, p. 113) about: Atmospheric Variations in Operational, Degraded, and Emergency Conditions
- Book "Spacecraft Systems Design and Operations" by Peters (2004, p. 364)

4.2.1.3 Food

"*Astronauts require high nutritional, well-balanced, and tasty food to maintain health and be active. Food must be stored, whilst maintaining its quality. It must be easy to prepare, but still be appealing and finally consumed. Trash has to be recycled or thrown away*." (Häuplik-Meusburger 2011, p. 218) Food preparation and dining activities are discussed in Sect. 4.4.

Students should consider all phases of food production and preparation in their design. They should be aware of the importance of the quality and quantity of food for the crew.

Sources for Further Research:

- NASA Factsheet: International Space Station Food System: http://www.spaceflight.nasa.gov/living/spacefood/index.html
- Book "Human Spaceflight Mission Analysis and Design" by Larson and Pranke (1999, p. 582) about: Crew Accommodations Mass and Volume Resource Model
- Book: "Architecture for Astronauts" by Häuplik-Meusburger about: Overview on food systems of past and present space stations (2011)
- Book "Spacecraft Systems Design and Operations" by Peters (2004, p. 529)
- Book "Introduction to Space: The Science of Spaceflight" by Damon (1995, p. 155)

4.2.1.4 Hygiene and Waste Collection

Astronauts and cosmonauts follow the same hygiene routines in space as they do on Earth but all hygiene procedures are different in microgravity and require special devices and techniques. They will be less different from Earth on the Moon or Mars, although partial gravity conditions will affect engineering design of devices and plumbing.

Students have to learn about implications of using water, toilet, shower, and other hygiene utilities in microgravity and the confined environment of a space module.

Sources for Further Research:

- Book: "Architecture for Astronauts" by Häuplik-Meusburger about: Overview on hygiene facilities of past and present space stations (2011)
- Book "Spacecraft Systems Design and Operations" by Peters (2004, p. 532)

- Book “Introduction to Space: The Science of Spaceflight” by Damon (1995, p. 158, 209, 212)

4.2.2 Hazards

The space environment consists of many hazards that pose problems for humans living and working in space. Many of them have direct effects onto habitation design. Examples are:

4.2.2.1 Micrometeoroids

Micrometeoroids are very small meteoroids—tiny pieces of rock or debris—that can be very sharp and reach high velocity in the deep space. Therefore they present a high threat to humans and systems.

Students have to learn about the possible origins of micrometeoroids and know about their potential danger for humans and systems and possible countermeasures.

Further Sources for Research:

- Book “Space Stations and Platforms” by Woodcock (1986, p. 70)
- Book “Introduction to Space: The Science of Spaceflight” by Damon (1995, p. 60, 208)

4.2.2.2 Microgravity

Microgravity conditions pose significant complications for human operations and performance and detrimentally affect human health. Intensive exercising can only partially offset negative influences of micro-gravity on the human body. Modules and facilities for space travel should provide means and interior arrangements to facilitate exercising and accommodate other possible countermeasures for micro-gravity environment. Anthropometric design issues are discussed in Sect. 4.3.2. Artificial Gravity and its implication for space architecture are discussed in Sect. 4.5.

Students have to learn physiological changes induced by microgravity as well as countermeasures necessary for crew health maintenance.

Sources for Further Research:

- Book “Introduction to Space: The Science of Spaceflight” by Damon (1995, p. 162)
- Book: “Space Physiology and Medicine” by Arnold and James (2012)
- Microgravity: A Teacher’s Guide With Activities in Science, Mathematics, and Technology, NASA 1997 [online]

4.2.2.3 Radiation

Beyond the Earth's magnetic shield and atmosphere, humans are exposed to ionizing and non-ionizing radiation. During deep space exploration, the crew will be exposed to Galactic Cosmic Rays (GCR) and Solar Particles Events (SPE). Both radiation types are extremely hazardous for the human body and may cause equipment failure or malfunctioning (see Appendix—Glossary).

Students should understand the types of radiation that space travelers face, countermeasures that are currently available, and the dangers of insufficient countermeasures.

Sources for Further Research:

- Book "Spacecraft Systems Design and Operations" by Peters (2004, p. 113)
- Book "Introduction to Space: The Science of Spaceflight" by Damon (1995, pp. 49, 159)
- Book "Curriculum for Aerospace Architecture" by Donna Duerk (2004, p. 5)

4.2.2.4 Other Specific Environmental Issues and Safety Hazards

Hazards may include biological threats of potentially unknown nature, such as the chemical composition of soil (or dust), and its physical qualities such as electrostatics, particles sharpness, cohesiveness, etc.

Students should understand what types of hazards, potential risks, and specific environmental issues they must include in planning for a particular mission destination.

Sources for Further Research:

- Book "Spacecraft Systems Design and Operations" by Peters (2004, p. 108)

4.2.3 Behavioral Implications

A number of biological changes associated with space travel have implications for astronaut's life and work performance. Examples are: changes in perception, alterations in the vestibular system, physiological deconditioning, lack of motivation, boredom, and depression. Other stressors include situational stressors such as isolation and confinement.

Students should obtain a basic knowledge about the effects that a space environment can have upon human body and mind of crewmembers.

4.2.3.1 Personal Space and Privacy

The term 'personal space' was introduced by psychologist Robert Sommer in the 1960s and is defined as follows: "*Personal space refers to an area with invisible* *boundaries surrounding a person's body into which intruders may not come*" (Sommer 1969, p. 61).

Privacy can be identified differently, depending on person's social and cultural background. In the constrained environment of a space module, maintaining a preferable privacy level can be challenging and require sufficient design accommodation.

Students should gain a basic knowledge about effects of privacy regulation on an individual and the whole crew. (Note: privacy is a ***continuum*** *from being all alone to being completely social.)*

4.2.3.2 Social Interaction Versus Isolation

Isolation and confinement has severe psychological and also social effects (cf. Connors et al. 1985). In general "social behavior is defined by interaction"[4] between two or more individuals. Social interaction is very important for maintaining a crew's psychological health and can be facilitated through design interventions and architectural solutions. Isolation missions to study social interaction are discussed in Chap. 6.

Students should understand the importance of providing space and means for social interaction during a spaceflight.

Further Sources for Research:

- Book: Living Aloft—Human Requirements for Extended Spaceflight by Connors et al. (1985, pp. 82–97) about: Meaning and functions of Privacy, Crowding, and Territoriality
- Book: Space Psychology and Psychiatry by Kanas and Manzey (2003)
- Report: Coping with the problems of space flight. Reports from astronauts and cosmonauts by Suedfeld et al. (2009). In: Acta Astronautica, 65, pp. 312–324
- Paper: The Environmental Psychology of Capsule Habitats by Suedfeld and Steel (2000). In: Annual Review of Psychology, 51, pp. 227–253.
- Report: Diary of a Cosmonaut—211 Days in Space by Lebedev (1990)
- Report: Off the Planet: Surviving Five Perilous Months Aboard the Space Station MIR by Linenger (2000)
- Paper: The Perfect Boring Situation by Regina Peldszus, R. Dalke, H. Pretlove and Chris Welch in Acta Astronautica (2014), 94(1), pp. 262–276

4.2.4 Discussion and Tasks

Discuss how different environmental aspects of space habitation have severe consequences upon a human body. Discuss which conditions may have

[4]See 'Social interaction' in http://www.britannica.com/topic/social-interaction.

significant influences on design and why. Propose a few design interventions as countermeasures to environmental hazards. Rate using HRL 1 as a minimum requirement.

4.3 Humans and Environment Interaction

Questions for Exploration
What influences does gravity have on the human body? How does this affect design solutions for habitats and equipment? Can different gravity conditions be used to an advantage? Which other environmental factors have effects on the human body and how?

4.3.1 Effects of Gravity

Gravity levels have important influences on the design of all space facilities. These conditions present complex and often difficult physical and psychological adaptation challenges for crews who are accustomed to Earth conditions. The designer's responsibility is to plan safe, comfortable facilities that ensure health, safety, performance, and comfort. Space craft designers have to deal with different gravity conditions that often require substantial differences in design. This sub-chapter summarizes various facets of spacecraft architecture and human factors design for the following gravity conditions:

- Partial gravity (Moon and Mars);
- Microgravity (Low-Earth Orbit and Phobos/Deimos);
- Artificial gravity (centripetally induced).

Experiences in Earth orbit and on Lunar surface missions have provided important lessons about altered gravity implications for design. Variable-gravity conditions affect individual performance, human-equipment interaction, and engineering design. Even after relatively short-term space missions, people experience changes in bones, muscles, and brain neurophysiology. Long-term Russian Mir and US Skylab missions revealed physiological changes that included bone deterioration, fluid shifts, and muscle atrophy during extended periods in microgravity. Accommodations for exercise were recognized to be important to minimize ill health effects. Yet even with multiple hours of daily exercise, such as on a treadmill under a 1 g load, about 1 % of bone mineral content per month is lost during LEO

Table 4.2 Effects of gravity conditions on human activities (NASA [Research] 2015; Clément 2011, p. 158; NASA [Gravity] 1966)

Effects of microgravity environment	Effects of partial gravity
Weightlessness does permit astronauts to use space three-dimensionally and in all directions	Humans walk and run 40 % slower on the Moon
	The stepping rate is less than on Earth
It is much easier to pull the feet to the chest than to bend over	Humans have a reduced ability to change direction quickly
A person may be stranded in the middle of a large space module if there are no means provided to pull to or push from for propulsion	Stopping and turning are difficult Mobility of surface vehicles is challenged by lack of traction

flight missions (cf. Clément 2005). Exercise may not be sufficient to maintain crew health and conditioning during long-term flights such as to Mars. Artificial gravity is often proposed as a method to minimize the detrimental effects of microgravity.

When gravity conditions are different from that on Earth, a number of 'unusual' effects on human activities can be observed. Some of them are summarized in Table 4.2.

In the case of artificial gravity applications the following adaptation challenges can be expected (Guedry and Benson 1976):

- Psychological adjustment to unfamiliar conditions influencing task performance.
- Disorientation due to an altered "ground" reference producing head and limb movement confusion and mistakes.
- Maintaining balance in a rotating "artificial gravity" spacecraft with Coriolis forces/cross-coupled accelerations.
- Replacing beneficial effects of gravity that hold people/items securely in place and provide surface traction for pushing.
- Nausea and confusion during transitions from one gravity level to another posing physiological and psychological problems.

4.3.1.1 Consequences for Design

Table 4.3 correlates some key influences of different gravity levels with human factors and design/engineering requirements.

4.3.2 Anthropometric Design

"*Adequate gravity regime and ergonomic design is required for living and working spaces*." (Häuplik-Meusburger 2011, p. 29) This is even more important in a microgravity environment that is different from what humans are used to on Earth.

Table 4.3 Considerations according to different gravity levels and their correlation with design

Considerations	Microgravity	Partial gravity	Artificial gravity
Human mobility and operations	Movement is effortless but restraint systems are needed for people and equipment	Mobility (e.g. lifting and climbing) will be facilitated by reduced gravity conditions	Mobility can be handicapped by Coriolis forces and cross-coupled accelerations (see *Appendix: Glossary*)
Psychological adaptation	Need of visual cues to establish a local vertical and avoid spatial orientation confusion	Provides a gravitational up/down reference similar to conditions on Earth	Need of cues to define direction of spacecraft rotation for crew orientation and balance
Physical adaptation	Loss of muscle mass, bone density, and body fluids produce deconditioning	Some deconditioning may result due to reduced physical exertion in reduced gravity	Transitions from normal to artificial gravity conditions may produce nausea and sense of imbalance
Engineering design challenges	Microgravity influences fluid systems and negates heat convection	Reduced gravity can make traction and excavation processes more difficult	Artificial gravity can complicate spacecraft docking, add structural mass, and cause vibrations
Housekeeping and maintenance requirements	Dust and other contaminates float freely and are difficult to control	Abrasive dust particles can degrade equipment and visibility	Dust and other contaminates float freely during de-spin operations

Different gravity conditions have impact on the human body (Fig. 4.2) and on the design and engineering requirements (Fig. 4.3).The image shows the neutral body position in relation to different gravity regimes. The neutral position is a body posture that is relaxed, lengthened, and joints are naturally aligned.[5]

Figure 4.2 illustrates severe implications for design:

- Dimensions are different: e.g. Reach envelope
- Orientation changes: The head is tilted down
- Modes of translation and stabilization change (e.g. people and items need means to secure their positions in zero-gravity conditions; examples are given in Table 4.2)

4.3.2.1 Orientation

In a partial gravity environment, spatial orientation is similar to Earth environment: ‘Down’ and ‘up’ are connected to the force of gravity and people usually work standing on their feet with their head up. In a microgravity environment ‘up’ and ‘down’ are no

[5]Further Resource: Anthropometric Source Book Volume II: A Handbook of Antrhopotmetric Data, NASA, 1978: https://archive.org/details/nasa_techdoc_19790005540.

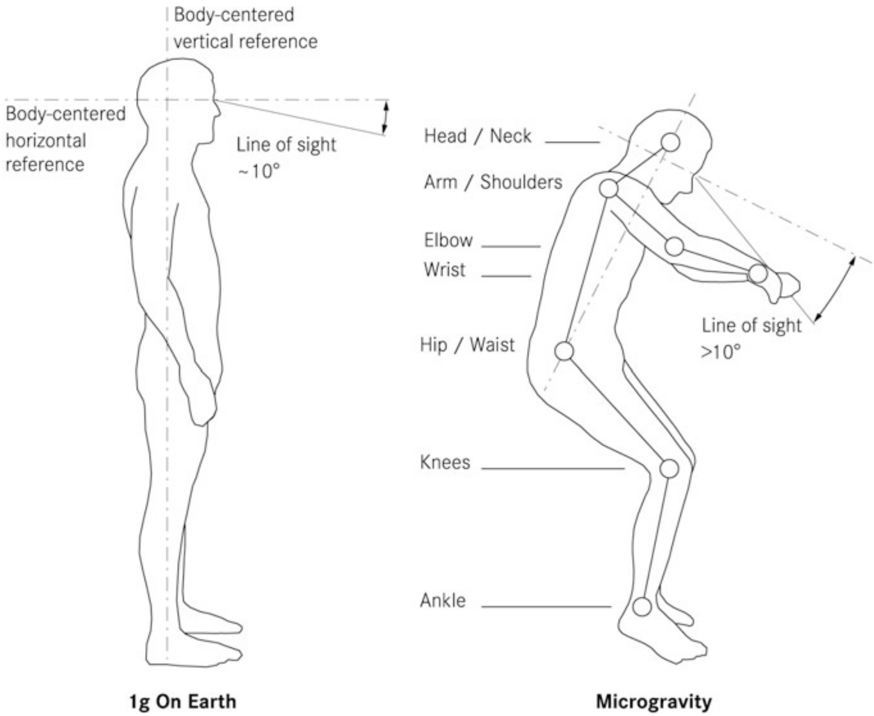


Fig. 4.2 The Neutral body position on earth and in micro gravity (as published in architecture for astronauts, Springer 2011, p. 19; NASA)

longer defined and the body position can be in any orientation. In the past this has led to performance impairment (cf. Skylab NASA Bulletins 7 and 8; Häuplik-Meusburger 2011). "*Natural cues, like a defined up and down or sunlight coming from 'Above' are missing in a microgravity environment.*" Häuplik-Meusburger (2011, p. 246), thus making spatial orientation more difficult.

The Soviet and Russians introduced a color system that identifies 'floor', 'walls' and 'ceiling' to help astronauts in orientation. On-board Skylab, different orientations were used. It has been shown that for work areas, a defined up and down is functional.

NASA has established the following orientation design requirements within a space module (NASA [MSIS] 8.4)[6]:

- Consistent orientation within one activity center.
- Visual orientation cue to allow quick adjustment to the orientation of the activity center or workstation.
- Separation of activity centers with different orientations.

[6]Source for Research: Volume I—Man Systems Integration Standards (MSIS) online: http://msis.jsc.nasa.gov/downloads.htm.

Designers must not forget that humans' expectations in space are still bound to Earth traditions. A change of body position can turn a familiar room into a totally different one (cf. Haigneré 2009; Lebedev 1990, p. 150; Connors et al. 1985), which can have a positive or disruptive effect.

Key design interventions for reduced gravity can be summarized as following:

- Appropriate visual orientation cues and other information systems for each gravity condition.
- Convenient and coherent layouts of interior areas, crew work and leisure accommodations, and equipment to maximize safety, access, and use.
- Personal mobility aids along with proper restraint devices for people, equipment, tools, and supplies.
- Exercise systems that are used to counteract deconditioning effects of long low-gravity exposures.
- Planning of all systems for easy operation and maintenance under reduced gravity conditions.

4.3.2.2 Restraints and Mobility Aids

As a consequence, in a microgravity environment, multiple kinds of restraints are used to stabilize the body or to hold the body in a certain position. Examples are: handhold restraints, waist restraints, torso restraints, foot restraints and tethers, such as bungees, straps, and harnesses.

Handrails are the most common restraint in the International Space Station (Figs. 4.3 and 4.4). Note: Handrails used in Russian modules are designed differently from European and US segments.

4.3.2.3 Example: Sleep Station Restraints

Since the Apollo missions, sleep restraints were provided for the crew. Table 4.4 shows a summary and comparison of the different sleep restraint systems that have been used.

4.3.3 Other Environmental Factors

4.3.3.1 Odors and Smell

"*Few people have experienced traveling into space. Even fewer have experienced the smell of space. Now this sounds strange, that a vacuum could have a smell and that a human being could live to smell that smell.*" (ISS Science Officer Don Pettit, Expedition 6).[7]

[7] http://spaceflight.nasa.gov/station/crew/exp6/spacechronicles4.html.

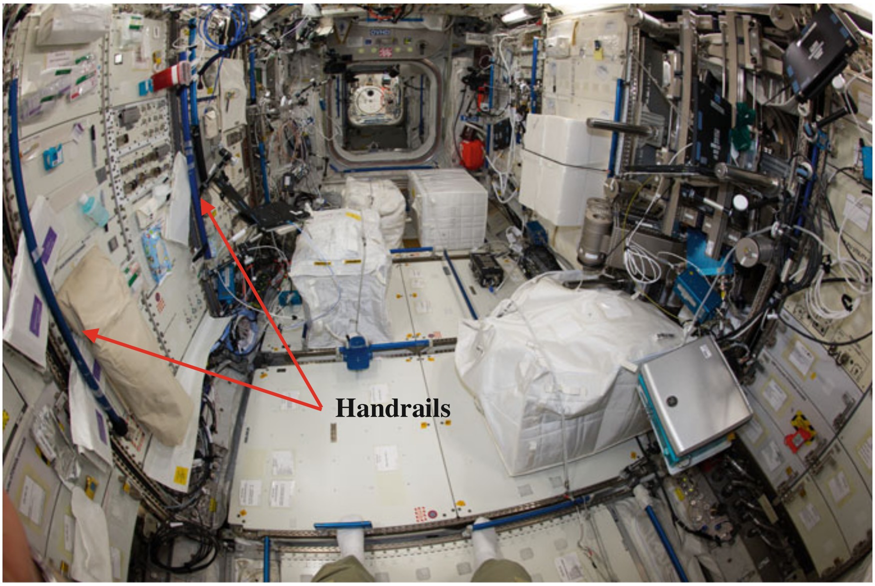
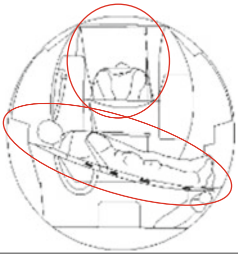
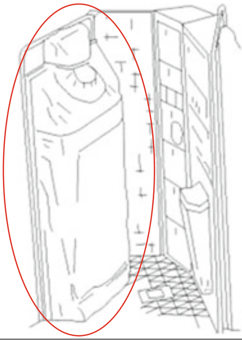
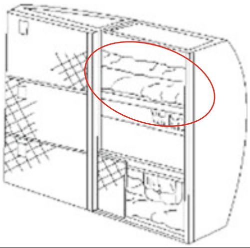
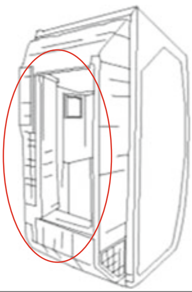


Fig. 4.3 The interior of the columbus laboratory showing blue handrails and foot restraints, as well as clamps; Photographed by an expedition 40 crew member on the international space station (2014). ISS040-E-008058 (NASA)

Fig. 4.4 The interior of the module FGB/zarya, showing the handrails and stowage panels (1996). STS096-378-037 (NASA)

Table 4.4 Sleep restraints and crew quarters in different space stations (images and text taken from the book architecture for astronauts, 2011)

Summary sleep restraints in previous space stations	
Diagrams	Key features
	Early sleep restraint during the Apollo missions Sleeping bags and hammocks were used and proved efficient for short-term missions
	Sleep restraint during the Skylab missions Every crewmember had his own private area. Crew quarters were permanent and included sleeping bags in vertical position, private storage, and communication facilities.
	Sleep restraint for the Space Shuttle Orbiter. On-board the shuttle, different sleeping configurations were used, depending upon the schedule. On selected mission so-called sleeping boxes were used (usually when crews were meant to work shifts)
	Current sleep station onboard the ISS Currently private crew quarters are provided for the crew of 6. They have integrated storage, communication, and also radiation protection

Astronauts, cosmonauts, and researchers have been working on making the ISS environment minimally harmful and maximally comfortable for the crew. This includes controlling odors and smell inside the habitat. People have different smell preferences on Earth and it is the same in space, but odors in space may change their qualities and feel different or even become unpleasant in the confined environment of a space module. Researchers at NASA's White Sands Test Facility in Las Cruces, New Mexico, investigate, evaluate, and categorize different smells. They rank odors on a scale of zero to four where 0 is not noticeable, 1—hardly noticeable, 2—clearly noticeable, 3—unpleasant and 4—unbearable. George Aldrich, a chemical specialist at the White Sands Test Facility's Molecular Desorption and Analysis Laboratory, calls the last type a "get-me-out-of-here" smell.[8]

Detecting toxic and dangerous chemicals in the habitat atmosphere is vital for crew survival and special equipment is required to trace those chemicals before they become harmful for astronauts. An example of such technology is an Electronic Nose or ENose that has been operated on the ISS since Expedition 18 (October 2008–April 2009). Design of the habitat has to provide means to remove dangerous or just unpleasant odors from the atmosphere of the module as soon as possible. It also has to accommodate zoning and space for experiments and activities with potential risks of the release of non-desirable gasses into habitat's environment.

4.3.3.2 Lighting and Illumination

In addition to natural light, artificial light is very important for working and living in space. Natural light is not available at all destinations and not always at desired times. The space station orbits Earth every 90 min implying quick changes from light to dark lighting levels. The lunar cycle (around the equator) is 14 days of daylight and 14 days of darkness.

Overall, general lighting and task related lighting are required, whereas different light levels are used for lighting specific tasks.[9] In addition, lighting design is not for functional purpose alone; visual comfort of lighting plays an important role as well as aesthetics.

4.3.3.3 Colors and Texture

The use of colors became evident in the seventies during the Skylab and Salyut missions because of long-term human spaceflight goals. It is important to remember that people are either visual or vestibular dominant. For visual dominant people colors are especially important for spatial orientation. Colors can be used in various ways:

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[8] http://spaceflight.nasa.gov/shuttle/support/people/galdrich.html.

[9] Further Research: Lighting design requirements for exterior lighting, emergency lighting and controls can be found in the NASA-STD-3001, Volume 2, Chapter 8.7 Lighting.

Fig. 4.5 Mir station interior, mock-up

Spatial Orientation: Colors were used to mimic 'Earth orientation' in the Soviet and Russian space stations. The core module of the space station Mir, for example, had a brown floor, yellow walls, and a white ceiling. For the interior of the International Space Station, 9 colors have been used (cf. Durao 2003; Häuplik-Meusburger 2011).

Color-Coding: Some objects and items are color-coded or have a contrasting color to increase their visibility (compared to the background) for safety reasons or for differentiation. Defining a dominant color is very important; colors are also related to status lights (green, yellow, red). Food containers, for example, have been color-coded since the Apollo missions. Mir station had colors assigned to its "floors"—brown, "walls"—beige, and "ceiling"—light blue (Fig. 4.5).

Comfort and Spaciousness: The use of color can enhance the feeling of comfort and increase the feeling of spaciousness. Some colors are perceived as warm (usually red, yellow, or brown) while others usually create a "colder" feeling (such as blue and green). Sleep compartments in the Soviet stations were, for example, colored in muted and cool tones.

The following design requirements for colors have been defined (NASA [MSIS]):

- Color Selection: neutral and lusterless colors for workstations; black or grey colors for controls to provide good contrast to the background.
- Color Code: The use of colors including its intensity and chromaticity depends upon the location.
- Consistency: same colors shall be used for the same applications throughout the space module.

4.3.4 Discussion and Tasks

Discuss different gravity conditions and the consequences for design? What do you think can be used for humans' benefits? Why? What challenges and possibilities do partial or zero gravity conditions present for designers? Which environmental issues have direct consequences for the design?

4.4 Human Activities and Social Interaction Design

Questions for Exploration
What human activities are related to habitability in space? What environmental stressors do people have to deal with during a space flight? What are the main issues associated with habitability? How can human activities be integrated into the interior design? How do people work and live in space?

4.4.1 Habitability Issues in Spaceflight

In 1985 the NASA report 'Living Aloft' (Connors et al. 1985) described some of the habitability issues of extended spaceflight. In 2010 Stuster identified 24 issues with behavioral implications for human spaceflight. He used a content analysis of personal journals that were maintained for this purpose by NASA astronauts during expeditions onboard the International Space Station. According to Stuster, the study provides the first quantitative data on which he based a rank-ordering of the behavioral issues associated with long duration space operations (Stuster 2010). The top 10 issues account for 88 percent of all astronauts' journal entries that he had examined and are listed in Table 4.5. In Architecture for Astronauts (2011), a comparative analysis of human activities within the space craft environment was carried out to retrieve issues that influence the habitability system.

Table 4.5 summarizes behavioral and habitability issues identified by various researchers in Human Factors Research.

The issues from the table are considered to be fundamental for habitability and core issues for HRLs (Habitability Readiness Levels).

4.4.1.1 Stressors and Architectural Countermeasures

Many stressors can lead to degraded performance. Among the common ones are "*problems associated with interior space, food, hygiene, temperature, décor, lighting, odor, and noise.*" (Connors et al. 1985, p. 60) Some of their countermeasures are directly related to habitability and to space architecture.

Table 4.6 lists examples of stressors and their architectural countermeasures.

In an interview, French astronaut Clervoy answered the question: "*What is it that you can say?—This is my home?*" with the following answer "*This is MY bed, this is MY kitchen, this is MY cupboard, with MY stuff in it. Don't mess with it.*" (Clervoy 2009). Most of the literature and experience from the interviews indicate that astronauts' requirements for levels of privacy increase with mission length.

Table 4.5 Relevant issues identified in human factors research

Relevant issues identified in human factors research	Author/source
Work, outside communication, adjustments, group interaction, recreation/leisure, equipment, events, organization/management, sleep, food	Stuster Jack (2010)
The physical environment (interior space, food, hygiene, temperature and humidity, décor and lighting, odor, noise), health and leisure (recreation, exercise), privacy (crowding, territoriality), complex effects	Mary et al. (1985)
Sleep (rest, relaxation, sleep and storage), hygiene (personal hygiene, shower, toilet, housekeeping), food (store, prepare, grow, consume, and storage), work (operations, experiments, communication, education, training, and storage), leisure (free-time activities, exercise, intimate behavior, and storage)	Häuplik-Meusburger (2011)

Sources as in table

Table 4.6 Stressors for Long-term human spaceflight and possible countermeasures related to space architecture

Stressors associated with habitability	Architectural countermeasures	Degraded performance
Volume limitations	Interior layout, windows, virtual reality	Lack of privacy, feelings of claustrophobia
Confinement, isolation, separation	Layout (social events, visitors, private communication with family and friends)	Feelings of claustrophobia, lack of motivation, "cabin fever"
Noise and vibration	Vibration isolation and control, zoning	Sleep disturbances, poor communication
Lighting	Lighting design (natural light)	Fatigue, irritability, blurred vision

Sources Dudley-Rowley (2004)

Likewise, research from analogue environments show that under prolonged isolation and confinement the need for private space increases (Stuster 1996; Kanas and Manzey 2003; Connors et al.1985).

Providing an adjustable and adequate design for different levels of privacy is an architectural challenge that is important for maintaining a healthy psychological atmosphere in extra-terrestrial communities. Privacy conditions affect each individual and the whole crew differently, depending on their social and cultural backgrounds. Design solutions can accommodate those individual and group needs. Design arrangements have to evolve as the community and settlement grow. Personal and group demands and requirements also change with time, number of occupants, availability of resources, and other aspects specific to human society.

Table 4.7 Summary of Habitation volumes (rounded off) of historical missions

Habitation type	Crewmembers	Mission duration (d) (max/min)	Volume per crew (m^3)	Volume total (habitable volume) (m^3)
Apollo CM (with LM)	3 (2)	6d 3 h (Apollo 8)	2.22 (4.27)	10 (6)
Skylab	3	28–84	120	320 without Apollo CS OWS: 270
Salyut	3	16–237	33–55	~90
Mir	2–3 (and visiting crew)	73-438	45–181	~380 Core module: 90
ISS	2–6 (and visiting crew)	215	85–201	935 at assembly

Sources Cohen (2008) and Häuplik-Meusburger (2011)

4.4.2 System Sizing and Early Volume Considerations

> Adequate internal size, in terms of volume and surface area, are to be provided to ensure crewmembers can safely, efficiently, and effectively perform mission tasks, including work, sleep, eat, egress, ingress, and other tasks necessary for a safe and successful mission. It is important to consider all types of volume – pressurized, habitable, and net habitable, in accordance with JSC 63557, Net Habitable Volume Verification Method – when determining the amount of volume that is necessary. (NASA [STD-3001-2] 2015, p. 95)

Although "*design of vehicle and surface elements depends on what needs to be done*" (Larson, p. 150), it is still a tradeoff between the minimum for weight concerns and the optimum for crew comfort. One basic parameter when designing a habitat is the available space and the allocation of the required or optimum habitable volume. References show that "*adequate living space is important [and] that lack of space (volume) can lead to negative physical and psychological problems*." (Bluth and Helppie 1987, p. 6)

The largest habitable volume within one module was provided by the Skylab space station (320 m^3 for a crew of three with a maximum diameter of 6.6 m), as its architecture was formed by a converted third stage of a Saturn V moon rocket. An overview of historical habitation volumes is shown in Table 4.7.[10]

Over time, many studies have tried to ascertain an exact amount of how much spatial volume a person needs. However, so far, no mutual consent on a specific number or approach has occurred. In 2008, Marc M. Cohen analyzed the so-called "Celentano Curve" hypothesis (Celentano, Amorelli and Freeman, 1963) and its variations that are used to predict the amount of required pressurized volume per

[10]Further Research: Book: Architecture for Astronauts by S. Häuplik-Meusburger: Comparison of the Architectural Concept (88–89) and Interior Layout (90–91) of space habitats.

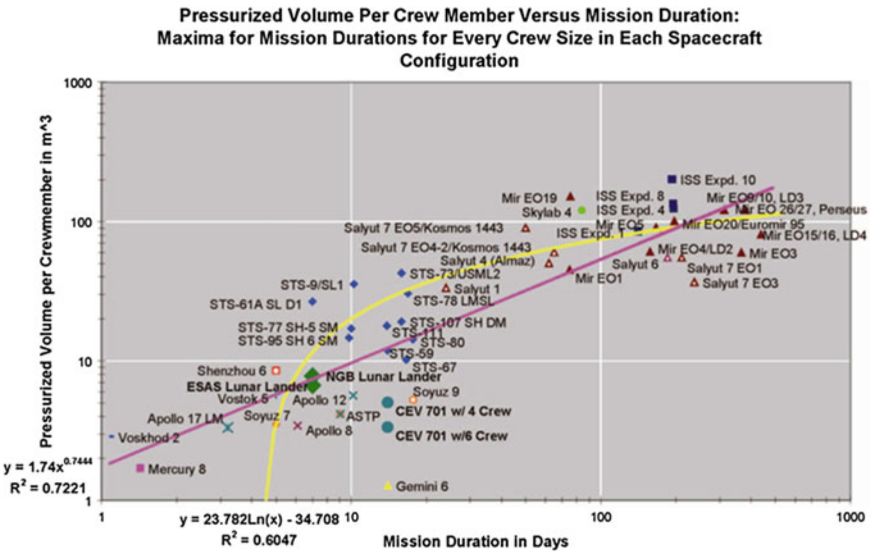


Fig. 4.6 Plot of the "Celentano Curve" showing pressurized volume per crewmember of specific missions in the designated spacecraft. ESAS Lunar Lander, NGB Lunar Lander, and CEV 701 are speculative data points from the cancelled constellation program (Cohen 2009, p. 20)

crewmember.[11] An example of the Celentano Curve showing pressurized volume per crewmembers of past realized and planned missions is shown in Fig. 4.6.

Based on Cohen's research the following rules of thumb can be used for orientation:

1. Mission duration drives volume (per crewmember).
2. Crew size drives volume, whereas crew size is not a variable for volume.
3. Mission, functional, and operational requirements drive volume (and design).

4.4.2.1 Module Types and Spatial Organization

The interior spatial organization of modules can be radial, linear, in a grid, or circular. The configuration is defined by or defines interior circulation, zoning, and access/egress points. All three of these design factors depend on each other and have to be addressed in the design process simultaneously. In this section, conventional, hard shell telescopic, and spherical inflatable modules types are used to demonstrate design considerations. It has to be noted that other pressurized shapes can be used and combined, e.g. toroidal inflatable, vertically or horizontally oriented cylindrical, and their combinations. The spherical shape of a pressurized

[11]Research: Paper by Marc M., Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume. 08ICES-0046.

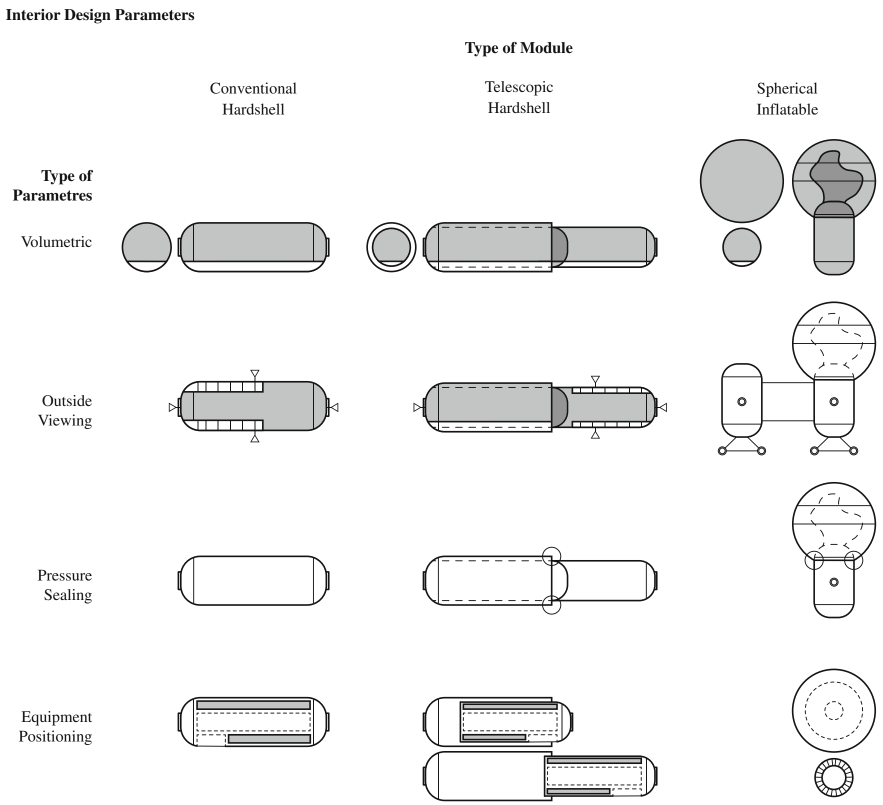


Fig. 4.7 Examples for interior design parameters of different modules (Bannova 2007)

structure is the most efficient due to equal pressure distribution and structural consistency.

Private or group domain zoning can be defined by allocated function and depends on available space and volume and on activity flow and schedule. Other spatial organization selection criteria include the potential for evolutionary growth and emergency evacuation options.

Interior arrangement options are dependent on the selected surface module type. Key Factors include volumetric characteristics, outside viewing possibilities, pressurization features, and equipment/utilities arrangements as highlighted in Fig. 4.7.

A conventional module is launched fully pressurized and ready for the crew to move in. The same conditions are applied to telescopic hard-shell modules. They have to be pressurized before a telescopic part is deployed on the surface. Inflatables are launched non-pressurized and folded within a payload shroud or module and deployed on the surface of a planet or in space. They are ready for the crew habitation after pressurization and deployment operations are finished. This requires the crew to integrate equipment and utilities before the module can be used for its purpose.

Volumetric characteristics for different module types are important for surface module class selection:

- In both types of conventional modules all equipment can be pre-integrated before launch.
- Floor area in telescopic modules can expand at an approximately 1:1 ratio with a smaller diameter of a telescoping section.
- Inflatable modules offer extra space for a crew's multi-functional activities, providing relief from a closed and cramped hard module confinement. This is vitally important for good crew morale and performance which significantly influences mission success and safety (see also Sect. 5.3.3: Inflatable Structures). In inflatable modules the area of the inflatable section expands rapidly with increased diameter as a function of r^2.

From a volume point of view, inflatable modules are the most efficient scheme. They should be designed to minimize deployment and equipment/utility integration requirements, and may be most practical to implement after crew operations have been established using conventional module(s) (Other possible shapes of inflatable pressurized structures are shown in Chap. 5, Fig. 5.28).

Outside Viewing positioning options vary in different module types:

- Conventional hard-shell modules may accommodate several viewports with the penalty of losing valuable real estate space along a module's walls where equipment racks and other elements can be located.
- Telescopic hard-shell modules may be equipped with viewports in the ends of the deployable part of the structure. Same real estate concerns apply here as in conventional modules.
- Although there is a possibility to integrate a viewport structure into the soft-shell of an inflatable module, it will increase module weight and risks a pressure leakage. Therefore, outside viewing might best be located in a hard-shell structure combined with an inflatable or in conjunction with the airlock.

Pressurization/Safety is a very important issue to secure the modules' pressurization, which depends on the sealing characteristics between sections, modules, and interfaces.

- Telescopic module requires a hard seal at the mating connection between the two module sections.
- Vertical inflatable module requires only one seal attachment between hard and soft sections to minimize leak and maintenance problems.
- Both types of conventional modules use standard module construction, which guarantees no pressurization complications.

Equipment positioning:

- Conventional "hard" modules afford good pre-integrated equipment capacity along with design simplicity using proven systems. This will be of particular

importance for early surface missions to enable rapid operational implementation with the least amount of crew set-up time.
- If the inflatable section stowage is inside the hard part of the module, the relatively large deployment opening and stowage containment areas will be likely to consume much of the volume that would otherwise be available for pre-integrated or stowed equipment.

Another approach is to attach the stowed inflatable externally, in-line with the hard module, avoiding the need to deploy the inflatable from within. Stowed equipment volume is quite limited by the small circular floor plan, requiring that other modules be attached to supplement capacity.

Many more configurations and combinations are possible and depend on site conditions, mission tasks, crew members and their number.

4.4.3 Functional Activity Areas: Zoning and Layout

Previous and current space habitat design examples demonstrate evolution of a spacecraft interior design that mostly follows activity function allocation. Table 4.8 lists the allocation of basic functions/activities in past and present space habitats (refer to Fig. 4.8 for a visual representation).

Typically the organization of the interior layout follows the functional needs of the crew, such as working, hygiene, preparing and eating food, etc. A typical kind of diagram used by architects to "*explore relationship among the sizes, adjacencies, and approximate shapes of the spaces needed for various activities*" (Blackwell 2001, p. 143) is the 'Bubble Diagram' like the one shown in Fig. 4.8. Sometimes text, lines, or arrows are used in addition to show the relationship between functions. Diagrams help to evaluate design considerations and make functional constraints visible. These kinds of diagrams can also be used to analyze existing designs.

Figure 4.8 shows the functional zoning of the Apollo Lander, Skylab, Mir and the International Space Station. The diagrams show, for example, that in the Apollo Lander, all functional activities overlap (which was efficient for short term missions); In Skylab crew quarters and galley were spatially separated, whereas the galley had a window to the outside. In the Mir space station the crew quarters were spatially separated as well, but had a window. The Food and Exercise areas were next to each other (in the main module).

The 'Adjacency Matrix' is a tool that helps to analyze linkages between functions and subsystems (Fig. 4.9).

A diagram, such as in Fig. 4.10 can be used to allocate activities according to preliminary requirements. For example, crew quarters are considered private/individual domain. They should be located in a quiet area in the habitat. Actual layouts for the diagrams depends on the specific mission and can vary.

Table 4.8 Allocation of activities in historic and present space habitats

Station	Sleep	Hygiene	Food	Work	Leisure and exercise
Apollo	In main module	In main module	In main module	In main module Outside on the lunar surface (EVAs)	In main module Outside on the lunar surface
Salyut	In main module	Deployable shower and personal hygiene in work area Toilet close to work area	Wardroom with table in work area	Instrument area could be partitioned from living area EVAs	Exercise and recreation in main module
Skylab	Spatially separated in private crew quarters	Collapsible shower in work area Spatially separated hygiene area	Spatially separated wardroom for preparation and eating of food	Experiment area and Dome in the OWS EVAs	Dedicated area for exercise in work area, private crew quarters
Shuttle	Depending on mission; in main module (sleeping bags) or dedicated spatially separated area (sleep boxes)	No dedicated area for advanced personal hygiene Separate toilet area	No dedicated area to eat; galley rack for food preparation	In main volume EVAs	Exercise and recreation in work area (Middeck, Flight Deck)
Mir	Spatially separated in individual cabins	Permanent shower in Kosmos Toilet with curtain in core module	Food cabinet with table in work area	In core module and dedicated science modules EVAs	Exercise in work area, but in different modules; Recreation in individual cabins; other modules
ISS	Spatially separated in individual crew quarters	No shower Two toilet compartments	Food cabinet with table for all astronauts	Dedicated modules and rack system; EVAs	Exercise in work area, but in different modules; Recreation in crew quarters

Sources Häuplik Meusburger (2011)

Fig. 4.8 **a** Bubble diagram, showing the preliminary zoning of the lunar lander, skylab station, mir station, and the international space station—zones are color-coded: sleep (*blue*), food (*green*), hygiene (*yellow*), work (*red*), leisure and exercise (*purple*); (as published in Architecture for Astronauts, Springer, 2011). **b** Legend for Fig. 4.8a. (as published in Architecture for Astronauts, Springer, 2011)

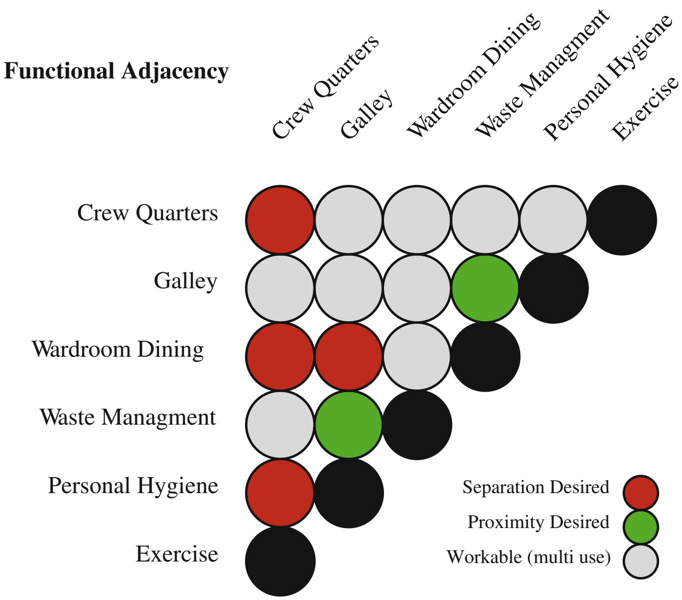


Fig. 4.9 Adjacency matrix for the collocation and separation of functional zones (adapted from Brand N. Griffin)

4.4.3.1 Stowage and Object Management

Living and working in a space station is complex. Especially storage and managing objects is challenging in extra-terrestrial habitats. In an interview, astronaut Clervoy pointed out "*the number one challenge by far (…) is managing objects*" (Häuplik-Meusburger 2011, p. 248)

The ISS uses a rack system to "*support efficient integration and interchangeability of payload hardware*" (NASA [UG] 2000, p. 19) and the majority of stowage is accommodated in International Standard Payload Racks (ISPR) (Fig. 4.11). It provides a volume of 1.6 m^3 (55.5 ft^3) of internal volume and measures 2 m (79.3 in) height, 1.05 m (41.3 in) wide, and 85.9 cm (33.8 in) deep. It weighs 104 kg (230 lbm) and can accommodate 700 kg (1540 lbm) payload equipment. The ISPR has internal mounting provisions for the attachment of secondary structures and a standard power interface of a 3 kW feed.

Other stowage racks used include:

- The Zero-G Stowage Racks (ZSR) are comprised of a collapsible shell and a fabric insert. It has a capacity of 1.2 m^3 (42.8 ft^3) and is an on-orbit stowage restraint system only.

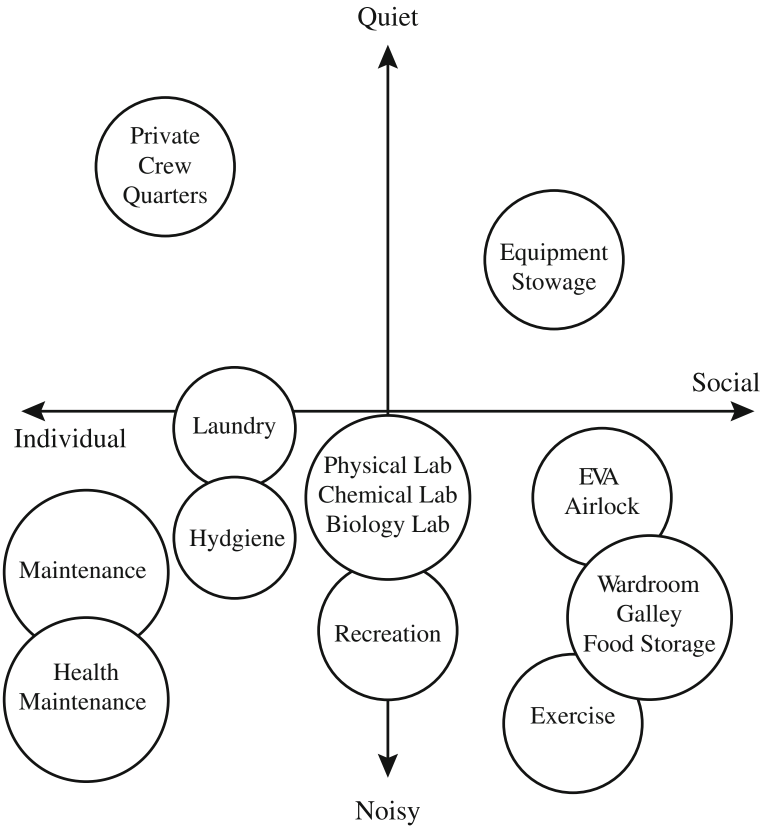


Fig. 4.10 Diagram used for the principle zoning of areas

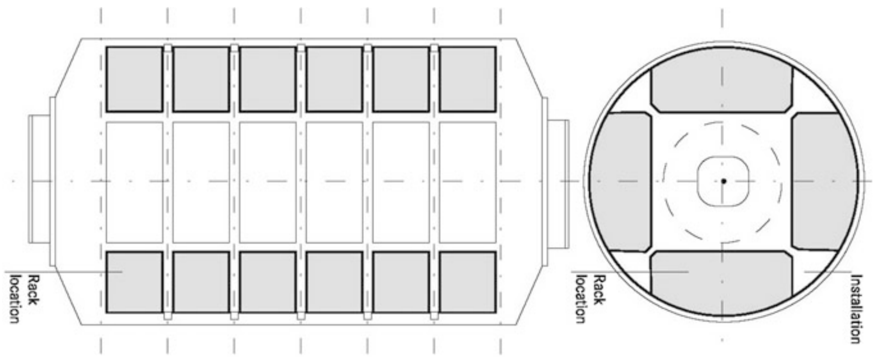


Fig. 4.11 International space station rack configuration (as published in architecture for astronauts, Springer, 2011; based on NASA documentation)

- Resupply Stowage Rack (RSR) has a capacity of 1.1 m^3 (37.5 ft^3) and stores small items and lockers of various sizes.
- The Resupply Stowage Platform (RSP) is a carrier system for transporting cargo to and from the station.

4.4.3.2 Example: Eating and Dining in Space

Having dinner is a social activity shared by many cultures and is one of the habitual social customs that people carry into space. Those customs inherit social rules that influence the requirements and design.

Astronauts generally dislike talking to a colleague who is upside-down while having dinner together. On Skylab missions, crews refused to ‘float’ over the table, as it was seen as inappropriate behavior. They had, for the first time, a large dedicated area for food preparation and dining and were eating together on a specially designed table, eating with knives, forks and spoons (Fig. 3.7a, Chap. 3). From then on, a table for having meals together has been considered to be of importance by the crew and became a requirement (Table 4.9). Still, having dinner together is an important social activity in space. “*At dinner at night, we have a time, even if you are busy; you set this time to make jokes and to have fun*.” (Astronaut 2009) .

Today a variety of food is available for astronauts, but still, available food can get boring if you are on a long-term mission. To increase the variety of tastes astronauts are inventive in creating new meals by mixing food ingredients—they are doing space “cooking.”

In the future, specially designed facilities may improve the astronaut’s habitability by supporting them in food experimentation.[12]

Packaging and expiration date of consumables must also be taken into consideration.

Further, the kind of activities and astronaut personal preferences can vary to a high degree (e.g. sleeping). Table 4.10 gives examples of dimensions related to the human body and dining, sleeping and exercising activities in partial and full gravity conditions. The full table with the summary of general allocations of volume and area can be found in Appendix A.

4.4.4 Discussion and Tasks

> Discuss habitability characteristics and their importance. Suggest three design related approaches that may help the crew to fight environmental stressors. Discuss your suggestions with the class and defend your opinion.

[12]Further Reading; ‘Astronauts orbiting on their stomachs’ by Häuplik-Meusburger (pp 114–117) in ‘Space Architecture: The New Frontier for Design Research, Wiley 2011.

Table 4.9 Food systems in different space stations (images and text taken from the book architecture for astronauts, 2011, p. 216–217)

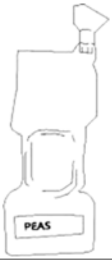
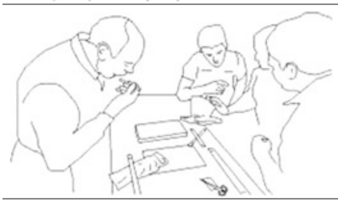
Summary food systems in previous space stations	
Diagrams	*Key features*
	**Dehydrated and bite-sized food** Food was developed with regard to long term human flights
	**Wardroom with a table for three** The table was especially designed and situated next to the wardroom window. It had several restraints and astronauts could individually prepare their food
	**Food tray on-board the Shuttle** Astronauts had a wide range of food. On short mission they didn't always eat together
	**Food system on board the ISS** In the Zvezda module is a preparation and eating area for all astronauts. A greenhouse for fresh food is provided.

Table 4.10 Summary of general allocations of volume and area

Function	Notes	Dimensions in cm (in)	Minimum volume
Dining	accommodates crew of 6 Width/crew member: 70 cm [28″]	H: > 215 [84″] L: 300 [118″] W: 254 [100″]	for a crew of 6: 16.4 m^3 [579,1 f^3]
Sleeping partial G and full G	Volume orientation must be horizontal to the local vertical Human envelope: W: 85 cm [33″] D: 85 cm [33″] exclusive of access area	H: 85 [33″] L: 215 [84″] W: 85 [33″]	1,55 m^3 [54.4 f^3]
Exercise	for a crew of 4–6 treadmill	W: 251 [99″] L: 150 [59″] H: 245 [96″]	9.22 m^3 [325,6 ft^3]

Sources Adams (1999)

4.5 Guest Statement: Artificial Gravity and Implications for Space Architecture (Theodore W. Hall)

Gravity is the aspect of Earth's environment that's the most uniformly experienced, across time, place, and culture, and yet it is the most radically altered when leaving the Earth to live elsewhere. Within the hulls of our space habitats, we can recreate any habitable Earthlike condition of heat, humidity, pressure, light, sound, and so on, but recreating Earthlike gravity is especially problematic. To understand the problem and propose a viable solution, in the absence of previous direct experience, we must turn to our most fundamental and reliable theories to guide our analysis. Though it may seem far removed from the concerns of architecture, it's worth spending a few minutes to ponder the deep realities of gravity and our experience of it. Only then are we prepared to try to replicate it. There are many misconceptions regarding artificial gravity that lead to flawed analysis and can be dispelled only through an understanding of the physics. Since there is yet no practical experience of building and inhabiting artificial-gravity space habitats, we have nothing but theory and imperfect ground-based experiments to guide us.

4.5.1 What Is Gravity?

Modern physics posits Four Fundamental Forces or "interactions": strong nuclear, weak nuclear, electromagnetic, and gravitational. Every interaction in the physical universe is ultimately reducible and attributable to these Four. Among these, gravity stands apart as the only one that doesn't conform to the Standard Model of particle physics. Each of the other three operates through some mediating particle: the electromagnetic interaction, through photons; the weak nuclear interaction, through W and Z bosons; and the strong nuclear interaction, through gluons. Some physicists hypothesize a graviton, to bring gravity into line with the others and arrive at a Theory of Everything, but the theory remains incomplete and is not yet supported by experimental evidence. In Einstein's Theory of General Relativity, the apparent gravitational force is a consequence of the curvature of four-dimensional space time.

The strong and weak nuclear interactions operate only at the scale of atomic nuclei. They're relevant to atomic fusion, fission, and radioactive decay. Apart from that, all of the interactions between atoms and molecules, whether biological, chemical, or mechanical, are due to gravity and electromagnetism.

According to Newton's Law of Gravitation, there's a mutually attractive force between every pair of particles in the universe. The force (F) is proportional to each of their masses (m) and inversely proportional to the square of the distance (d) between them, scaled by the Universal Gravitational Constant (G):

$$F = G\frac{m_1 m_2}{d^2} \tag{4.1}$$

The total gravitational force acting on each particle is the sum of its interactions with all of the other particles. The gravitational force is the weakest of the Four Fundamental Forces. It takes enormous concentrations of mass—on the scale of planetary bodies—to produce any force noticeable to humans outside of a physics laboratory. Gravity tends to pull particles together into spherical clumps, though other factors may intervene to yield oblate spheres or disks. The gravitational force between a particle and a planet is the sum of the forces between the particle and all of the planet's particles. With a bit of calculus, it can be shown that any homogeneous spherical clump of particles exerts the same net gravitational force as if the sphere's entire mass were concentrated at its center. This is a special attribute of spheres that doesn't apply to other shapes. It's a very handy simplification and a good enough approximation for at least initial calculations of planetary gravity. If one of the masses in the numerator of Eq. (4.1) (m_1 or m_2) is a planet, the d in the denominator should be the distance to its center (not its surface).

Newton's Second Law of Motion relates force (F) to mass (m) and acceleration (A):

$$F = mA \tag{4.2}$$

Newton's Laws apply only in inertial, non-accelerated coordinate systems. In other words, the acceleration A must be measured relative to a coordinate system that is not itself accelerated.

Considered together, Eqs. 4.1 and 4.2 show why hammers and feathers fall at the same rate in a vacuum (without the interference of atmospheric drag). The m's in Eq. 4.1 are gravitational masses, whereas the m in Eq. 4.2 is inertial mass. But, in Newton's Laws, as well as in Einstein's Theory of General Relativity, gravitational and inertial mass are equivalent and can be divided out of both sides:

$$F = G\frac{m_1 m_2}{d^2} = m_1 A_1 = m_2 A_2 \tag{4.3a}$$

$$A_1 = G\frac{m_2}{d^2} \tag{4.3b}$$

$$A_2 = G\frac{m_1}{d^2} \tag{4.3c}$$

The gravitational acceleration of each body toward the other depends only on the other body's mass, not on its own. If m_1 is the Earth, A_2 is the same whether m_2 is a hammer or a feather. Near the surface of the Earth, the acceleration due to gravity is 9.81 m/s^2, which is commonly referred to as 1 g.

Stars, planets, and moons produce noticeable tides on each other because they're somewhat large relative to the distances between them. For example, the Moon pulls harder on the particles at Earth's near side than at its far side, causing the nearside particles to accelerate toward the Moon a bit faster than the far side particles, causing the Earth to stretch, and vice versa. In principle, the Earth exerts tides on astronauts in orbit, but because they're so tiny in proportion to their distance from the center of the Earth, the effects are far too miniscule to be biomechanically significant.

Gravitational force draws atoms together until they meet. Once they meet, the electromagnetic interaction between their shells sets boundaries for how close they can get and prevents them from interpenetrating. The mechanical forces conveyed from atom to atom through bodies—tension, compression, torsion, shear—are all manifestations of the electromagnetic interaction, not gravitation.

4.5.2 What Is Artificial Gravity?

Einstein proposed a thought experiment: if a man is enclosed in a chest, out in space, far from any significant gravitational field, and the chest is accelerated "upward" at a uniform rate, then every experiment the man can perform within the chest will run exactly as if the chest were suspended motionless in a gravitational field. If the man drops a ball, he'll observe that it accelerates toward the floor of the chest at a uniform rate regardless of its mass or composition. He'll observe that mechanical forces propagate through structures in precisely the same way, with maximum compression at the bottoms of columns and maximum tension at the tops of hangers. Einstein concluded that, "a gravitational field exists for the man in the chest, despite the fact that there was no such field for the coordinate system first chosen." (Einstein 1961) In other words, acceleration by something other than gravity essentially creates gravity.

Artificial gravity is the inertial reaction to acceleration due to the electromagnetic interaction between atoms. If "artificial gravity" is a misnomer, that's not because it's not gravity, but rather because it's not artificial. A gravitational field exists in any non-gravitationally accelerated frame of reference.

Standing on Earth, we feel weight not because gravity pulls us down, but rather because the electromagnetic interaction with the ground pushes us up. Remove gravity but keep the upward push—as in a rocket—and weight remains. On the other hand, keep gravity but remove the upward push—as in a drop tube, an airplane flying parabolas, or an orbital space station like the ISS—and weight disappears. Evidently, gravity is neither necessary nor sufficient to induce the weight that keeps human bodies healthy on Earth.

There are many deleterious effects on humans in prolonged states of weightlessness. Space life scientists continue to discover them even after more than 50 years of human spaceflight—for example, blurred vision due to increased intraocular pressure. Many of these effects are triggered by the redistribution of fluids from the legs toward the torso and head due to weightlessness. Devising countermeasures for myriad individual symptoms is fraught with difficulties. Even if each is completely effective in its limited domain, such as preserving bone and muscle mass, how can we be certain that we're not missing some other insidious undiscovered effect?

Our best physical theories tell us that, whatever the ill effects of spaceflight, if weightlessness is the root of the problem then artificial gravity is the solution. We can travel from place to place without having to enumerate all of the things that might go wrong in microgravity, as long as we remain in a state of constant 1-g acceleration.

Constant linear acceleration would be a perfect gravity generator, except that it requires vast and unmaintainable energy input and doesn't allow the accelerated thing to remain near any planet. Kinetic energy increases with the *square* of speed, so not only must the energy continually increase, but the power as well.

However, it's not necessary for the acceleration to be collinear with the velocity. Position, velocity, and acceleration are all vectors with direction as well as magnitude, and acceleration is any change in velocity, whether in its direction or its magnitude. Centripetal acceleration is perpendicular to velocity and changes only its direction. Because the velocity magnitude (speed) remains constant, the kinetic energy also remains constant. This means that centripetal acceleration is sustainable. Constant-magnitude centripetal acceleration produces circular motion. A simple spinning structure provides constant, self-sustaining centripetal acceleration, through conservation of angular momentum and energy, and the spinning structure can remain in orbit around a moon, planet, or star. These considerations make it the only viable strategy for producing gravity in space for extended durations away from a planetary surface.

With some elementary knowledge of vector calculus, it can be shown that for a particle in circular motion at radial distance R and angular velocity $\mathbf{\Omega}$ radians per unit time, the position ($\mathbf{R}$), velocity ($\mathbf{V}$), and acceleration ($\mathbf{A}$), vectors are related according to Eqs. 4.4 and 4.5. The derivation is beyond the scope of this chapter, but can be found in textbooks on mechanical dynamics as well as other sources (Hall 1994).

$$\begin{aligned}\mathbf{V} &\equiv \dot{\mathbf{R}} \\ &= \Omega \times \mathbf{R}\end{aligned} \tag{4.4}$$

$$\begin{aligned}\mathbf{A} &\equiv \dot{\mathbf{V}} \equiv \ddot{\mathbf{R}} \\ &= \Omega \times \mathbf{V} \\ &= \Omega \times (\Omega \times \mathbf{R})\end{aligned} \tag{4.5}$$

The bold font represents vectors. The dots above symbols represent the vectors' rates of change. By definition, velocity is the rate of change of position, and acceleration is the rate of change of velocity. Figure 4.12 illustrates the relationships of these vectors. The position is measured out from the center of rotation. The velocity is tangential. The acceleration is centripetal, directed in toward the center of rotation.

The somewhat more familiar scalar (magnitude-only) formulas are shown in Eqs. 4.6–4.9. The angular velocity Ω must be expressed in radians per unit time, and the units for time and distance must be consistent:

$$\Omega \equiv |\mathbf{\Omega}| \tag{4.6}$$

$$R \equiv |\mathbf{R}| \tag{4.7}$$

$$V \equiv \mathbf{V}| = \Omega R \tag{4.8}$$

$$A \equiv |\mathbf{A} = \Omega V = \Omega^2 R = \frac{V^2}{R} \tag{4.9}$$

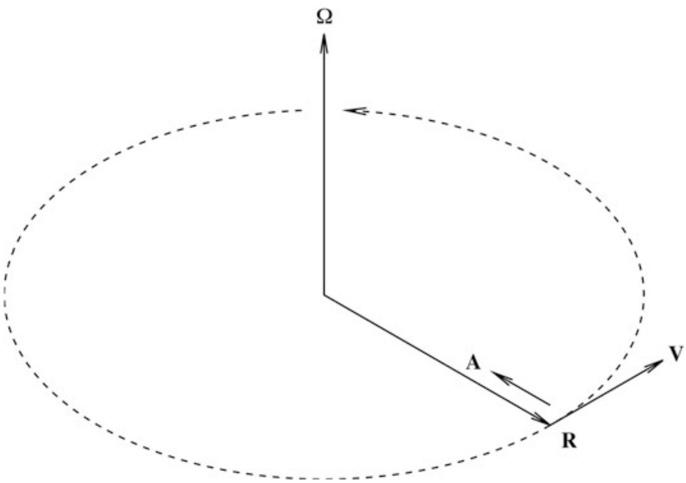


Fig. 4.12 Angular velocity, position, tangential velocity, and centripetal acceleration in circular motion (Theodore W. Hall)

The formulas for tangential velocity and centripetal acceleration are *not* a result of finding "best fits" for measured data. Rather, they are purely mathematical derivations from the definitions of circular motion, position, velocity, and acceleration. Measuring the centripetal force acting on a particle in circular motion confirms that it is consistent with the computed acceleration and Newton's Second Law of Motion.

Although the magnitude of the centripetal acceleration is constant, the direction is not. The ever-changing direction leads to some peculiarities of relative motion in rotating structures that designers must be aware of.

4.5.3 Relative Motion in Artificial Gravity

There are (at least) two common misconceptions of rotational artificial gravity:

- that a spinning structure somehow generates a centrifugal force that pushes particles out to the rim;
- that a spinning structure somehow generates a Coriolis force that causes falling particles to deviate from vertical.

Which of the Four Fundamental Forces account for these? Is it a Fifth Force? What happens if a resident of the rotating structure throws a ball in the counter-rotating direction? The notion of these mystical pixie forces arising and vanishing into the ether, depending on the spin of the structure and the motion of objects within, makes artificial gravity seem complex, unknowable, and unreliable.

Both of these fallacies result from trying to apply an intuitive sense of Newton's Laws of Motion within a rotating frame of reference. However, rotation is acceleration, and Newton's Laws are not applicable to accelerated frames of reference.

Everything becomes pure and simple if we evaluate the situation from a non-rotating, inertial frame of reference, where Newton's Laws prevail. Figure 4.13 shows the path of a falling ball dropped from height h above the floor of a rotating artificial-gravity structure with floor radius R_f.

Once the observer releases the ball, no force acts on it. No force, no change in velocity. Its linear momentum carries it on a straight-line tangent through a distance S, out from its initial radius of rotation R_h, until it strikes the floor, where centripetal acceleration resumes. It subtends an angle of $\theta_{\square}$. If the observer had not dropped it, it would have traveled the same distance S on an arc of the inner circle and subtended the larger angle θ_o with the observer.

Figure 4.14 shows the situation from the observer's rotating frame of reference. Because $\theta_{\square}$ is less than θ_o, the particle's path appears to deviate from vertical *as if* a force were pushing it. But, this is just an illusion due to the observer's rotation. The ball falls on a straight line in inertial space and neither centrifugal nor Coriolis

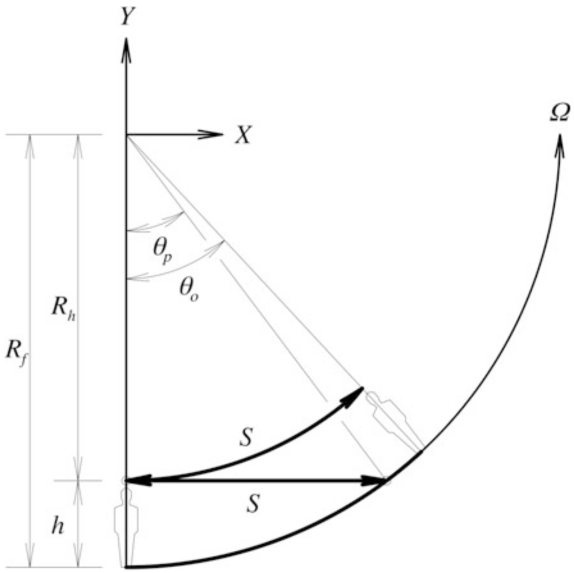


Fig. 4.13 The inertial view of a falling particle in artificial gravity (Theodore W. Hall)

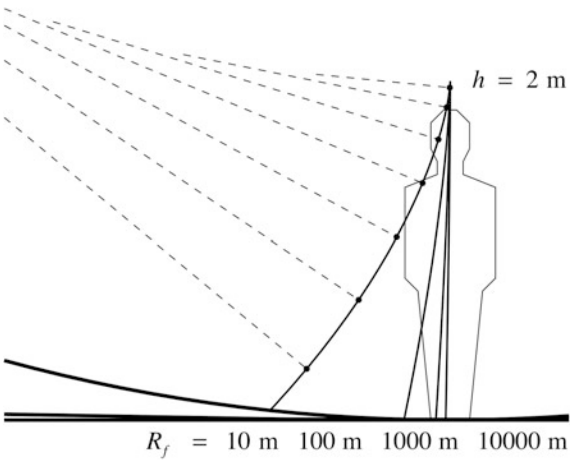


Fig. 4.14 The rotating view of a falling particle in artificial gravity. The initial height of the particle is 2 m. The involute curves correspond to radii of 10, 100, 1000, and 10,000 m. The dotted lines show the apparent rotation of the particle's straight-line trajectory, as seen by the rotating observer, for the 10 m radius (Theodore W. Hall)

forces act on it during the fall. The ball's straight-line trajectory appears to rotate from the observer's rotating point of view, like a thread unwinding from a spool, as shown by the dotted lines. The ball at the endpoint of the "thread" traces an involute curve in the observer's frame of reference. Figure 4.13 shows an initial height *h* of 2 m, and traces involutes for floor radii R_f of 10, 100, 1000, and 10,000 m. Referring back to Fig. 4.12, it's apparent that the geometry of the fall is independent of the speed at which the structure spins. In Fig. 4.13, the shapes of the involutes are determined by the ratio of h/R_f, regardless of the gravity level. The smaller that ratio, the straighter and more Earthlike the fall. If h is proportional to human height, and R_f is a design parameter, then it follows that R_f should be large relative to a human, to keep this ratio small.

Coriolis force does not cause the freefalling ball to curve. On the contrary, if we want to enforce straight-line motion relative to the rotating structure, then we must apply a Coriolis force to *prevent* the kind of curvature seen in Fig. 4.13 Turning to vector calculus again, we can write an equation of motion for a particle traveling at constant velocity **v** relative to a rotating frame with angular velocity **Ω**. If we evaluate the position, velocity, and acceleration of this particle as functions of time in an inertial reference, we find that the total acceleration is a sum of centripetal and Coriolis components as shown in Eq. 4.11. Mathematically inclined readers can find the full derivation in mechanical dynamics textbooks and elsewhere (Hall 1994):

$$\begin{aligned} \mathrm{V}_{tot} &= \Omega \times \mathbf{R} + \mathbf{v} \\ &= \mathbf{V}_{\tan} + \mathrm{v} \end{aligned} \tag{4.10}$$

$$\begin{aligned} \mathbf{A}_{tot} &= \Omega \times (\Omega \times \mathbf{R}) + 2\Omega \times \mathbf{v} \\ &= \mathbf{A}_{cent} + \mathbf{A}_{Cor} \end{aligned} \tag{4.11}$$

As a vector cross product, the Coriolis acceleration and the force necessary to provide it are perpendicular to both the axis of rotation **Ω** and the relative velocity **v**. It's greatest when **Ω** and **v** are perpendicular to each other, and zero when those two vectors are parallel. In other words, there's no Coriolis acceleration for axial motion (**v** parallel to **Ω**). The maximum Coriolis acceleration occurs during motion perpendicular to the axis—any combination of radial and tangential. Its magnitude in that plane is:

$$\mathrm{A}_{Cor} = 2\Omega v = \frac{2V_{\tan} v}{R} \tag{4.12}$$

For radial motion "up" toward the rotation axis, the Coriolis acceleration is toward the "west"—decreasing the tangential velocity. For radial motion "down" away from the axis, the Coriolis acceleration is toward the "east"—increasing the tangential velocity. For "easterly" motion, the Coriolis acceleration is "up"—adding to the centripetal acceleration. For "westerly" motion, the Coriolis acceleration is "down"—subtracting from the centripetal acceleration.

For easterly and westerly motion around the rim, there's yet one more acceleration term. Because that motion is curved, it involves centripetal acceleration relative to the rotating structure, independent of the structure's rotation. Expanding from Eqs. 4.9 and 4.12, we have:

$$\begin{aligned} A_{tot} &= \frac{V_{tot}^2}{R} \\ &= \frac{(V_{\tan} \pm v)^2}{R} \\ &= \frac{V^2 \pm 2V_{\tan}v + v^2}{R} \\ &= A_{cent} \pm A_{car} + a_{cent} \end{aligned} \tag{4.13}$$

Because the Coriolis acceleration is a distortion of the design gravity, it's important to consider it in proportion to the design value:

$$\begin{aligned} \frac{A_{cor}}{A_{cent}} &= \frac{2\Omega v}{\Omega^2 R} \\ &= 2\frac{v}{\Omega R} \\ &= 2\frac{v}{V_{\tan}} \end{aligned} \tag{4.14}$$

In the plane of rotation, the ratio of Coriolis to centripetal acceleration equals twice the ratio of the relative velocity to the tangential velocity. If v is proportional to human speed, and V_{tan} is a design parameter, then it follows that V_{tan} should be fast relative to a human, to keep this ratio small.

The R and V_{tan} in Eqs. 4.12–4.14 correspond to the particle's instantaneous position, not necessarily the outer rim of the rotating structure. When moving toward the center of rotation, R, V_{tan}, and A_{cent} all approach zero, but if the rotation rate Ω and relative velocity v (in this case, radial velocity) remain constant then A_{cor} also remains constant. At the center, the acceleration is entirely Coriolis.

Figure 4.15 shows the situation for someone climbing a radial ladder up toward the center of rotation (The rotation is counterclockwise in this view.). The x and y coordinate axes are tied to the rotating structure. The climber carries his own sense of coordinate axes with him, here labeled ξ and η, with his "up" axis η tied to his total acceleration vector **A**, which is the sum of his centripetal and Coriolis components. His horizontal axis ξ is perpendicular to that. As he approaches the center, his centripetal component approaches zero, but if he maintains constant radial speed then his Coriolis component remains constant. His acceleration vectors, as he traverses the diameter, converge through a point offset from the center of rotation by the Coriolis component, as shown by the dotted lines. At the center, it's all Coriolis. If he ascends on the "west" side of the ladder and passes through the center of rotation, he'll descend on the "east" side of the ladder at its opposite end.

Figure 4.16 shows the situation as the climber might perceive it. As he ascends the ladder, it seems to teeter-totter over a hill. The apparent slope gets shallower and the apparent gravity gets weaker as he approaches the center, as shown by the dotted lines. Because the slope is proportional to the distance from the center, the curve is a catenary arch—the same basic shape as a rope supporting only its own

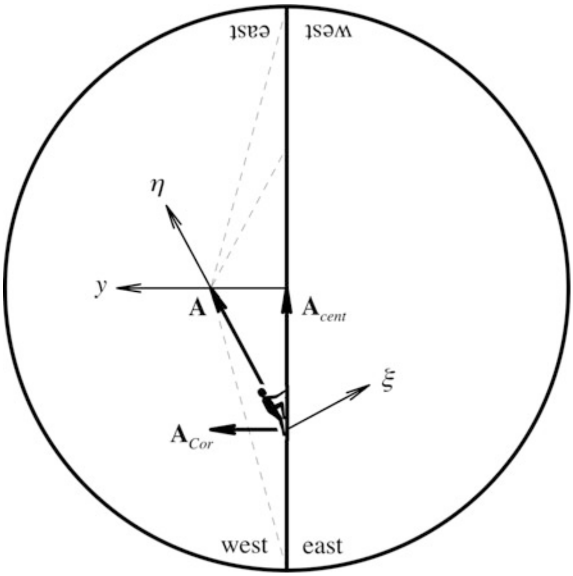


Fig. 4.15 Ascending a radial ladder in artificial gravity. (The structure's rotation in this view is counterclockwise.) (Theodore W. Hall)

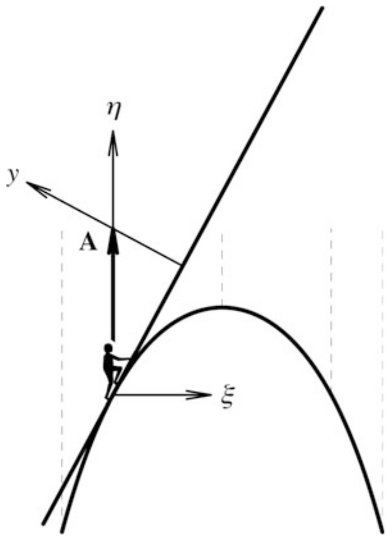


Fig. 4.16 Apparent slope of the ladder and strength of gravity perceived by the climber in Fig. 4.15 (Theodore W. Hall)

weight, but upside down (For the mathematical derivation, see Hall (1994) or Hall (1999)). It's important that the climber ascends on the west side of the ladder and descends on its east side, in order to stay on top of that arch. If he attempts to traverse on the wrong side of the ladder, he'll find himself hanging on for dear life from underneath the arch.

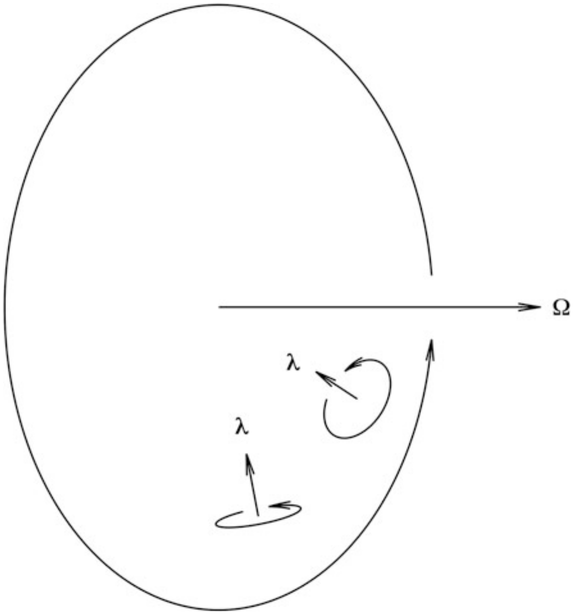


Fig. 4.17 Cross-coupled rotations (Theodore W. Hall)

However, the relative motion that's perhaps most counterintuitive, and also most associated with dizziness and motion sickness, involves rotating one's head around an axis that's not aligned with the rotation of the structure, as suggested by Fig. 4.17. Because of the way angular momentums and torques combine, these misaligned rotations cross-couple to affect the semicircular canals of the inner ear in such a way to produce a vestibular illusion of rotation around a mutually perpendicular axis. For example, if the structure is rotating with angular velocity $\mathbf{\Omega}$ around the x axis, and an occupant rotating with it turns his head with relative angular velocity $\boldsymbol{\lambda}$ around the$y$ axis, then he'll experience a vestibular illusion of rotation around the z axis. Actually, he must apply some torque around z in order not to precess around that axis. The effect is predicted by Euler's Equations of Motion for rigid bodies. The details are beyond the scope of this chapter, but in summary they're purely mathematical derivations from the definitions of torque, momentum, and inertia, and are ultimately reducible to Newton's Laws of Motion. Being quintessentially dynamic and three-dimensional, the effect is impossible to convey adequately in static two-dimensional illustrations. An Internet search for "gyroscopic precession" videos finds many illustrative examples. Investing some time in playing with a gyroscope is most illuminating.

4.5.4 Comfort in Artificial Gravity

In the early years of spaceflight there was considerable doubt that humans could long tolerate weightlessness. It was widely assumed that space stations would rotate to provide artificial gravity. Experiments in Earth-based centrifuges, rotating rooms, and space-station simulators aimed to define the limits for "comfortable" rotation. As shown in Eq. 4.9, there are four fundamental interrelated parameters: angular velocity Ω, radius R, tangential velocity V_{tan}, and centripetal acceleration A_{cent}. Any two of these may be selected independently; the other two are then dependent and computable from those. The gravity is most Earthlike when A_{cent} is 1 g, V_{tan} is fast, R is large, and Ω is slow. Unfortunately, this combination corresponds with large mass, kinetic energy, and ultimately cost. Economics pushes in the opposite direction, toward smaller R, slower V_{tan}, and faster Ω.

Comfort charts for artificial gravity, delineating limits for these four parameters, appeared in papers by Hill and Schnitzer (1962), Gilruth (1969), Gordon and Gervais (1969), Stone (1973), and Cramer (1985). There was significant variation between them, not only in their format, but more importantly in the boundaries they presented. Considered individually, each of these charts portrayed the "comfort zone" with hard-edged certainty. Only by examining them as a group do the uncertainties become apparent. Table 4.11 summarizes their recommendations. Figure 4.18 superimposes their boundaries in a consistent graph format to illustrate the areas of agreement and disagreement.

A larger radius (R) provides more uniform gravity throughout a person's height (less head-to-foot gravity gradient), as well as more normal behavior for falling particles as shown in Fig. 4.13.

A slower angular velocity (Ω) reduces the dizziness associated with cross-coupled head rotations, as well as the Coriolis acceleration associated with relative linear velocity as shown in Eq. 4.12.

Table 4.11 Boundaries of the hypothetical "comfort zone" for rotation

Author	Year	Radius R (m)	Angular velocity Ω (rpm)	Tangent velocity V_{tan} (m/s)	Centripetal acceleration A_{cent} (g)	
		min	max	min	min	max
Hill and Schnitzer	1962	?	4	6	0.035	1.0
Gilruth	1969	12	6	?	0.3	0.9
"Optimum"			2			
Gordon and Gervais	1969	12	6	7	0.2	1.0
Stone	1973	4	6	10	0.2	1.0
Cramer	1985	?	3	7	0.1	1.0

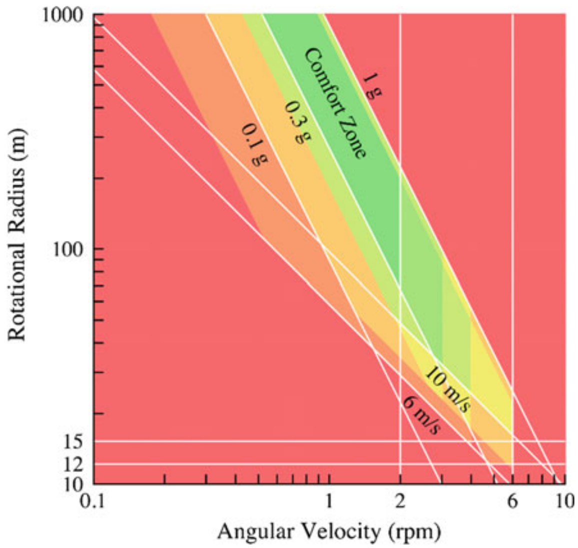


Fig. 4.18 Consolidated comfort chart for artificial gravity, based on charts published by Hill and Schnitzer (1962), Gilruth (1969), Gordon and Gervais (1969), Stone (1973), and Cramer (1985). Green areas depict conditions that all agree are comfortable. Red areas depict conditions that all agree are uncomfortable. Hues ranging through yellow and orange depict areas of disagreement (Theodore W. Hall)

A faster tangential velocity (V_{tan}) reduces the ratio of Coriolis to centripetal acceleration, as shown in Eq. 4.14. For a given radius, increasing Ω increases both the Coriolis and centripetal accelerations as well as V_{tan}, but the centripetal acceleration increases faster, so the ratio decreases. There's a tradeoff between reducing cross-coupled head rotations and Coriolis accelerations with a smaller Ω and V_{tan}, versus reducing the Coriolis/centripetal ratio with a larger Ω and V_{tan}.

A higher centripetal acceleration (A_{cent}) provides better floor traction for walking, and seems likely to be a more effective countermeasure against the unhealthy effects of microgravity. The minimum to preserve health remains unknown, due to lack of experience. It's unnecessary and possibly even unsafe to exceed 1 g.

Based on extensive research with human subjects in a 15-foot diameter "slow rotation room," Graybiel (1977) reported that: "In brief, at 1.0 rpm even highly susceptible subjects were symptom-free, or nearly so. At 3.0 rpm subjects experienced symptoms but were not significantly handicapped. At 5.4 rpm, only subjects with low susceptibility performed well and by the second day were almost free from symptoms. At 10 rpm, however, adaptation presented a challenging but interesting problem. Even pilots without a history of air sickness did not fully adapt in a period of twelve days."

More recently however, Lackner and DiZio (2003) concluded that: "sensory-motor adaptation to 10 rpm can be achieved relatively easily and quickly if subjects make the same movement repeatedly. This repetition allows the nervous system to gauge how the Coriolis forces generated by movements in a rotating reference frame are deflecting movement paths and endpoints and to institute corrective adaptations."

4.5.5 Designing for Artificial Gravity

There are two common faulty assumptions in considering artificial gravity for space habitat design:

- that the gravity will be Earth-normal as long as the magnitude is 1 g;
- that any rotation will be hopelessly uncomfortable and any period of adaptation is unacceptable.

The truth is probably somewhere between these extremes.

In designing for artificial gravity, the first thing that the architect must acknowledge is that the gravity will *not* be Earth-normal, even if the centripetal acceleration is 1 g, unless the radius is very large. This is evident, for example, in Fig. 4.13, where the deflection of falling particles depends only on the ratio of the initial height to the floor radius, regardless of the velocity or acceleration. The inhabitants are probably going to have to endure a period of adaptation.

Nevertheless, the alternative to artificial gravity is not "normal" gravity; the alternative is microgravity. Microgravity also requires a period of adaptation. About half of all spacefarers endure space adaptation syndrome lasting from one to three days (Connors et al. 1985; Merz 1986). This is accepted; it has not precluded microgravity space habitats. Considering the likely health benefits that artificial gravity offers, a similar period of adaptation seems reasonable. Experiments in Earth-based rotating rooms indicate that most people adapt to 3 rpm with little difficulty, and several estimates of the "comfort zone" set the upper limit as high as 6 rpm. Higher rpm values permit lower mass, kinetic energy, and cost. Though we won't know for sure how well Earth-based experiments translate to orbital habitats until we gain actual experience, artificial gravity appears feasible. It does not appear to require a huge radius.

However, architects should not take adaptation for granted or be dismissive of the discomfort, even if it's only temporary. They have both the opportunity and responsibility to assist the inhabitants in adapting to the peculiarities of the rotating environment. This means being continually mindful of the rotation, Coriolis accelerations, and cross-coupled head rotations, and laying out the plan to either minimize these or orient them to the inhabitants' advantage (Ramsey 1971; Hall 2002). In Earth gravity, all horizontal directions are gravitationally "neutral," but not so in artificial gravity. Coriolis acceleration distinguishes between the north-south (axial) and east-west (tangential) directions.

The best way to begin the module layout might be to draw a big arrow on the floor to represent the tangential velocity. Whether or not the actual design includes such a literal element, if the direction of rotation isn't discernable then the design might be inadequate. Since Coriolis effects occur only during relative motion, it will be advantageous to incorporate visual cues such as color or form that keep the inhabitants passively oriented to the direction of rotation. Such cues allow them to prepare themselves for the Coriolis consequences of, for example, sitting down and standing up.

For a habitat comprising cylindrical modules, the first thing to resolve is the orientation of the modules with respect to the rotation. Figure 4.19 illustrates the three principal orientations: axial, tangential, and radial.

In the axial orientation, most occupant movement is parallel to the axis of rotation with minimal Coriolis effects (due only to the slight rising and falling of the hands and feet during a stride). Floor curvature (or apparent floor slope) occurs only across the width of the module, not its length. Moreover, occupants can scan vertical displays on the sidewalls without cross-coupling head rotations; head pitch is aligned with the habitat rotation (Side-to-side head yaw will cross-couple with the habitat rotation in any case.). Unfortunately, this orientation might be the least dynamically stable. Schultz et al. (1989) performed an end-body dynamic analysis for tether-suspended modules and found that small misalignments with the rotation axis would tend to grow rather than dampen. Based on this, they recommended the tangential orientation. Nevertheless, the advantages of the axial orientation are so significant that it's worth considering stabilization strategies.

In the tangential orientation, most occupant movement is perpendicular to the axis of rotation and will encounter significant Coriolis acceleration unless the radius is very large. Moreover, if the module length subtends more than a few degrees of arc around the rotation axis, then the floor should be curved or the occupants will feel a floor slope. (The centripetal acceleration is always radial and will not be perpendicular to a flat floor at the module ends.)

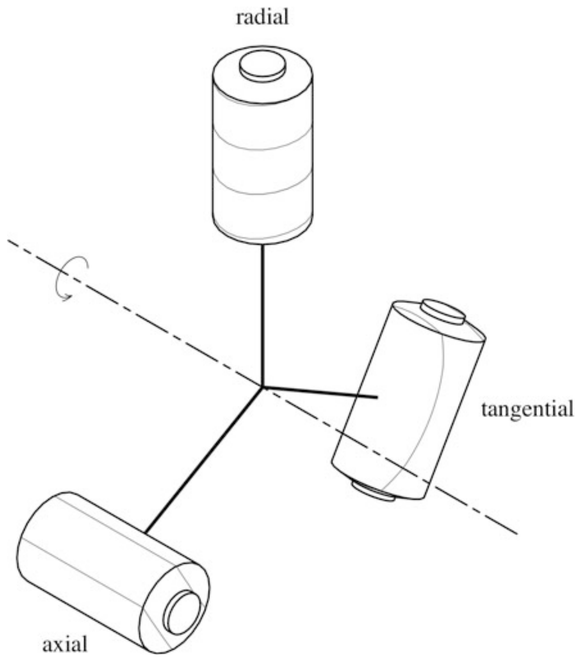


Fig. 4.19 Axial, tangential, and radial module orientations (Theodore W. Hall)

The radial orientation might be the most dynamically stable, but it's the worst orientation in several other respects. It practically demands a multilevel design. Climbing ladders involves elevated risk and inconvenience even on Earth. In artificial gravity these are compounded by gravity gradients and Coriolis accelerations. The circular plan also leads to circular layouts with no particular alignment to the rotation axis or Coriolis effects. This places the greatest adaptation burden on the occupants.

If, despite all that, a multilevel design is mandatory, then ladders must be oriented such that their planes are parallel to the axis of rotation and perpendicular to the Coriolis acceleration that accompanies radial movement. Moreover, if there's only a single ladder, then it must be accessible from opposite sides for ascending and descending. Figure 4.20 shows three options. The middle option, with two ladders at opposite sides of a single floor opening, is the most spatially efficient.

Besides the gravity environment, there are many other considerations for rotating space habitats. To name just a few:

- orientation of the rotation axis to the orbital plane and its effect on dynamic stability;
- orientation of the rotation axis to the sun and its effect on sunlight strobing through windows;
- rotating joints for communications antennas, solar collectors, and docking ports.

In regard to windows, some commentators argue that rotating spacecraft shouldn't have them, that a rotating view of the outside universe will induce dizziness and motion sickness. This attitude might be misguided. It's not a rotating view per se that makes people queasy, but rather the mismatch between visual and vestibular senses of rotation: seeing rotation and not feeling it, or vice versa (Connors et al. 1985; Merz 1986). Since there will be no hiding the rotation from the vestibular system, it may be best not to hide it from the visual system either. Windows may be not only tolerated, but encouraged, not only for the emotional benefits of an outside view, but also as an aid to rotational adaptation.

Since the first artificial-gravity space habitat has yet to be built, it's premature to conclude anything—except, that the architect must relinquish assumptions of

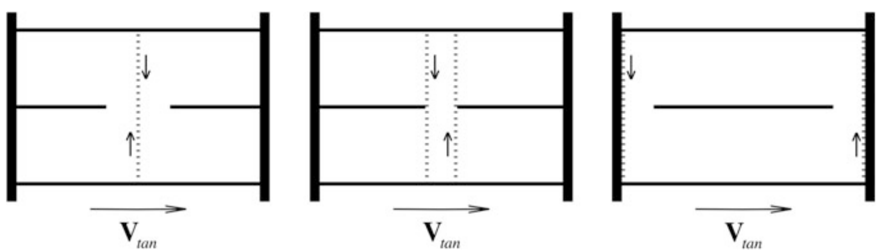


Fig. 4.20 Three options for orienting ladders in artificial gravity (Theodore W. Hall)

Earth-normalcy, be well versed in theory as well as experimental evidence, conscientious of the user experience, and ready to try something completely different. It will be an adventure for all.

4.6 Guest Statement: The Role of the Space Architect—Part 2 Design Integration (Brand N. Griffin)

The work of space architecture can be grouped into three major areas, **requirements**, **functional integration,** and **design integration**. Because both requirements and functional integration are thoroughly described in systems engineering documents, this chapter concentrates on design integration, the area most closely associated with space architecture.

4.6.1 Design Integration

4.6.1.1 Process Description[13]

Design integration is an ugly process. It is nonlinear and iterative; it advances and retreats. It simultaneously benefits from discipline and serendipity. And, considering what actually gets built, personality, pride, and position often trump process. For some this is too random, lacking affirmation and ultimately, discouraging. For others, it is the real-world overhead that comes with the work of design integration. The following descriptions provide insights on the design integration work of a space architect.

4.6.1.2 The Myth of "the" Answer

Akins' law[14] number 12 states, "*There is never a single right solution. There are always multiple wrong ones, though.*" Brent Sherwood adds, there is no such thing as "the correct" answer. Both are trying to enlighten the analytical mind to the fact that design is not an algorithm with one repeatable answer. In fact, there is an observable behavior pattern associated with design maturity. Those with limited design experience tend to fall in love with their first solution then spend extraordinary resources defending that one concept. In contrast, mature designers create many workable

[13]Brent Sherwood's contribution to the "International Space University's 1993 Space Architecture Curriculum Notes" is used to structure this section. Griffin (1993)

[14]"Akin's Laws," by David L. Akin, Associate Professor in the Department of Aerospace Engineering, University of Maryland, Director of the Space Systems Laboratory.

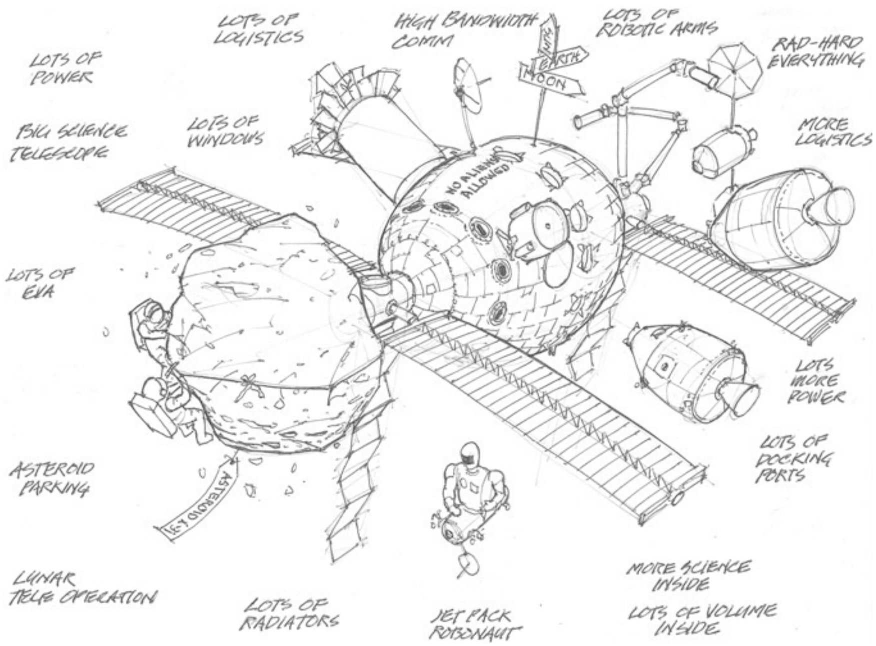


Fig. 4.21 The ideal deep space habitat (Brand N. Griffin)

solutions producing the opposite challenge of selecting from amongst the options. Although there is no single right answer, usually only one solution gets built. For this reason, the space architect is often the arbitrator amongst competing interests where the only ideal solution exists in the fantasy of a cartoon (Fig. 4.21).

Therefore, design integration is both about generating options and down-selecting to a solution.

4.6.1.3 Where to Begin?

Tabula rasa means blank slate and it can paralyze all designers. Confronted with a complex design problem and a blank page, it is hard to know where to start. Worrying about making a mistake, making a poor decision, starting in the "wrong" place, or pursuing a "dead end" often chokes progress because it keeps the designer from even getting started.

Experienced space architects realize that rarely does the first mark or decision remain unaltered throughout the entire process. Therefore, it doesn't matter what the first step is, as long as the process is flexible enough to permit change (cf. Doucet and Janssens 2011). The process is cyclical so there are multiple entry points around the loop. The key to overcoming the terror of the blank page is to begin anywhere, with anything (an estimate, a trial mark, a guess) and then react to that initial decision.

Professor Akin provides some additional wisdom, "Not having all the information you need is never a satisfactory excuse for not starting the analysis."

4.6.1.4 Balance

Balance is one of the tools space architects use to avoid majoring in the minors that is, focusing on lower level issues at the expense of comprehensive integration. Balance prevents any given aspect from exerting too much influence over the final result. This is generally good. However, based on experience, an unbalanced approach is sometimes used to preserve attributes that otherwise would disappear without early and strong advocacy. For example: maintainability. Maintainability is out of balance with the system definition during preliminary design, but a space architect may keep it in the mix knowing that it is extremely difficult and disruptive to integrate later in the process.

Rechtin stated the space architect is not a generalist, but a system-oriented specialist (cf. Rechtin 1991). This still begs the question, is it more important to know a little about everything (knowledge breadth), or a lot about a few things (knowledge depth)? Design integration needs both. However, depth can be achieved through a team of specialists, while breadth is essential to the work of the space architect. This is because the architect is an integrator and this necessarily requires a comprehensive and simultaneous overview of technical and non-technical factors.

Integration also balances the resources of time, money, and capability. For this, the space architect must have programmatic peripheral vision. That is to say, what is the funding profile for other "competing" projects within the organization and what is a realistic strategy for acquiring and managing monies? Budget busting solutions are not likely to be considered. Developing a schedule strategy for implementation including make/buy decisions and time for institutional procurement is essential for large scale systems integration.

Because all projects must work within resource constraints, it is important to prioritize decision-making. Resources must be allocated carefully because the project cannot afford to devote too much effort to decisions which affect limited aspects of the design.

Sherwood and Rechtin draw a decision-making parallel with the following analogy: The term *triage*[15] is used by doctors in wartime or other disaster situations where the number of people needing treatment overwhelms the medical capacity to treat all of them.

Effort should be focused first on making the most important decisions—that is, those which affect the greatest portion of the project, or which must precede the

[15]*Triage* is the process of dividing wounded people into three categories: those who will die no matter what the doctor does, those who will live even if the doctor does nothing, and those who will only live if the doctor treats them. The doctor only treats the third category, that is, the cases where his effort will make the most difference. Design integration requires the same philosophy.

largest number of decision to follow. Decisions which will not affect the final outcome, and decisions which can be made later, should be avoided.

4.6.1.5 Spiral Evolution and Iteration

Most systems engineering textbooks include the concept of spiral evolution or the path to greater understanding with a convergence on a design solution. As decisions are made, the pathway enables more precise requirements guiding the process to the next higher level of project refinement (Fig. 4.22). The spiral returns again and again to the same issues but with a more advanced understanding each time. The precision of the geometry is somewhat misleading, because in reality there are gaps and divergent rabbit trails.

Iteration or revisiting the same question multiple times is vital to integration for reasons of process efficiency and flexibility. Space architects include these revisits in the process to avoid getting stalled, losing balance, and getting locked into poor solutions. In addition, this discipline contributes to a healthy skepticism, avoiding overconfidence in any one solution.

With the knowledge that the prior decisions were made to move the project forward, they should be held “loosely” and treated as temporary. This avoids getting stuck merely because there is not enough information to make a clear decision at that time. The space architect then chooses to insert a place holder deferring detailed treatment while keeping the process moving. Iteration provides a

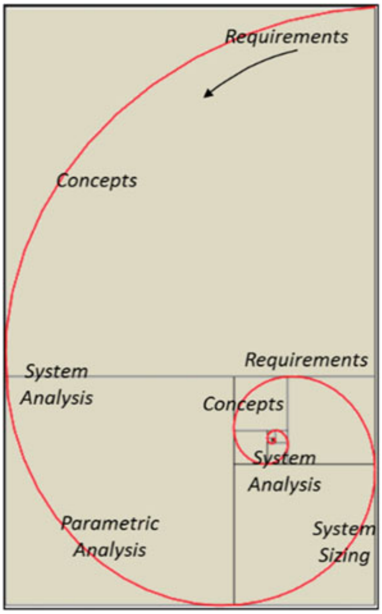


Fig. 4.22 Spiral evolution (Brand N. Griffin)

structured, cyclical way to incorporate new data as developed and automatically encourages a fresh look each time.

The more iterative cycles a project can afford the more refined and robust the product can be. Therefore, for a given interval of time, increasing the frequency of cycles improves the prospect for a good result.

4.6.2 Developing Options

4.6.2.1 Gap and Overlap Identification

There are design challenges with what we already know, but it is the gaps or missing information that cause trouble, most often by invalidating or compromising our results. Therefore, key to effective integration is the identification and prioritization of knowledge gaps. Five steps to address high priority gaps are: (1) characterize the state of present knowledge; (2) identify the areas with the greatest uncertainty; (3) decide the specific questions that need to be answered to reduce the uncertainty; (4) decide which among the questions should be answered next; and (5) take action to acquire those answers. Overlaps represented by disparate results are also a concern. If quantifiable, they should be resolved by analysis. Otherwise the space architect should make a decision with the option for review during the next iteration.

4.6.2.2 Literature Search

Making claim to concept originality without a thorough literature search is professionally irresponsible, a waste of resources, and sometimes embarrassing. Granted, with pressure to show early progress, managers do not stress this research and it is often difficult to distinguish the credible sources. Regardless, as the integrator, space architects must encourage contributors to spend time exploring what has been done before. This is basic scholarship, yet treated casually within the space community. A literature search should be done with an open yet skeptical mind, because there are built-in biases that may run counter to a balanced solution.

4.6.2.3 Concept Generation

Depending on the experience of the space architect, it is possible to begin developing mission options or configurations early in the spiral. This is the first scratch on the *tabula rasa* and serves the important step in organizing the team around a solution. As represented in Fig. 4.23, it is recommended that before broad distribution, a small experienced team review and comment on the initial designs. This helps to prevent a large team from solving problems on immature or poorly

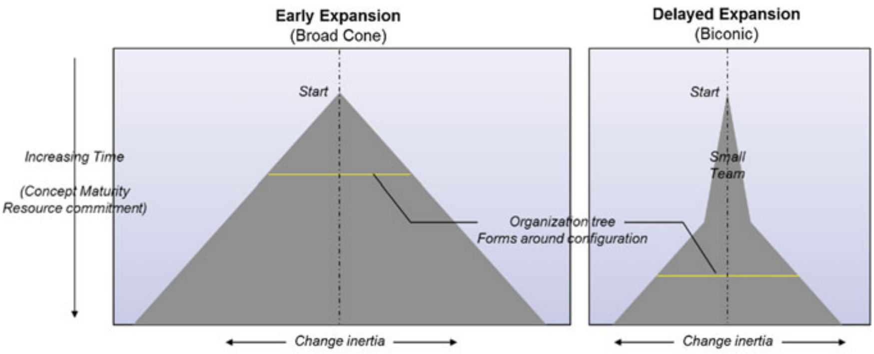


Fig. 4.23 Concepts matured by a small team minimize change for configuration-based organizations (Brand N. Griffin)

conceived designs. Like inertia, once the expanded team starts working on the concept, it is difficult to redirect without changing the organization.

The easy and safe approach is to begin with a concept that is a derivation of a previous solution. This is reassuring to engineers. On the other hand, architects are intrigued with daring and innovative concepts which bring uncertainty. This is unnerving to engineers, evoking the refrain, “You can’t do that!” For new, non-intuitive concepts, space architects must expand their role beyond a managerial integrator to that of a charismatic leader. WARNING: It is rare for large mature bureaucracies to eagerly embrace new concepts so, it is important to know how to persevere, when to lay low, and when to drop ideas.

Although the perception is otherwise, there is nothing about engineering that restricts creativity. In fact, engineers are responsible for many remarkable, novel solutions.

Outside of science fiction, there were no precursors for the Apollo Lunar Excursion Module (LEM). The adaptation of Jules Verne’s From the Earth to the Moon (Verne 1865) rendered the lander as an oversized 45 caliber bullet. From tabula rasa, The LEM engineers created a revolutionary archetype that continues to inspire today’s spacecraft designers. As such, it stands out as a remarkable example of engineering creativity that made it through a large aerospace organization into reality.

4.6.2.4 System Sizing

System sizing and concept generation are interdependent activities swapping leadership roles. Experience (heuristics) allows the space architect to produce a “straw man” concept before actually sizing the systems, but sizing confirms or reshapes that initial concept. Design choices are quantified in the system sizing step of the spiral. Because this step inter-relates multiple components, systems, and elements, it is at the heart of design integration. Pursuing the interdependent effects of system selection and sizing is the engine which drives the integration cycles. During the first

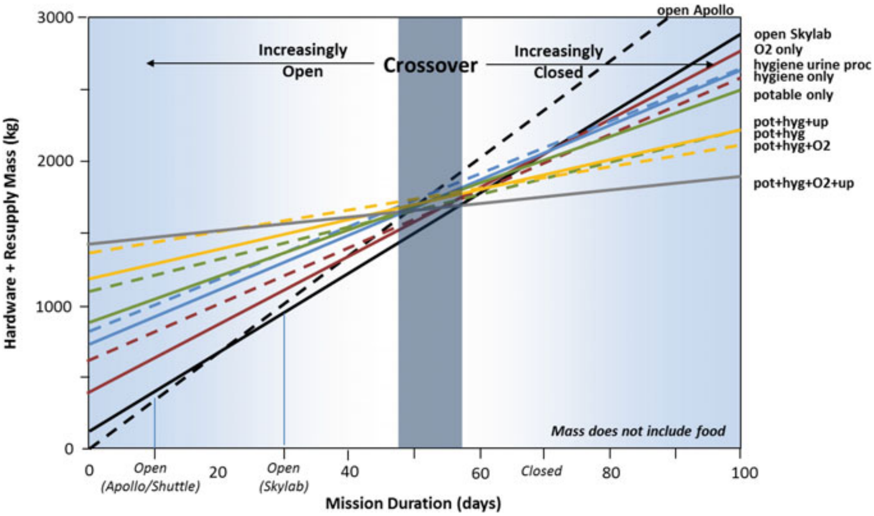


Fig. 4.24 Parametric data allows flexibility in space system sizing decisions (Brand N. Griffin/Boeing)

few cycles, space architects prefer parametric rather than specific solutions. This allows revisits and adjustments based on sensitivities in mass, volume, and power. For example, Fig. 4.24 compares the hardware mass for the environmental control life support system as a function of mission duration. The data shows a crossover from an open to closed (regenerative) system at about 57 days. Other data, like consumable mass and technology readiness are required to make system sizing decisions, but if the mission duration changes it is easy to assess the impact by revisiting the chart rather than running another dedicated analysis.

4.6.3 Internal Layout

The following steps provide a guide for spacecraft internal layout. cf. Griffin et al. (2013), Griffin (1978, 1982), Olson et al. (1988) Creating a consistent up/down (local vertical) is important even in the weightless environment. Zoning organizes activities and establishes physical proximity.

4.6.3.1 Local Vertical

Whether on a planetary surface or in weightless space, a local vertical is imposed to provide a common up and down across the spacecraft. This heuristic establishes the orientation for controls and display, labeling, and is useful in face-to-face communication. Like sunlight and overhead lighting, spacecraft illumination is used to

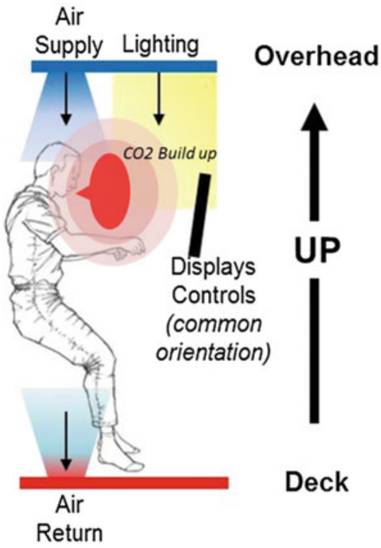


Fig. 4.25 A common local vertical (Brand N. Griffin)

imply an "up" direction and because there is no convection, a head-to-toe airflow washes away exhaled carbon dioxide, provides a reinforcing orientation cue and is preferable to having air blow up the nose (Fig. 4.25). Without foot restraints, weightless astronauts must stabilize themselves using their hands. Because this prevents two handed operations, having floor mounted foot restraints allows stability with both hands free. The local vertical provides a reference but does not restrict the crew from assuming different orientations out of personal preference or for improved accessibility.

4.6.3.2 Zoning and Functional Adjacency

Zoning and functional adjacency are guiding principles that provide constraints for positioning internal systems. Zoning is the grouping of elements that share common attributes or resources. Typically, this includes separating quiet and noisy activities, placing crew access functions such as galley/wardroom and personal hygiene in the wall location, positioning subsystems in the overhead and floor locations, and grouping microgravity science at the best location within the spacecraft. Functional adjacency refers to a proximity assessment determining which activities prefer to be next to one another, separated, or are indifferent. An adjacency matrix is created to provide guidance on functional proximity (Fig. 4.26). These guiding principles provide a point of departure for the internal layout; ultimately the final arrangement is the result of an iterative process that integrates other factors including mass, volume, cost, schedule, technology level, and maintainability.

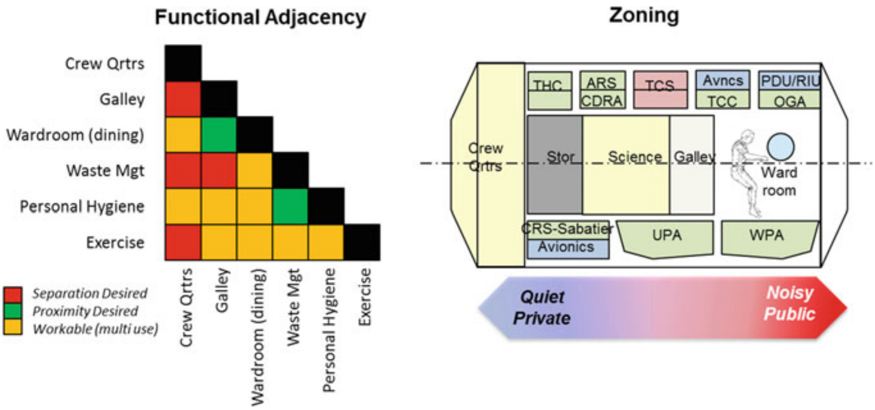


Fig. 4.26 A functional adjacency matrix and zoning diagram help guide the internal layout (Brand N. Griffin)

4.6.3.3 Utility Distribution

The space architect is responsible for creating a logical, efficient, fault-tolerant, and serviceable system for the distribution of power, data, fluids, and gases. This critical task interconnects external elements like solar arrays, antennas, and radiators with internal conditioning and processing components to crew equipment such as in the galley and hygiene compartment. Line length and failure modes play key roles in determining the number, routing and isolation control of the utilities lines. Air handling dominates the layout because efficient, low-noise, ducts require a large diameter and particular placement for thermal control, fire detection, and crew gas exchange. Utility distribution is a highly iterative process integrating crew accommodations and secondary structure. Space architects tend to develop an integrated modular system that allows flexibility in layout.

4.6.3.4 Subsystem Schematics and Component Packaging

Most functioning subsystems can be characterized by a schematic diagram. This identifies the major components and the interconnectivity of power, data and cooling lines. In a Master Equipment List (MEL), subsystem analysts record component mass, power, dimensions, and technology readiness. Using the schematic, MEL, and a concept for line replaceable units, the subsystems are packaged for launch loads, connection to utilities, and crew servicing. For the International Space Station, systems were packaged into identical racks then attached to standoff trays for utility connection. New approaches are being explored because this concept was based on delivery and outfitting by the retired Space Shuttle.

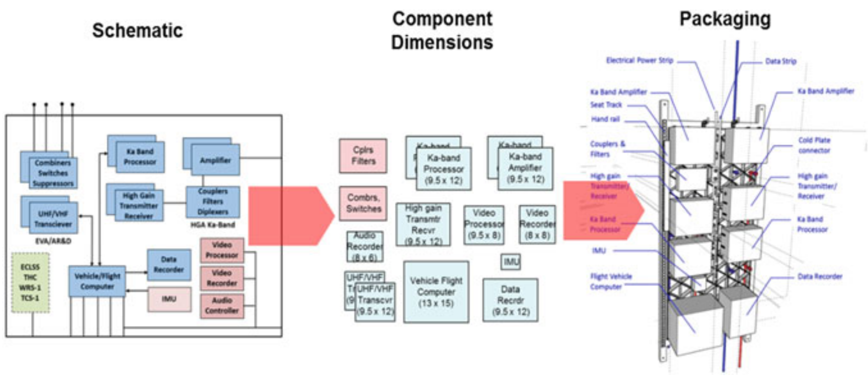


Fig. 4.27 A step-wise process is used for packaging subsystems (Brand N. Griffin)

New concepts are needed for long duration human missions beyond low-earth orbit (Fig. 4.27). These mission will have infrequent and possibly no resupply and therefore must be designed for in situ repair and maintenance.

4.6.4 *Selecting Options*

4.6.4.1 Constraints and Preserving Options

Constraints are the boundary conditions imposed on the design from requirements, specification standards, management, or the laws of physics. They also can be self-imposed, reducing a broad array of options in order to get the project moving with proper emphasis on important issues. Frank Lloyd Wright said that constraints are the architect's best friend.

Constraints can represent different levels of commitment. A temporary or soft decision keeps the design cycle moving while allowing changes based on future discovery. Hard decisions eliminate options fixing on a particular solution. As important as it is to constrain the problem, it is equally important to preserve options. This is difficult for the analytical mind which wants to simplify decision-making by imposing hard decisions. The synthetic mind wants to keep the options open until the last minute. Spinrad puts it this way, "*Hang on to the agony of decisions as long as possible*." (Maier and Rechtin 2000, p. 203) This is why designers take as much time as given. Keeping many options viable as long as practical helps prevent fixating on a particular configuration prematurely, and trying subsequently to force it to fit new constraints. Systems Architecting offers "Build in and maintain options as long as possible in the design and implementation of complex systems. You will need them."

Space architects must be cautious of "solutions looking for problems." It is no surprise that contractors and vendors with a particular product line will promote solutions that benefit their services or products. This is not necessarily bad, but has a way of contaminating an otherwise pure trade space. For example: inflatable habitats. There are options for the primary structure, but once "inflatable" is accepted as a hard constraint, it directs many other decisions.

4.6.4.2 Optimization

Optimization is the process of adjusting multiple system parameters simultaneously to achieve overall system benefit.

Computational techniques are well-known for optimizing mathematically modeled problems, even extremely complex ones. Such techniques work better the more fully the system can be characterized quantitatively. Therefore, they are well suited for well-bounded subsystems where the problem domain is small enough to be captured by a practical, credible numerical model.

The space architect is commonly faced with problems impossible or impractical to describe mathematically. There is no escaping the difficult job of exercising human judgment. Avoiding entrapment in the local optimum requires maintaining the most inclusive possible balance. Still, the space architect can apply numerical optimization techniques using them to derive partial constraints, or solution drivers or visibility of quantitative trends for assessing partitioned problem domains. Ultimately, the space architect's human reasoning provides the ability for massively multivariate, fuzzy, simultaneous integration.

4.6.4.3 Compromise

Compromise is the negative way to optimize. It means forcing competing constraints each to yield part way. The result is workable, but only partially meets all "pure" functional requirements. In reality, compromise is the most common approach taken. In extreme cases compromise may represent the "lowest common denominator" of competing functions—the only characteristic acceptable to all. Like least-common-denominator treaties, such a resolution tends to be optimal only in making all parties equally unhappy; it represents minimal progress. Space architects should consider compromise like any other expediency: acceptable if no better way can be found.

4.6.4.4 Synergy

Synergy is the positive way to optimize. It means satisfying competing constraints in such a way that the satisfaction of one enhances the satisfaction of others. It resolves competing requirements by inventing ways to satisfy all of them, rather than resorting to "buying off" competing requirements by nibbling away at all of them. Figure 4.28 shows an example of arranging the stowage to assist in radiation

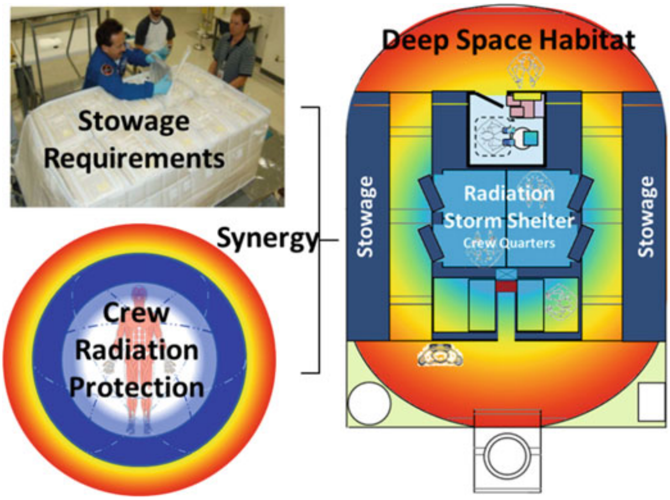


Fig. 4.28 Stowage doubles as radiation protection (Brand N. Griffin)

protection for the crew. The unique gratification of design integration lies in innovating system configurations which achieve a high degree of synergy. Synergy generally implies efficient utilization of system resources, as well as the most complete satisfaction of individually competing requirements possible. Synergistic designs tend to appear more inevitable as integrated solutions, even to uninformed reviewers. “A designer knows that he has achieved perfection not when there is nothing left to add, but when there is nothing left to take away.” (de Saint-Exupery’s Law of Design)

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Chapter 5
Habitation and Design Concepts

Abstract Scientific research is the foundation of design and concept development. The chapter addresses the next stage of design and planning; focusing and informing requirements for site selection with examples from Apollo and Mars Science Laboratory Curiosity rover programs; habitat structural systems, habitats and settlements concepts, and means to enable sustainable human presence beyond Earth.

5.1 Introduction and Chapter Structure

The chapter introduces requirements for site selection, presents possible habitat concepts, their structural and construction characteristics, and habitability support systems principles. Following design and planning research principles discussed in Chap. 4, this chapter addresses the next level of project development (Fig. 5.1).

The content of this chapter correlates with the Technology Readiness Levels and Habitation Readiness Levels 2, 3, and 4 (Table 5.1). Detailed descriptions are given in Chap. 3, Tables 3.11 and 3.12.

The chapter concludes with three guest statements. Cesare Lobascio[1] (2007) talks about Environmental Control and Life Support Systems and future challenges. The guest statement from Kriss J. Kennedy[2] discusses the Design and Development of the TransHab module (Testing and Evaluation of the TransHab module will be discussed in Chap. 6). The guest statement from Haym Benaroya[3] and Leonhard Bernold[4] talks about engineering and construction issues for Lunar Base design.

[1]Thales Alenia Space Italia, Life Support and Habitability Expert.
[2]NASA Johnson Space Center, Space Architect, Texas Architect #15161.
[3]Rutgers University.
[4]Universidad Technica Federico Santa Maria.

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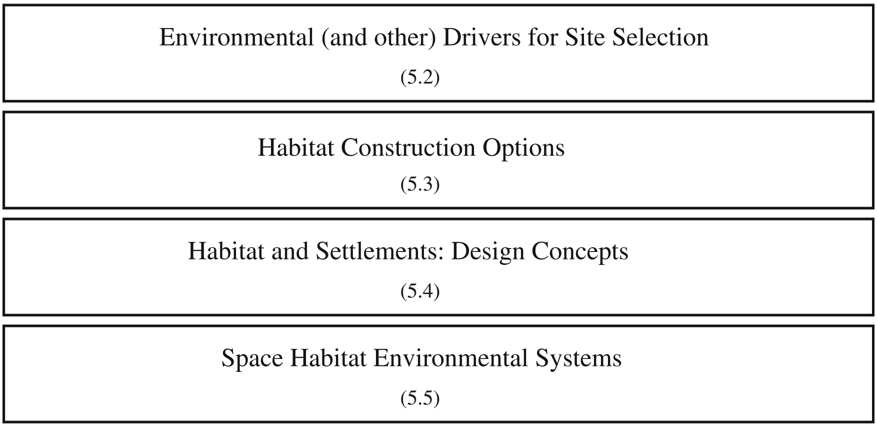


Fig. 5.1 Basic design process for habitation and design concepts development

5.2 Siting and Transportation

Questions for Exploration
Where do we go? How do we get there? Where is the base and infrastructure? What are the specific environmental conditions? What conditions are different from Earth and what consequences are there for design? Which resources are available in situ? How can they be processed and used? Which infrastructure is necessary? What impact do different environmental conditions have on the design?

Following the choice of primary mission objectives, a specific site as well as launch and transfer vehicle types have to be identified. This process is influenced by several factors, such as environmental conditions, surface conditions, magnitude of surface operations, ISRU availability, power sources, radiation, and dust mitigation methods, etc. Launch and transfer vehicle types are referenced in the book's Appendix and are subject to the respective space agency and country's resources. This section discusses site selection processes and draws examples from the Apollo and Mars rovers' missions.

5.2.1 Environments and Characteristics

Environmental conditions on the Moon, Mars, and in Deep Space vary significantly. The physical environment in space and on planetary bodies is quite different from Earth. It is inhospitable. In the conference proceedings 'Human Performance,

Table 5.1 Definition of the Habitation Readiness Levels 2–4 in relation to Technology Readiness Levels (Connolly et al. 2006, p. 5; ESA [TRL] 2008)

HRL	Definition of the Habitation Readiness Levels 2–4	TRL	Definition of the Technology Readiness Levels
2	Habitation design and concepts, functional and task analysis An HRL Level 2 Habitation System is at a stage where requirements and operations assumptions have been firmed up, but still preliminary. The habitation system concept has matured to a point where interior and exteriors designs, functions, subsystem suites, etc. are being traded rather than researched. To comply with the Habitation Readiness Level 2 the design stage has to cover development of habitation and design concepts, functional and task analysis with reference to mission objectives, environmental characteristics, and potential in situ resources	Any TRL	
3	Internal configuration, functional definition and allocation, use of reduced scale models An HRL Level 3 Habitation System is at a stage where a spatial and operational allocation for all habitation system functions has been completed for the concept, including human functions per an assumed operations concept and mission timeline. Volume assignment, equipment assignment, analysis for co-location, separation, and adjacency, as well as vehicle volume integration have been performed. The external and internal concept is modeled with virtual systems and as reduced scale physical modules. The models generated allow the flexibility to accommodate change, validate the accommodation of the human, analyze the concept for various other factors (e.g. lighting, reach, collision avoidance, functional allocation of volume), and present the concept in three dimensions	>6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space) Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application
4	Full-scale, low-fidelity mockup evaluations An HRL Level 4 Habitation System is at a stage where using the information generated in the analysis and conceptual design development, full scale mockups are developed to allow for the evaluation of crew tasks to assist in verification of human operations compatibility with the design. Habitat volumes are evaluated with the full-scale mockup. Mockup fidelity is at a low level such that most habitat subsystems are non-functional		

Table 5.2 Summary of relevant characteristics for habitation design in different environments

	Earth	Outer space	Moon	Mars
Diameter (km)	12,756	–	3475	6792
Period of revolution (year)	365 Earth days	Not applicable	28 Earth days	792 Earth days (26 months)
Period of rotation (day)	24 h	Not applicable	672 h; 28 Earth days	24.66 h
Gravity	9.8 m/s^2	Microgravity	1.62 m/s^2 1/6 of Earth	3.69 m/s^2 1/3 of Earth
Mean surface temperature	15 °C Max +60 °C Min −89 °C	– Max +200 °C (radiant energy) Min −270 °C (cosmic background radiation)	−20 °C (much colder at the poles in deep craters) Max +123 °C (possibly up to 140 °C in some locations on the equator) Min −233 °C (surface)	−65 °C Max −5 °C Min −87 °C
Length of day (h)	24.0	–	708.7	24.7
Radiation	Natural protection by the Earth's atmosphere equivalent to about 1000 g/cm^2 and the Van Allen Belt	Exposure to Solar Particle Events and Galactic Cosmic Rays	Exposure to Solar Particle Events and Galactic Cosmic Rays; mass of the surface gives "half protection" but the surface also generates secondary thermal neutrons from bombardment	Atmosphere gives about 30 g/cm equivalent protection. Mass of the planet gives about "half shielding"
Atmospheric pressure	1 bar (N_2, O_2)	0 bar (vacuum)	0 bar (almost a perfect vacuum)	0.01 bar
Other specific characteristics		Extreme bright light and glare	Extreme bright light and glare	

Sources Edited from the book Architecture for Astronauts, 2011
Original sources NASA [Moon] (2014), NASA [Mars] (2014), Eckart (1999), Williams (2007), Cohen (2009)

Situation Awareness, and Automation', Kring et al. (2000) characterized extreme environments as "… *settings that possess extraordinary technological, social, and physical components that require significant human adaptation for successful interaction and performance.*" (2000, p. 119) Table 5.2 provides a characteristic overview on the differences between selected environments.[5]

[5]Further Reading: Book "Clementine Atlas of the Moon" by Bussey, Ben and Spudis, Paul, D. (Bussey and Spudis 2012); NASA [Moon] (2014). Solar System Exploration—Facts & Figures [Online] http://solarsystem.nasa.gov/planets/profile.cfm?Object=Moon; NASA [Mars] 2014. Solar System Exploration—Facts & Figures. [Online] http://solarsystem.nasa.gov/planets/profile.cfm?Object=Mars.

Table 5.3 Translating the environmental characteristics into architecture related characteristics using the example of a transfer mission to Mars (Larson and Pranke 1999, Chap. 22, p. 733)

General characteristic	Specific characteristic of the environment	Architectural characteristics
Gravity	Microgravity during travel; 1/3 g on Mars after landing	During transit: visual cues required, all surfaces are available for operation, means for securing people and objects in place required On the surface: architecture and design in relation to changed ergonomics of humans
Radiation	Exposure to GCR and to solar particle events (SPE)	Radiation protection needed, shelter for SPE needed
Micrometeoroids	Sharp and high speed objects	Exterior protection needed
Temperature	Close to absolute 0 K outer space temperature. Surface temperature swings between +120 and −100 °C. Interior heat accumulation	Thermal insulation and radiators required
Lighting	Limited natural lighting due to viewports restrictions and flight direction	Artificial lighting required
Dust	Interior dust suspension	Using materials with minimal dust producing qualities, dust mitigation techniques needed

Environmental characteristics are directly linked to a number of design decisions. Table 5.3 gives an example of how specific characteristics (of the selected environment) can be translated into architectural characteristics and requirements.

5.2.2 *In Situ Resources*

"*In situ resources are resources existing in the environment, in the atmosphere or at the surface of a planetary body*" (Eckart 1999, p. 607). In situ resources can provide essential materials for life support systems, energy provision, and construction and production materials. Resources found in situ will be a key issue for future human space missions. According to NASA, "… *in situ resource utilization will enable the affordable establishment of extra-terrestrial exploration and operations by minimizing the materials carried from Earth*" (NASA [In Situ] 2008). In different environments, and locations in situ resources vary. Table 5.4 lists resources available in outer space, on the Moon, and Mars, in comparison to the Earth environment, and highlights their potential applications.

Note: Considering all necessary components for ISRU processing is important for mission planning. Most production developments will require significant power resources as well as labor (manned or robotic), they will also be time-consuming

Table 5.4 Available resources on possible landing sites in comparison to the Earth environment (Häuplik-Meusburger 2011, Table on p. 16; Larson and Pranke 1999, p. 478)

Resources	Earth	Outer space	Moon	Mars	Remarks and potential use
Gravity	9.8 m/s^2	Microgravity	1.62 m/s^2 1/6 of Earth	3.69 m/s^2 1/3 of Earth	Material processing
Presence of water	70.8 % of surface is covered with water	Known to exist in comets	Water in the deep, permanently shadowed craters at the poles	Found in a variety of “special regions”	Propellant, life support
Dust/Soil	Exists in the atmosphere, generally not harmful except for allergies	Exists but minimal	Pervasive on the surface: abrasive, sharp, potentially toxic, electromagnetic cling, lofts above the surface	Pervasive on the surface, very fine grain, dust storms in Mars atmospheric winds, potentially toxic and abrasive	Radiation shielding, Construction (melted, sintered soil)
Solar energy	Depends on geographic location and weather conditions	Maximum potential depending on orientation of the spacecraft	Capacity depends on surface location, high risk of micrometeoroid damage	Capacity depends on surface location and periodic obstructions due to dust storms	Power
Minerals and chemicals	Depends on geographic location, big variety of useful mineral resources	N/A	O, Si, Fe, Ca, Al, Mg, He_3, other	Al_2O_3, MgO, CaO, SO_3, SiO_2, Ni, Na_2O, Zn, other	Propellant, life support, manufacturing
Vacuum	Atmosphere	Vacuum	Vacuum	Near-vacuum	Material processing
Other		Solar wind	Lava tubes	Traces of possible signs of life	

operations and have to be planned in advance (see Mission Planning chapter). Technologies need to be well tested beforehand and relatively to available resources.

5.2.3 Site Selection and Its Implications for Habitation Design

The site selection strategy for habitation and relevant infrastructure is critical for the satisfaction of mission goals. It should consider (1) scientific objectives in an interplay with system capabilities, (2) resource utilization, (3) operational considerations and constraints, and (4) strategic purposes (Taylor and Taylor 1996; Eckart 1999).

A first assessment of potential landing and construction sites can be based on available surface observation data and by visual evaluation (e.g. even or uneven surface, presence of large rock formations, cracks on the surface and their depth). An important aspect of evaluation is the proximity of a landing and/or ascending site to a settlement site and power sources. Depending on mission objectives, different surface transportation means can be selected (pressurized and/or non-pressurized rovers). Those will influence the layout of the base as a result of distances between structures, modules, and facilities.

Radiation protection strategies may also play a significant role in the site selection process. Local topography can be used as a passive radiation mitigation approach. In situ resources, such as regolith, can be used as active radiation shielding (e.g. burrowing structures under thick layers of regolith or using 3D printed elements for building protective shells), but such an approach will require extensive surface robotic and possibly manned operations. Either way it will affect the site location and settlement configuration.

Tables 5.5 and 5.6 show examples of landing sites in relation to their scientific or economic objectives. Space architecture considerations in relationship to the dedicated site are exemplified. In general, there is no 'ideal' landing site for all purposes and each site has implications for the habitat design.

5.2.3.1 Example: Landing and Construction Sites on Mars

Potential landing and construction sites are illustrated in Fig. 5.2 and Table 5.6 lists advantages and disadvantages of mission related activities at the most likely landing sites (proposed sites for Curiosity rover landing).

Besides the particular characteristics of a specific landing or building site, general Space Architecture considerations include:

- Safe distance from pre-deployed structures and elements.
- Relatively smooth and flat terrain.
- Close proximity to points of scientific research and ISRU sites.
- Ease of transportation to and from the landing site.
- Availability of natural (landscape) protection from environmental hazards.

5.2.3.2 Example: Curiosity Rover Mars Mission

The Curiosity mission was launched at 7:02 a.m. PST, on November 26, 2011 (10:02 a.m. EST); with an Atlas V launch vehicle by United Launch Alliance and it landed in Gale crater at 10:32 p.m (Fig. 5.3). PDT, on August 5, 2012 (1:32 a.m. EDT, August 6, 2012).

> This landing site selection was made in June 2011 and it marked the end of a process that began in June 2006, when Mars scientists from around the world attended a workshop and compiled a list of **100 potential landing sites**. Using the most powerful cameras and

Table 5.5 Examples of site parameters on the Moon and Mars in relation to their scientific or economic objective

Site	Parameters	Relevance	Space architecture considerations
Moon	Latitude and elevation	Astronomy (within 10 % of the equator and near the Lunar limb)	Long lunar nights on the equator increase energy storage when solar power is used
	Topography and terrain	Geology (near a mare, highland), resource extraction (near a mare, regolith)	Large areas of flat terrain allow easier habitat and infrastructure construction operations as well as safe and easy surface mobility
	Radiation and temperature	The body of the Moon provides 50 % protection from SPEs and GCR. Surface temperature fluctuations	Shielding and thermal control required
Mars	Latitude and elevation	Astronomy (between 45°N and 45°S), geology (elevation +1 km)	Sites above 30°N are difficult to observe with Direct-to-Earth (DTE); reduced availability of sunlight with increased latitude
	Time and season	Resource extraction	Seasonal and Martian daytime related complications for landing/deployment operations (Southern winter is long and intense with less solar irradiation, this increases energy storage needs)
	Landing ellipse	Proximity to pre-deployed structures and transportation to and from the landing site issues	Protection from landing ejecta
	Topography and terrain (relief, slopes, rocks)	Construction, soft landing, and transportation capabilities	Landing site has to be free of rocks, mobility system is pre-deployed on surface
	Atmospheric parameters	Landing	Site-specific hazards (jet streams, winds, and turbulences)
	Radar reflectivity and thermo-physical properties	Landing (measurement of altitude and velocity)	Available surface materials
	Reflectance spectroscopy	In situ resource utilization	ISRU-plants and mines influence surface mobility and layout of the base

Implications for space architecture are listed (Eckart 1999; JPL [MSL] 2007; Howe and Sherwood 2009)

> spectrographic instruments ever sent to the red planet, Mars Reconnaissance Orbiter has been collecting data to help scientists evaluate each potential landing site in greater detail. Four candidates were selected in 2008. An abundance of targeted images enabled thorough analysis of the safety concerns and scientific attractions of each site (NASA [Mars JPL] 2014).

The final decision to use Gale Crater as a landing site for the Curiosity rover was based on scientific and technologic considerations. That site is convenient as a starting platform for exploration and has a relatively even surface for landing. Also, scientists preferred Gale Crater as the landing site due to signs of water presence

Table 5.6 Example sites on Mars in relation to their scientific or economic objective along with some implications on space architecture

Potential sites	Objectives (why go there?) (+) advantages and (−) disadvantages	Space architecture considerations (+) advantages and (−) challenges
Holden crater	(+) Deposits of more than 3 billion year old sediments formed by running water, wind, and erosion offers clues to the history of water on Mars (+) Some of the most ancient rocks can be examined here (+) Possible ancient lake with well-exposed deposits (+) Geologically interesting, light-toned clays, and megabreccia (+) Safe landing ellipse containing one (scientific) key objective: smooth, flat surface, trafficable route to the main scientific target (+) Consistent thermal inertia/surface material (−) Perhaps not a good environment for preserving potential biological sediments (−) Unclear environmental history and complex geological framework	(+) Availability of a high plateau of eroded material offers landing site for rovers or a construction site for infrastructure to be built (+) Phyllosilicates (sheet silicates) could be mined and processed for construction material (+) Relatively dust free (−) Steep slopes with rough terrain may present difficulties for surface exploration (−) Mean ground temperature instabilities throughout Martian year (−) Southern latitude—long and intense winters (−) Higher energy requirements, increased complexity of thermal protection
Eberswalde crater	(+) Wide, meandering delta containing clays—some of the best evidence that Mars for some time had continuous water (+) Evolution of a crater lake, the history of hydrologic and climatic changes and a sedimentary depositional environment that might have been favorable to the preservation of organic materials and/or other kinds of biosignatures (−) Relatively limited variety and modeled abundance of phyllosilicate (sheet silicates) minerals known to preserve organics detected from orbit (−) Science in landing ellipse is secondary to that outside of the ellipse	(+) Relatively flat landing site, significantly lower than its surrounding allows some radiation protection (+) Clay minerals on the surface can be used for ISRU purposes (+) Increased solar energy gain, minimized complexity of dust control and maintenance (−) Steep slopes may present difficulties for surface exploration (−) Higher energy requirements, increased complexity of thermal protection
Mawrth Vallis	(+) This site provides the opportunity to understand the potential for early habitability on the planet and may be representative of global conditions on Mars (+) Rocks contain more than 50 % phyllosilicates (sheet silicates), which have good biologic preservation potential (−) There is no consensus on the depositional setting or the mechanisms for concentrating or preserving organics and it is unlikely that the depositional setting will be further refined prior to landing and in situ evaluation	(+) Hazard-free landing zone next to an ancient channel valley created by floods (+) Cliffs are rich with clay that can be used for ISRU purposes (+) Northern site—receives more solar energy—minimizes required mass of the energy storage subsystem (+) Availability of regolith for building (−) Location in the boundary between high southern and low northern hemispheres may present challenges for surface operations

(continued)

Table 5.6 (continued)

Potential sites	Objectives (why go there?) (+) advantages and (−) disadvantages	Space architecture considerations (+) advantages and (−) challenges
Gale crater	(+) Strata within the 5 km thick mound of layered sediments within Gale crater record a sequence of aqueous habitable environments over an extended period. These strata contain multiple hydrous minerals (sulfates, phyllosilicates) that indicate varying aqueous environmental conditions (−) Relatively limited variety and modeled abundance of phyllosilicate (sheet silicates) minerals known to preserve organics detected from orbit. Science in landing ellipse is secondary to that outside of the ellipse	(+) Clay minerals near the bottom of the mound and oxygen-bearing minerals above them may be useful for ISRU purposes (+) A flatter side is suitable for landing. The site has been explored by the Curiosity rover (+) Little variation in mean ground temperature throughout the Martian year (−) Relatively narrow flat area may prevent settlement's evolutionary growth (−) High ridge of the crater may pose challenges for surface transportation and exploration (−) Design for dust control: avoid habitat contamination, limit maintenance

Sources NASA JPL [MSL] (2007)
Further Reading about landing sites: http://marsoweb.nas.nasa.gov/landingsites/index.html, http://mars.jpl.nasa.gov/msl/mission/timeline/prelaunch/landingsiteselection/holdencrater2/

over its history. Water is considered to be a key ingredient of known life. The expected near-surface atmospheric temperatures at the Gale Crater landing site during Curiosity's primary mission (1 Martian year or 687 Earth days) range from −130 to 32 F (−90 to 0 C).[6]

The rover has traversed over 9 km in two years after landing on Mars on August 05, 2012 and delivered data and images of various sites. Curiosity met its major objective of finding evidence of a past environment suited for supporting microbial life. The rover examined the geology and environment of crater areas and analyses rocks and soil samples (NASA [Curiosity Fact] 2014). Landing sites for manned missions should be planned comparably to it and take all scientific, technologic, economic, and safety considerations into the account (see also Chap. 3).

5.2.3.3 Example: Apollo Mission

During the Apollo program (1961–1975), the site selection process started with reviewing telescopic maps and other observations from Earth. That stage was followed by Surveyor's (1966–68) and Lunar Orbiter's (1966–67) observations of suggested areas for landing on the lunar surface. Initial requirements for a landing site included prospects for scientific research, landing limitations, and probability of launch delays (Cortright 1975).

[6]Further Reading about the curiosity mission: Curiosity: http://www.nasa.gov/mission_pages/msl/index.html. And: http://mars.nasa.gov/msl/mission/timeline/prelaunch/landingsiteselection/about-galecrater/

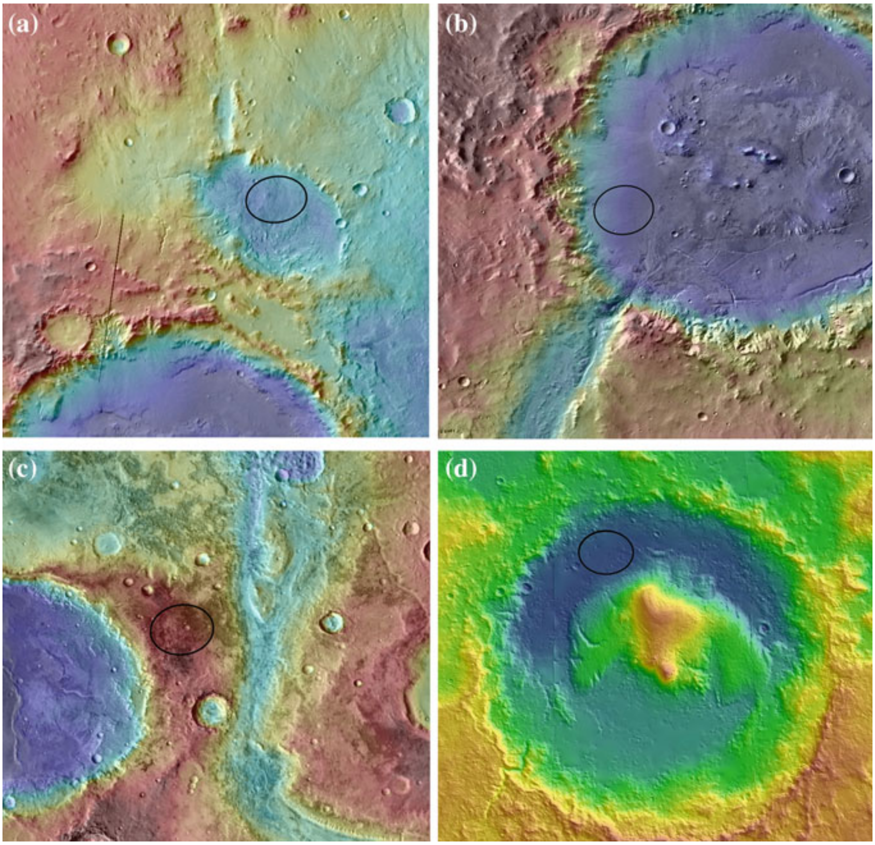


Fig. 5.2 Closeups of the four curiosity mars landing ellipses: **a** Eberswalde crater; **b** Holden crater; **c** Mawrth Vallis; **d** Gale crater (NASA, JPL)

Based on photographs received from the Orbiter mission, sites were assessed by the level of risk for landing operations. The hazardous surface conditions included ridges, slopes, craters, large boulders, and overall roughness of the surface. Landing ellipses were drawn based on a possibility of navigation errors of an Apollo landing module that would cause missing a target up to 1.5 miles north or south and 2.5 miles east or west. The least dangerous target points were selected within identified landing ellipses[7] (Fig. 5.4).

[7]Book "Introduction to Space: The Science of Spaceflight" by Damon (1995, p. 225).

Fig. 5.3 Having ejected the lower heat shield and the parachute, this image shows the sky crane lowering the rover onto the Martian surface (NASA/JPL-Caltech)

5.2.4 Discussion and Tasks

Discuss how site selection differs on Mars and Moon surfaces. How may the differences affect locations of surface modules and facilities and the transportation means between them? Select at least two sites either on the Moon or Mars, compare their characteristics and outline possible locations of surface structures.

5.3 Construction and Structures

Questions for Exploration
What are habitation modules and structures made of? How does a habitat module's structure withstand space environmental conditions? Which structural possibilities currently exist? How are space modules connected? What structural elements and techniques can be inherited from Earth, what is different?

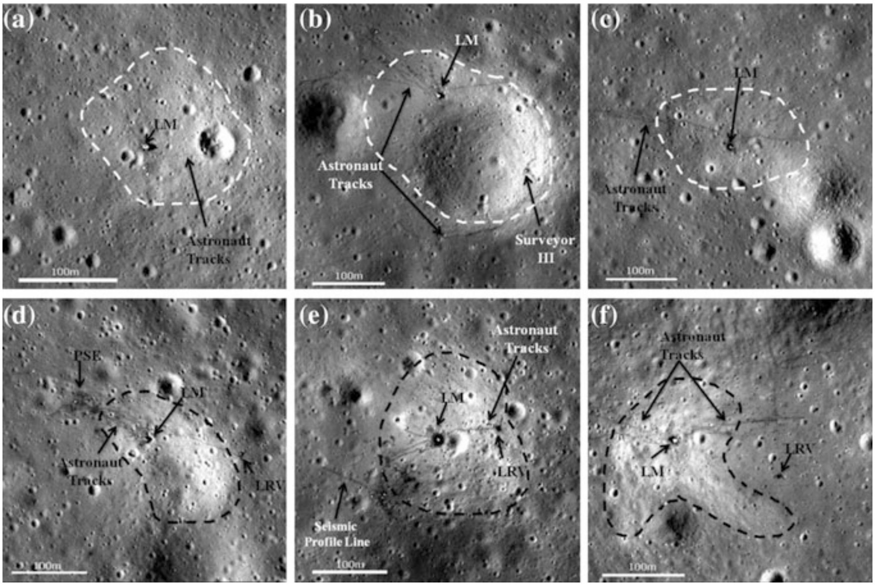


Fig. 5.4 Original NAC images of each Apollo landing site, cropped to the region around the LM and with important features labeled. **a** Apollo 11, image M150361817R. **b** Apollo 12 and Surveyor III, image M120005333L. **c** Apollo 14, image M114 06206L. **d** Apollo 15, image M119822622L. **e** Apollo 16, image M152770233R. **f** Apollo 17, image M113758461R (as published by Clegg et al. 2012) (Further Reading: Photometric Analysis of the Apollo Landing Sites, Ryan N. Clegg, Bradley L. Jolliff, Philip T. Metzger, Earth and Space 2012, ASCE 2012)

5.3.1 Space Habitat Structural Systems

All habitation modules in microgravity environments have to be pressurized in order to sustain human life. Thus, technical subsystems life support elements need to be integrated. Although structural possibilities are tied to a number of constraints, a variety of types and forms are available.

Generally speaking, human spaceflight structures have to meet the following (and many more) objectives:

- Structures shall provide moderate temperatures for the crew inside.
- The materials used shall be selected based on low outgassing criteria.
- Noise and vibration by technical subsystems shall be minimized.
- Fire and smoke proof materials and structures are necessary.
- Redundancy is vital for life support systems.

The longer the mission, the more space and volume are needed and the more elaborated the configuration of the internal structure has to be (see Chap. 4). Table 5.7 gives an overview of construction methods and their characteristics.

Table 5.7 Types and forms of construction for habitable environments in microgravity

Construction methods/examples	Characteristics
Pre-fabricated Almost all realized space elements (Skylab, Mir, and ISS modules)	Design: standard, simple[a] to design Launch: many (1 for each module) Operation: immediate operational capabilities Installation: easy pre-integration of equipment and utility systems, can be installed and checked prior to launch Materials: have been demonstrated, good structural integrity and reliability Engineering: easy integration of windows Constraints: habitable volume of internal capacity increased only by adding modules
Inflatables (Bigelow's Genesis I and II, BEAM)	Design: system has been demonstrated in space Launch: can be compactly packaged Installation: can afford some pre-integration Materials: multi-layered envelope, each layer with special features Architecture: larger habitable volume on site; not divided into smaller volumes
Hybrid	Design: inflatable and conventional elements are combined Materials: combination of hard and soft elements/combination of prefabricated and in-situ-produced materials Installation: pre-integration of utilities and equipment is partly possible Architecture: larger habitable volume and/or optimized habitability features
Emerging technologies	3D printing methods; active magnetic radiation shielding (electromagnetic interference (EMI) and radio frequency interference (RFI) Shielding); nanomaterials for radiation protection; biological protection through the use of new therapeutic gases; etc.

Sources Badescu (2012)
[a]Compared to other methods

5.3.2 Typical Pre-fabricated Module

A pre-fabricated, hard-shell, or conventional pressurized module consists of a primary and secondary structure. This module type dominates the architecture of the International Space Station, as well as the Chinese space station.

A module's primary structure provides the structural integrity of a pressurized envelope and includes ring frames, longerons, pressure shells, windows, and other integrated elements (e.g. trunnions). These elements can be seen in Fig. 5.5 (except for windows).

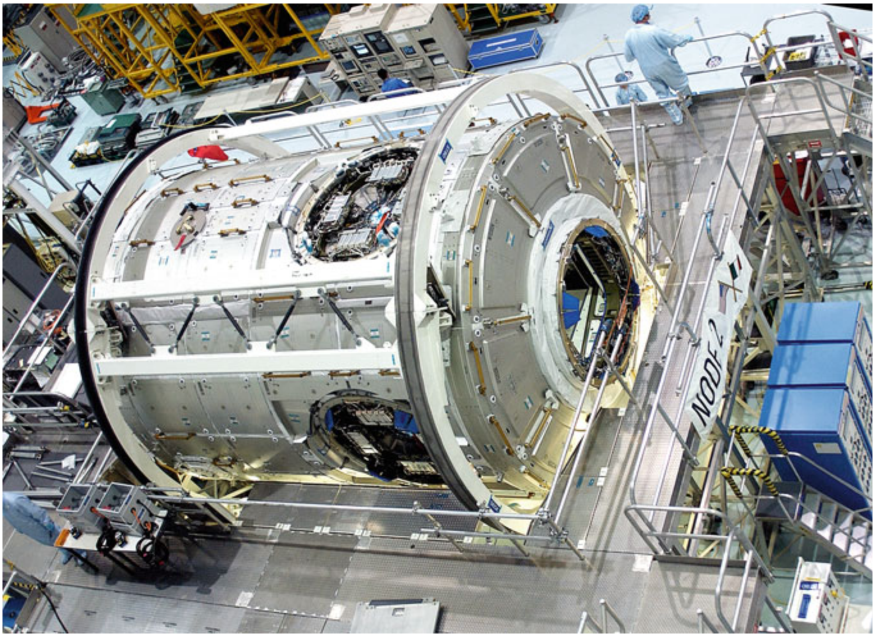


Fig. 5.5 ISS Node 2 (Harmony) module under construction (NASA)

The secondary structure of the module transfers structural loads to a primary structure and can be both internal and external. Racks of ISS modules are an example of a secondary internal structure. Handrails for EVA assistance are a secondary external structure example. These elements may vary on different modules.

Conventional modules use well-known pressure vessel construction technology. Those modules can accommodate proven means to incorporate penetrations and attachments including viewports, suitports, and hatches. The modules can potentially be pressurized to increase stiffness prior to landing, which is an important consideration for massive cylindrical elements that will experience impacts in their weak (horizontal) orientation.

The International Space Station is assembled with pre-fabricated modules produced by multiple countries but within ISS constraints and according to international participants' agreement requirements (Fig. 5.6).

5.3.3 Inflatable/Expandable Modules

An inflatable module is a type of expandable module and has the major advantage of offering extra volume and space after deployment. Another major advantage of

Fig. 5.6 Image of the International Space Station, photographed by an STS-134 crew member on the space shuttle (the principal contributors are the space agencies of the United States, Russia, Europe, Japan, and Canada). S134-E-010137 (NASA)

expandable modules and structures is the fact that they are launched in a packed configuration, which transfers a significant payload volume benefit (Fig. 5.7).

Inflatable structures offer the ability to launch and deploy habitats that greatly exceed the internal volume offered by hard-shell modules. Some systems have already been demonstrated in space, and some others are in various stages of design and testing. Pressure walls are invariably comprised of specialized pliable layers, each of them providing an essential feature for a pressurized environment. Earlier concepts of inflatable structures for space (Fig. 5.8) were developed by Goodyear Aerospace Corporation (GAC)[8] under contract with the NASA Langley Research Center during the 1960s (cf. Häuplik-Meusburger and Özdemir 2012).

Inflatable modules can be expanded in different configurations of pressurized envelops, including cylinder, capsule, torus, sphere, and combinations of them. They can be used as orbital (Fig. 5.9) and planetary (Figs. 5.7 and 5.10) modules.

A combination of hard shell modules with inflatable, expandable elements offers the advantages of both types of modules, although they present some concerns regarding pressure seal safety.

[8]GAC was purchased by the Loral Systems Group.

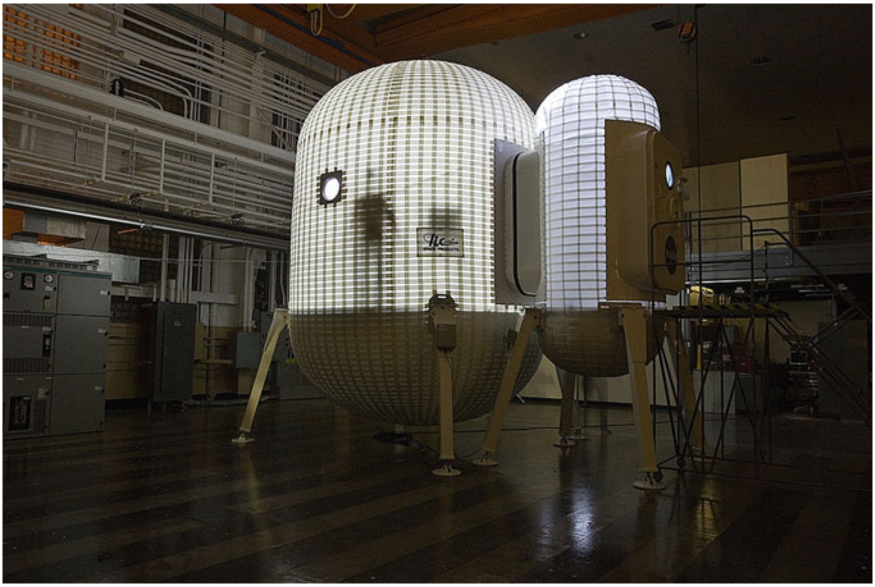


Fig. 5.7 Inflatable lunar habitat model at NASA's Langley Research Center in Hampton, VA (NASA/Sean Smith)

Fig. 5.8 Prototype of an inflatable space station concept with a solar power system collector from 1961 (NASA)

Such combined advantages of inflatable and conventional elements include:

- Soft inflatable sections provide relatively large internal volumes to optimize habitability features.
- Hard sections enable pre-integration of utility and equipment systems and can readily accommodate integral viewports, docking interfaces, and other structures.
- Conventional hard modules provide an initial operational capability with pre-integrated utilities and equipment.
- Inflatable laboratories and habitats can be added as required throughout growth stages.

5.3.3.1 Example: TransHab and Bigelow Aerospace

Bigelow Aerospace is working with NASA and a variety of contracting organizations. The company holds two license agreements with NASA:

- an exclusive license for two TransHab patents;
- a license for radiation shielding with exclusive and non-exclusive contracts.

Figure 5.9 shows the original NASA concept. It will be described in detail in Sect. 5.7. Figure 5.10 shows a full-scale mockup by Bigelow Aerospace. Bigelow is

Fig. 5.9 NASA's design for the canceled TransHab module (NASA)

Fig. 5.10 A full-scale mockup of Bigelow Aerospace's space station Alpha inside their facility in Nevada (Bigelow Aerospace)

developing ways to fold/package soft materials around a module's aluminum core to ensure that creases and critical seals such as windows don't leak when pressurized.

5.3.4 Structural Openings

Any structural openings present potential danger of air leakage and loss of pressure and have to be designed with maximum structural integrity. The Lunar landers during the Apollo missions had multiple windows to look outside, and one door, but no airlock. To exit, astronauts had to wear their space suits and vent the whole cabin. To prevent loss of valuable air during EVA operations airlocks were developed.

Generally, space habitation modules are equipped with hatches to connect with other modules and airlocks; they also have viewports or windows. Table 5.8 provides an overview of different types of openings (refer also to Sect. 5.3.6 Airlocks).

Note: Beyond Earth, the 'inside' and 'outside' is sharply divided. There is no "Zwischenraum" (as patios, or covered entrance spaces) like on Earth. In future long-term habitation concepts, such spaces will become important. As Brent Sherwood puts it "… *such indoor exteriors, including 'pocket parks', will be essential for inhabitants constrained to never actually experience the lethal exterior.*" (2002, p. 7)

Table 5.8 Different types of openings and related issues

Type of opening	Characteristics
Berthing and docking port	Connection between two modules or where the rover temporarily connects to the pressurized habitat Transfer between the habitat and a pressurized rover
Airlock	Separate pressure vessel, usually a vertical rigid cylinder with elliptical end domes and opposing hatches (Shuttle Airlock); inflatable airlocks are a special type and have been constructed
Suitlock or suitport	Integrated into the habitat or vehicle structure. The spacesuit remains in the airlock, but can be assessed for repairing and servicing (dust control)
Sample airlock	Used to pass samples collected by the astronauts to an interior glove box for further examination. "Airlock size is determined by the items to be passed through and the allowable air input to the glove box." (Cohen 2000, p. 11)
Trash airlock	Used to discard waste (cf. Skylab Trash Airlock)
Scientific airlock	"… is a versatile, self-contained unit with venting and pressurization capabilities …. Payloads are normally mounted on a sliding experiment table, which can be extended into space and/or into the module. … All mechanisms are manually operated." (Cohen 2000, p. 12, taken from den Haak 1983, p. 47)
Windows	Allows viewing to the outside, payloads Window types: flat windows within a module/node wall/cupola (space station windows) Hemispheric windows (rover) Have to be placed taking the natural body position into account

Sources Cohen (2000)

5.3.4.1 Windows

Mercury, Gemini, and Apollo missions proved that "adequate viewing windows" were of high value for the mission. Still, there was "… appreciable opposition when the wardroom window was proposed for Skylab." (NASA [Skylab LL] 1974, p. SLL1_7) The Salyut space stations and Mir had multiple windows installed for scientific purposes. Today, the seven-window observatory-module 'Cupola' offers views of robotic and docking operations as well as a 360° window to observe Earth (Fig. 5.15).

The ability to see Earth is vital for maintaining psychological health and morale of the crew during a space flight. Astronauts and cosmonauts describe viewing Earth from the orbit as the most beautiful image they have ever seen. "*Nevertheless it's better to see the Moon and the Sun than being in a closed room without seeing anything. Sometimes you need reference. You need something which is natural, not artificial things around you.*" (Haigneré 2009)

Earth observation and space observation will be very important during a space flight to Moon or to Mars as well. Windows in a habitat provide a visual reference for the crew first to Earth and then to the Moon and Mars as they approach. The importance of outside viewing has been demonstrated throughout all human space missions, and in addition to that, outside viewing offers:

- Monitoring and control of vehicle rendezvous/docking procedures.
- Operation of tele-robotic devices through direct eye contact.
- Discovery and photographic documentation of natural events and spacecraft hazards/damage.
- Crew recreation and morale to offset boredom and psychological confinement/isolation.

At some points of a spaceflight, outside viewing possibilities may be limited, either due to environmental constraints (e.g. radiation protection, movement of the space station) or due to a large amount of required equipment and utilities placed along the walls.

Windows' structure in a pressurized habitat has to be very secure, eliminating any risk of leakage and minimizing any structural compromise. Spacecraft windows also add substantial structural mass, pose pressure seal and transparency maintenance problems, and can reduce interior surface space that may be available for equipment and other uses:

- The size and number of windows must be correlated with launch and functional volume constraints.
- Locations must be selected for appropriate viewing orientation in relation to the vehicle's orbital attitude or spaceflight orbit and operational objectives.
- Window designs must accommodate viewing objectives and limitations.

Spacecraft windows can be constructed in various types and placed in different locations:

- They can be placed into module cylinder walls, end caps, pressure hatches, and attached cupolas.
- They can be flat or domed bubble geometries.
- They can be designed for general viewing, or can incorporate special optical features for photographic and scientific applications.

They can be outfitted with fixed or moveable UV filters and debris shields. Examples of structural concepts are presented in Figs. 5.11 and 5.12.

Another option to enhance viewing capability is attaching an additional element for external observations: a cupola (Figs. 5.13 and 5.14). The ISS has been equipped with a cupola and it provides extraordinary possibilities for Earth observations and research. The structure of a cupola element can be a faceted or a bubble type; both types can be constructed in various ways. The ISS cupola is a faceted type element.

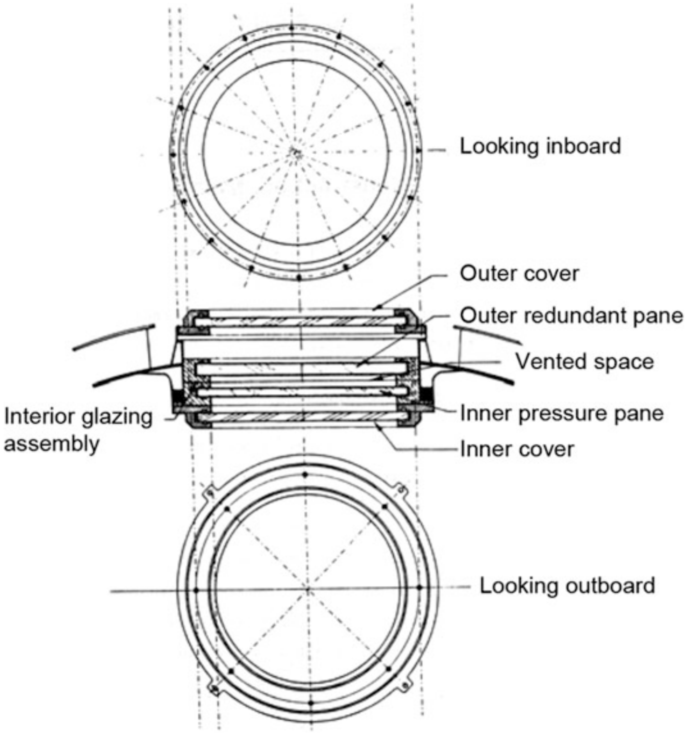


Fig. 5.11 The NASA Marshal Space Flight Center common module concept (based on NASA documentation)

5.3.4.2 Example: The Cupola Observation Module

The Cupola module was launched to the International Space Station in 2010. It is an attachment to Node 2 and provides a 360-degrees observation and control capacity for the robotic arm and other outside operations. The module is a pressurized observation and work zone with command and control workstations and other hardware. It has seven windows with protective shutters (Fig. 5.15). The cupola has a height of 1.4 m (4.7 ft) with a diameter of about 3 m.

5.3.5 Radiation Shielding

Outer space, Lunar, and Mars surface habitats and crews must be protected from micrometeoroid and radiation hazards with levels 'As Low As Reasonably Achievable' (ALARA). With regard to micrometeoroids, the goal is to afford a 0.993 "probability of no penetration" (PMP) over each 5 year period. While no firm radiation dose limits have been established for exploratory class missions, those which have been applied for low-Earth orbit (LEO) are presently recommended as

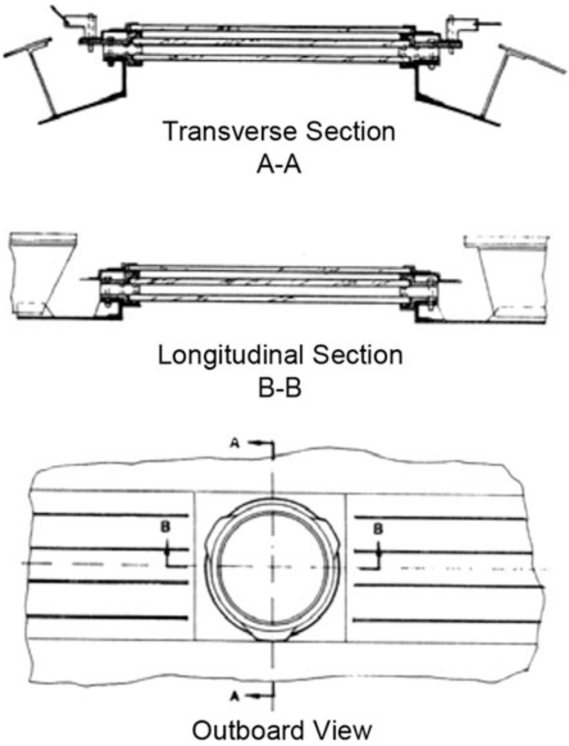


Fig. 5.12 152.4 mm (6 inch) diameter concept by Rockwell (based on NASA documentation)

guidelines (Table 5.9). These have been set by NASA (NASA-STD-3001) and the National Council on Radiation Protection and Measurements (NCRP Reports No. 132, 137 and 142).

There are various shielding approaches to protect habitats from micrometeoroid and radiation hazards that present major trade-off considerations. Popular scenarios envision covering modules with in situ regolith on the surface of Moon or Mars. Those will necessitate developing the means to excavate and move large amounts of material; will complicate evolutionary outpost growth; and may require long tunnels between connecting pressurized elements. Strategies that incorporate shielding materials into module structures or internal shelters add very substantial launch mass penalties. Utilization of water/hydrogen bladders can make efficient use of consumable/recyclable supplies, but may impose excess capacity deliveries at early development stages.

Galactic Cosmic Rays (GCRs) from deep space are comprised of protons, electrons, and ionized light elements. Due to high energy levels, they are nearly impossible to shield against completely, and biological effects are not well understood.

Types of possible radiation protection shielding for surface settlements and during spaceflight are presented in Table 5.10.

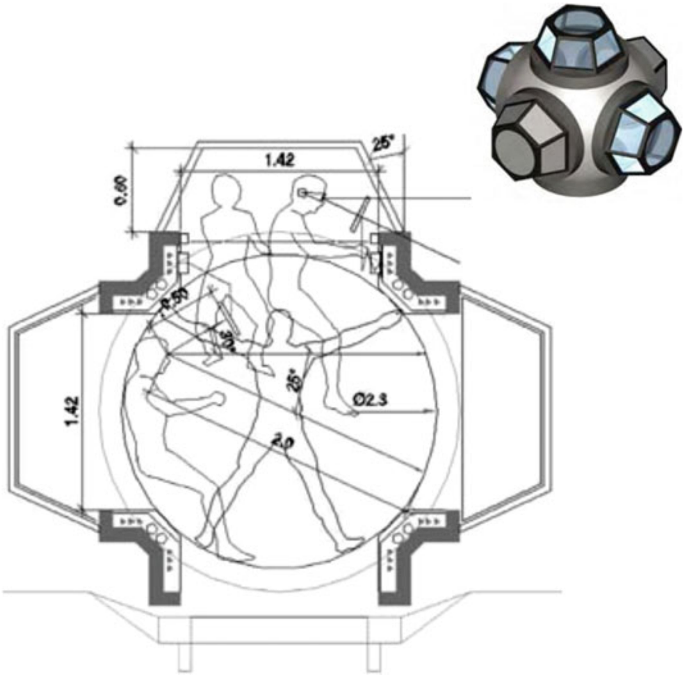


Fig. 5.13 Faceted (Maijinn Chen, SICSA)

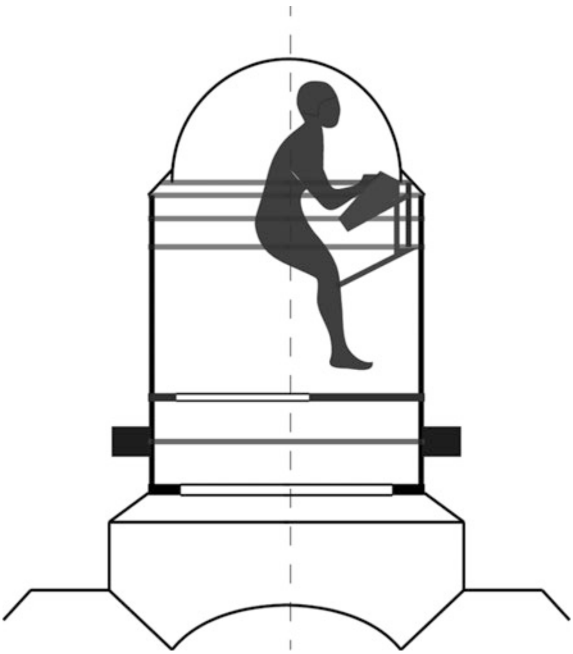


Fig. 5.14 Bubble type cupola (Bell & Trotti, Inc)

Fig. 5.15 The 'Cupola', attached to the nadir side of the space station, gives a panoramic view of our beautiful planet, said Expedition 25 commander Doug Wheelock. Fyodor (Yurchikhin) took this picture from the window of the Russian Docking Compartment (airlock): "*Here I am in the Cupola preparing a camera for our late evening Hurricane Earl flyover … trying to capture the moment …*" (NASA)

Table 5.9 Recommended NCRP radiation dose limits (mGy—milliGray, mGy-Eq—milliGray equivalent)

Organ	30 day limit	1 year limit	Career
Lens* (mGy-Eq)	1000	2000	4000
Skin	1500	3000	4000
BFO	250	500	Not applicable
Heart**	250	500	1000
CNS***	500	1000	1500
CNS*** ($Z \geq 10$)		100 mGy	250 mGy

*Lens limits are intended to prevent early (< 5 yr) severe cataracts (e.g., from a solar particle event). An additional cataract risk exists at lower doses from cosmic rays for sub-clinical cataracts, which may progress to severe types after long latency (> 5 yr) and are not preventable by existing mitigation measures; however, they are deemed an acceptable risk to the program
**Heart dose calculated as average over heart muscle and adjacent arteries
***Central Nervous System (CNS) limits should be calculated at the hippocampus

Table 5.10 Radiation shielding options

Available with current technologies and potential ISRU applications	Emerging technologies
Water shelters: deployable and permanent	MF (Magnetic Field) shielding using superconducting magnets
Regolith	ION shielding
Polyethylene	Nanotubes (hydrophobic or hydrophilic)
Natural landscape	Lava tubes (would require advanced technologies)

5.3.6 Micrometeoroids and Debris

Even small micrometeoroids and debris can cause severe damage to space habitat elements or the crew itself (when on EVA).

Micrometeoroids pass through space and the lunar surface at very high velocities. Since larger modules present bigger targets, they present greater hazard risks. A popular shielding strategy applies a 'Micrometeoroid and Secondary Ejecta' (MMSE) barrier to the external module structures, with particular attention to vulnerable top and side locations of surface modules that comprise about 3/4th of the module surface areas. A typical approach provides an exterior beta-cloth fabric layer with an interior Nextel/Kevlar blanket over the pressure shell. Estimated required MMSE shield mass is 10 kg/m^2 (Table 5.11).

For the Micrometeoroid and Orbital Debris (MMOD) at the International Space Station, three shielding configurations are used (NASA [Shielding] 2003):

Whipple shield: A two layer shield consisting of an outer bumper (usually Aluminum), spaced some distance from the module pressure shell wall; the bumper plate is intended to break up, melt, or vaporize a particle on impact.

Stuffed Whipple shield: It consists of an outer bumper (Aluminum), spaced a distance from the module pressure shell, with a Nextel ceramic cloth and Kevlar fabric in between.

Multi-layer Shields: They consist of multiple layers (fabric and/or metallic panels).

Table 5.11 Recommended micrometeoroid protection based upon ISS Meteoroid and orbital Debris Protection System (MDPS) design

Description	Material	Area density (kg/m^2)
Front bumper	Kevlar composite fabric 0.25 cm thick- 5 layers of 300 g/m^2 Kevlar fabric	1.5
Rear bumper	Nextel 0.30 cm thick	2.8
	Kevlar 0.64 cm thick	4.0
Spacer		1.7
Total		10

Source NASA-STD-3001, Volume 1 Crew Health, F 8. Space-permissible exposure limit (SPEL) for space flight radiation exposure standard

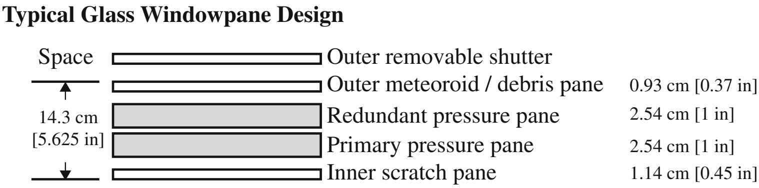
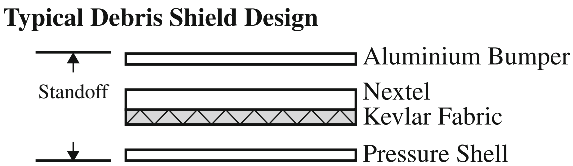


Fig. 5.16 Schematic design of glass window panel (based on NASA documentation)

Fig. 5.17 Schematic design of debris shield (based on NASA documentation)



Micrometeoroid Orbital Debris (MM/OD) shields are attached to the outside of a spacecraft to absorb projectile energy and break the particles into much smaller fragments before they reach the critical pressure shell. The "debris cloud" that reaches the shell distributes remaining energy over a much broader area to reduce penetration risks. Figure 5.16 shows a schematic debris shield design (Stuffed Whipple Shield). Another type of protection includes window shutters (to protect windows), and Fig. 5.17 shows a typical schematic design for a window with shutter.

5.3.7 Discussion and Tasks

What are benefits of hard shell modules versus inflatables and telescopic units? Pick one type of module and describe its structural challenges. Think about options for optimizing its construction.

5.4 Habitats and Settlement

Questions for Exploration
How many people will live and work in the habitat? For how long will they stay? What will they do there and what will they need? How can elements be powered and connected? How does the settlement develop and evolve? How will settlements be resupplied/sustain life on board?

5.4.1 Habitation Concepts

A habitat is a critical element of human space flight, especially in long-term missions. It is the place where people live and work, it protects them from hazards of the environment, and it enables the crew to perform their tasks and operations. Beyond Earth, the habitat is always a pressurized envelope with assistive technology components. It requires careful planning and construction.

Different options for the construction of orbital and planetary habitats have been developed through the history of human spaceflight, but only orbital habitats and short-term lunar habitats have been built and operated. Depending upon the mission conception and timeline, various habitation concepts may be proposed. Table 5.12 shows options for habitat construction using a class terminology (Smith 1993; Kennedy 2009; Howe et al. 2010). Class 3 and Class 4 options (combinations of module types) are yet to be tested in future space missions.

All habitable structures in the harsh environment beyond Earth must be capable of holding internal pressure loads of 0.6–1.0 atmosphere (without leaking). Subsequently, space habitats in general comply with the following requirements:

- All pressurized structures are primarily vessels with circular cross-sections that include spherical, tubular "sausage," or torroidal "inner tube" geometries (regardless of applied materials).
- Penetrations for windows, hatches between modules, orbital docking ports, utility passages, and other interfaces raise potential leakage concerns (for a discussion on structural openings refer to Sect. 5.3.4).

Table 5.12 Different approaches to habitat design (modified from the source: Howe et al. 2010)

	Class 1	Class 2	Class 3	Class 4 (combinations)
Construction	Pre-integrated modules from Earth	Pre-fabricated components that are assembled onsite	In situ resources are used for building structures	Combination of classes 1, 2 and 3
Examples	Apollo Lunar Module (1969–1972, NASA)	Inflatable or deployable structures: deployable Voshkod 2 airlock (1965, USSR), geodetic satellites, Genesis I and II prototypes (2006, 2007, Bigelow) space hotel	3D printing using surface material (regolith) Developing concrete and "bricks" using regolith as a major ingredient	Reconfiguration of hard shell "conventional" modules with pre-integrated interior elements and attached deployable (e.g. inflatable) volumes. Class 3 structures may be used for exterior protection
Requirements	Human factors EVA activities Surface mobility	Human factors EVA activities Advanced surface mobility	Human factors EVA activities Construction and mining facilities	Human factors EVA activities Greenhouse

5.4.1.1 A Comparison Between Orbital, Planetary, and Mobile Habitats

The architecture of orbital, planetary, or mobile habitats differs to a great extent. In Table 5.13 some differences between them are summarized. Orbital, planetary, and mobile habitats will be introduced in the following sections.

5.4.2 *Orbital Habitats*

There are multiple successful examples of orbital habitats: Salyut and Almaz series (USSR), Skylab (USA), Mir (USSR/Russia), and current operational orbital facilities—International Space Station and Tiangong 1 (China).

Typically orbital space stations are a combination of many elements. All pressurized models must be structurally stiff with the least amount of structural mass. In the case of a modular approach, they have to be securely connected with each other. Table 5.14 provides an overview and comparison of three orbital station architectures that have been built and used. The Skylab station and Soviet Salyut stations were single module space stations. Mir was the first modular space station.

The International Space Station is a modular space station with a truss backbone that offers the following advantages:

- Truss structures can be erected or automatically deployed to create larger structures. Elements can be launched from Earth in segments and in compact packages.
- Elements can be designed and adapted for a wide variety of configuration requirements.
- They provide multipurpose element attachment and configuration possibilities.

Different module construction approaches present advantages and limitations that must be considered within the context of mission objectives as well as mission constraints. Example considerations include the following:

- Volume and mass constraints are imposed by (available or planned) launch vehicles, orbital transfer and orbital entry systems, and surface landing/deployment capabilities.
- Interfaces are required for orbital rendezvous/docking of modules and possible transfer/landing of elements using automated expeditious means.
- Volume and equipment integration features (of different approaches) influence functional utilization.
- Deployment requirements (labor, equipment and time) to realize operational capabilities vary.
- Accommodations for emergency egress, outside viewing, EVA operations, and other external connections.
- Configurability for orbital or surface operations and evolutionary growth.

Table 5.13 Design parameters for orbital, planetary, and mobile habitats: a comparison (modified and adapted from the source: Cohen 1996)

Design parameter	Orbital habitat	Planetary habitat	Mobile habitat
Radiation shielding	Water is possible, but must be launched from Earth	In situ resources can be used for radiation shielding (Lunar and Martian regolith). It can be attached externally to the habitat or elements can be printed	Mass of shielding material is relevant
Pressure ports	Ports can be at distal axial ends	Ports with dust control are necessary	Ports with dust control are necessary
EVA airlock	May incorporate an airlock and zero gravity optimized suits	Can be landed separately and assembled on the surface	Inflatable airlock is a possibility
Countermeasures against micro gravity	Diverse types of exercise equipment required, countermeasures such as a small diameter, human-powered centrifuge	Less important in the 0.38G on Mars and 0.6G on the Moon, more spatial solutions are possible (on the surface). Exercise equipment needed	Less important for mobile habitat if mission duration is limited
Gravity orientation	Has to be optimized for 0G operations	Has to be optimized for partial G operations	Has to be optimized for partial G operations
Life support	Physical/chemical closed loop system with possible plant-growth unit	Physical/chemical system that includes local resources with CELSS component. Water can be extracted from the Mars CO_2 atmosphere through the Sabatier process. A large greenhouse is possible	Physical/chemical systems that can be connected to the 'main' habitation system. A small portable greenhouse is optional
Power systems	Solar panels, batteries	Solarfields with solar panels, batteries, possibly nuclear power generators	Solar cells and batteries (volume and mass)
Other	Interior orientation and navigation cues	Dust control and clean rooms	Mobility system, motor, and mechanism

Table 5.14 Different approaches to habitat design (modified from the source: Howe et al. 2010) (PM—Pressurized Module)

	ISS	Mir	Skylab
Advantages	PM-backbone structure ensures early operational capabilities Truss backbone architecture in US Orbital Segment allows higher electrical power and heat rejection performance Operational redundancy between Russian Orbital Segment and US Orbital Segment Many PMs aligned with the flight path direction (microgravity) Dual egress and redundant access for some US and Russian modules	Highly flexible in configuration Compact configuration allows for different flight modes, including gravity gradient Good growth potential	Single launch system Large pressurized volume (largest diameter) Significant reuse of flight-proven Apollo hardware Low-cost and low-risk design
Disadvantages	No gravity gradient stabilization Mass distribution leads to significant pitch deviations from local horizontal Solar array location leads to cyclic aerodynamic torque	Strong limitations for electric power (body-mounted collectors) Restricted space for external payloads	No reboost capability Limited (<1 year) operational lifetime Single payload complement (launched with Skylab)

In general, a space station's configuration, orientation, and orbital flight mode (including outside viewing capabilities) have critical impacts on planning and design options. The following must be considered[9]:

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

[9]Further Reading: SICSA lecture series: http://www.uh.edu/sicsa/library/media.

- Reducing hazard risks posed by space debris in LEO through configuration design and pointing.

5.4.2.1 Example: The International Space Station

The International Space Station (Fig. 5.6) is the largest space station ever built. It has been inhabited since 1998. "*This high-flying international laboratory is packed with some of the most technologically sophisticated facilities that can support a wide range of scientific inquiry in biology, human physiology, physical and materials sciences, and Earth and space science*." (NASA [ISS] 2010, p. 15)

Detailed online information can be found at:
Reference Guide to the International Space Station: Assembly Complete Edition by NASA [ISS] (2010):
https://www.nasa.gov/pdf/508318main_ISS_ref_guide_nov2010.pdf
International Space Station: Architecture beyond Earth by David Nixon (Circa Press 2015):
http://circapress.net/titles/international-space-station
NASA's interactive web site for the ISS: http://www.nasa.gov/mission_pages/station/main/index.html

5.4.2.2 Example: The Chinese Space Station

The Chinese space station is a modular space station. Precursor stations include the Tiangong 1. The Chinese space laboratory (Tiangong 2) and the space station (Tiangong 3) are scheduled.

Detailed online information about China's Shenzhou space program and its space station can be found at:

http://www.xinhuanet.com

5.4.3 Planetary Habitats

Surface habitat module design, dimensions, and orientations comply with the constraints of the selected launch vehicle, orbital assembly and transfer, landing strategy, and surface transportation and deployment. Transportation payload envelope and mass limitations are major drivers of critical design requirements. The only off-Earth planetary habitat that was built and used is the Lunar Module during the Apollo missions. The Lunar Module provided space for two astronauts and had a habitable volume of about 6.6 m^3. Launch vehicles were the Saturn IB and Saturn V. The longest mission included a surface stay of 12 days and 17 h (Apollo 15).

A planetary habitation design needs interfaces with transport and landing vehicles, as well as an EVA access determined by the elevation of module interior entrance levels. Modules need a stable footprint and a design with a center-of-gravity for landing and surface relocations. The size, design, and configuration of the modules determine a variety of utilization and operational consequences, such as interior habitable volume and its spatial and functional optimization (refer to Human Activities and Social Interaction Design in Sect. 4.4).

Educational examples for surface settlements can be found in Chap. 2.

5.4.3.1 Example: Lunar Module Apollo

Apollo's architectural elements consisted of:

Command module (CM) consisted of the in-flight crew quarters and flight control section;

Service module (SM) provided the propulsion and spacecraft support systems;

Lunar module (LM) delivered two crew members to the lunar surface, supported them on the Moon, and returned them to the combined Command and Service Module (CSM) in lunar orbit (Fig. 5.18).

Lunar Rover for surface operations was integrated with the Apollo 15 mission.

Detailed online information about the Apollo Missions and its architecture can be found at:

http://www.nasa.gov/mission_pages/apollo/missions/index.html

5.4.3.2 Example: 3D Printed Habitat

An industrial team including architects Foster + Partners and the Italian space company Alta SpA, together with ESA, proposed to build structures for lunar bases using 3D printing technology. A pressurized inflatable would form the primary structure for the habitation dome. Building blocks made from 3-D printed lunar soil cover the structure and shield against micrometeoroids and radiation (Fig. 5.19). The lunar poles offer the most convenient place for construction, due to its moderate temperatures for the production (printing) process.

Detailed online information can be found at:

The website of Foster + Partners: http://www.fosterandpartners.com

The ESA website about Lunar 3D Printing:

http://www.esa.int/Highlights/Lunar_3D_printing

5.4.4 *Surface Vehicles and Mobile Habitats*

Surface vehicles and mobile habitats expand the mobility of scientific activities and are necessary for surface operations as well as for crew safety. They enable expanded scientific exploration, maintenance operations of surface elements, and safe transportation to and from landing and ascension sites.

Fig. 5.18 This fish-eye camera lens view of the interior of the Apollo lunar module mission simulator at the Kennedy Space Center is one of several selected by the Apollo 9 crew to appear in *Apollo: Through the Eyes of Astronauts*. The book features images from the Apollo program that were selected by the crew of each mission. In the foreground is mission commander James McDivitt; in background is Russell Schweickart, lunar module pilot (NASA)

Fig. 5.19 Multi-dome lunar base being constructed, based on the 3D printing concept. Once assembled, the inflated domes are covered with a layer of 3D-printed lunar regolith by robots to help protect the occupants against space radiation and micrometeoroids (ESA/Foster + Partners)

The first mobile vehicle transporting a human on an extra-terrestrial body was the Lunar Roving Vehicle (1971). Other surface vehicles that have been built and used are the Lunokhod, Spirit and Opportunity Mars rovers, and the Curiosity rover, where only the Apollo rovers could carry humans.

Surface vehicles that are being developed include the Athlete concept (Constellation program) and NASA's Mars Pressurized rover.[10] See also DRATS.

An early example of a mobile habitat that would combine functions of an exploration vehicle with a pressurized habitat was explored in the USSR in 1960–70s. A long-term Moon base "Zvezda" (or DLB) project was developed in the USSR's Barmin Design Bureau between 1965 and 1980. This proposal included stationary modules together with an expedition train that contained a movable habitat and a pressurized heavy rover/lab.

Advantages of a mobile habitat include the following:

- Mobility to move landers and habitation modules from the landing zone (Safety).
- Mobility to move landers and habitation modules even long distances (Science and Exploration).
- Mobile habitats can perform functions to reduce astronaut EVA time such as excavation, drilling, and sampling.

5.4.4.1 Example: The Lunar Roving Vehicle

The LRV (Fig. 5.20) was a deployable, electric, four-wheel vehicle and was used during the Apollo missions: 15, 16, and 17. It was specially designed to operate under the low-gravity conditions of the Moon and to support the required mobility on the surface. The Lunar Rover was folded and stored in one of the triangle-shaped bays with the underside of the chassis facing out. On the lunar surface, it had to be deployed by the astronauts themselves (Badescu 2012, Chap. 20, pp. 465–466).

The deployed rover on the lunar surface was 3.1 m long and 1.8 m wide. When packaged, it was about 1.5 m by 0.5 m. The wheels were made of aluminium wire mesh. The foldable seats were made from aluminum and fabric covers.[11]

5.4.4.2 Example: The Lunar Electric Rover (LER)

NASA's pressurized rover is designed to assist the crew in a 'shirt-sleeve' environment with the surface exploration (including EVAs) on the surface of the Moon and Mars. It is 4.5 m long with a height of 3 m, and weighs about 3 t, with an additional payload capacity of 1 t. The rover interior volume provides enough space

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[10] http://www.nasa.gov/feature/nasas-exploration-plans-include-living-off-the-land/.

[11] Further Research: Young, A.: Lunar and Planetary Rovers. The Wheels of Apollo and the Quest for Mars. Springer-Praxis Books, Heidelberg (2007).

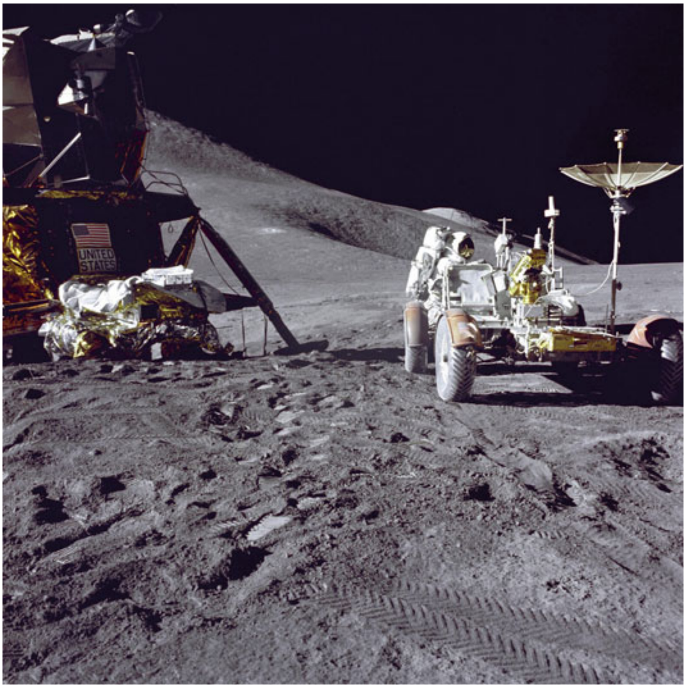

Fig. 5.20 Apollo 15 crew on the surface of the Moon (NASA)

for two astronauts to live and work relatively comfortably for about two weeks. In an emergency, it can support a crew of four. The rover also accommodates basic science lab needs. The structural design of the rover incorporates connecting interface for docking with a surface habitat, two suitports and a robust chassis system attuned to uneven and rocky terrain (please see Marc M. Cohen's statement in Chap. 3). The LERs can also serve as private "staterooms" in connection with habitats.

The concept has been further developed for the Space Exploration Vehicle, which is a modular multi-mission vehicle. The SEV consists of a pressurized cabin (Fig. 5.21) and a chassis, which can be a rover (for Moon or Mars missions) or a platform for orbital uses (Fig. 5.22).

Detailed online information can be found at:

http://www.nasa.gov/pdf/464826main_SEV_Concept_FactSheet.pdf

5.4.4.3 Example: The Athlete Vehicle Concept

The Constellation outpost concept consisted of elements assembled from multiple launches, a so-called Class II construction. Once the lander has reached the lunar surface, an 'All-Terrain Hex-Limbed Extra-Terrestrial Explorer' mobility system, called 'Athlete', is used to offload, assemble and construct the outpost.

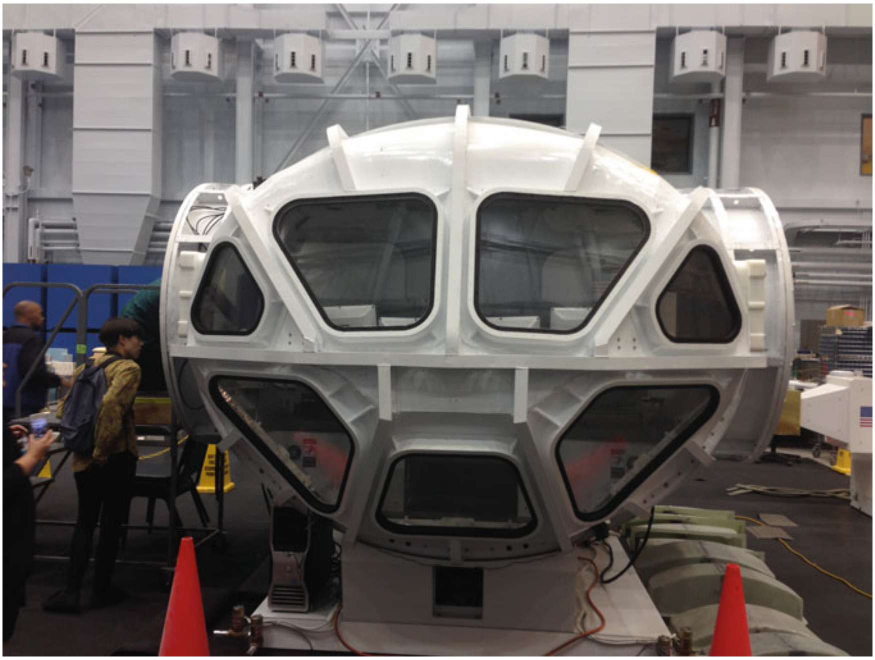

Fig. 5.21 Prototype of the Mars pressurized rover

Fig. 5.22 Tri-ATHLETE with a Hab module on the top (NASA)

Fig. 5.23 Two rover prototypes docked to the Habitat Demonstration Unit, next to the Athlete vehicle (NASA)

Currently NASA has based their mobile habitat concepts on the ATHLETE vehicle concept—the All-Terrain Hex Limbed Extra-Terrestrial Explorer' (Fig. 5.22)—that has been developed for the Constellation Program. This kind of habitat presents "… *a new approach to unloading, transporting, and handling cargo on the Moon* ..." (NASA [Athlete] 2010) and has a number of advantages compared to a stationary base.[12]

Figure 5.23 shows the following demonstration of NASA hardware: Space Exploration Vehicles; Habitat Demonstration Unit/Pressurized Excursion Module—a simulated habitat where the rovers dock to allow the crew room to perform experiments; Tri-ATHLETEs, or 'Terrain Hex-Legged Extra-Terrestrial Explorer'—two heavy-lift rover platforms that robotically move large cargo (such as the habitat).

5.4.5 The Space Suit

A space suit can be considered to be the smallest habitation module that provides adequate life support during EVA operations through an incorporated PLS (see Glossary) system. Such a suit is required for extra-vehicular activities.

Currently three different space suits are used: the Russian Orlan suit (Fig. 5.24a), the US spacesuit that cosmonauts and astronauts are using on the ISS, and the Chinese Feitian suit.

[12]Further Research on the Athlete concept: https://www-robotics.jpl.nasa.gov/systems/systemVideo.cfm?System=11&Video=140.

(a) (b)

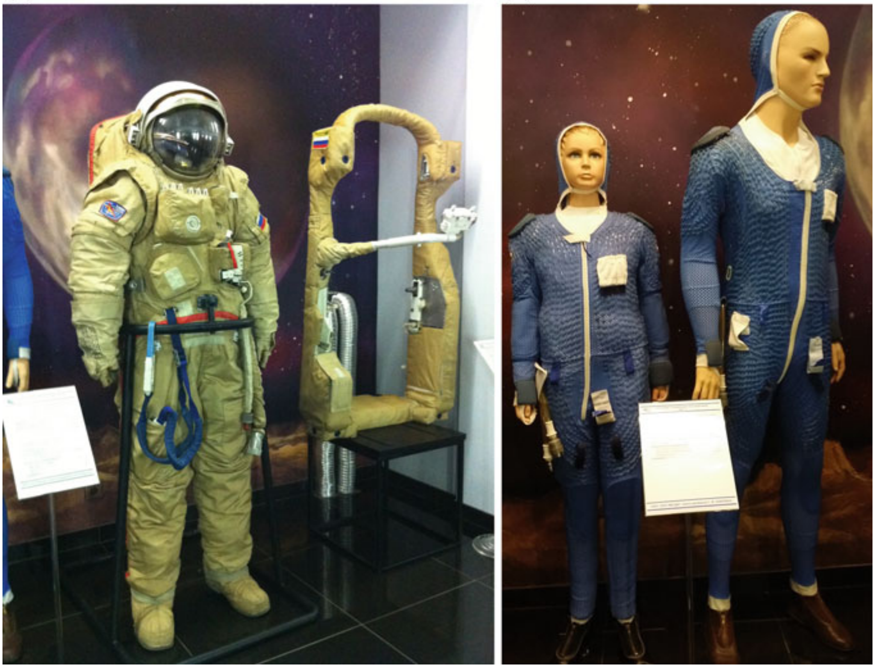

Fig. 5.24 **a** Russian spacesuit "Orlan-DMA" 18. **b** Under suit with thermoregulation system KVO-9 developed by NPP Zvezda

Space suits for Mars are under development and have different requirements. The Z-series-suits are semi-rigid and designed for a wider variety of purposes. It will offer surface capability as well as an interface for suit ports. NASA's Z-2 suit is the newest prototype and is shown in Fig. 5.25.

Issues that must be considered when designing a suit include:

- Environment (gravity, temperature, dust, radiation, pressure, etc.)
- Operational aspects (donning/doffing, cleaning, etc.)
- Interfaces (suitport, rover)
- Gloves and joints require special attention
- Thermal control and recently, avoiding water buildup

5.4.6 Airlocks and Extra-Vehicular Activities

Due to environmental conditions, an additional element is required for entering, exiting, or traversing between (1) pressurized modules, (2) pressurized vehicles, and (3) the surrounding environment. An airlock element serves these purposes.

Fig. 5.25 Prototype of the Z-2 spacesuit, intended for Mars exploration (NASA)

An **Airlock (AL)** minimizes exchange of air or other particles between different environments and is usually an independent pressure vessel that is connected to a habitat and has one hatch to the outside. A special form represents the concept of a deployable airlock, which was first used in 1965 during the Voskhod 2 mission (Fig. 5.26). The USSR demonstrated an inflatable airlock on its Voskhod-2 spacecraft in March, 1965. A miscalculation in the pressurized size of Alexi Leonov's EVA suit (which was difficult to foresee) made it very difficult to reenter the spacecraft through the airlock's small hatch.

A **Sample Airlock** is used to pass samples (e.g. rocks) from the outside to the inside, either by the astronauts on EVA or robotic arms. One of the great advantages of Sample Airlocks is to "… *operate experiments in space, with human interaction, without EVA*." (den Haak 1983, p. 49) The first airlocks to exchange material "*between two sealed doors*" (Cohen 2000, p. 11) were the Skylab Trash Airlock and the combined trash and scientific airlock on the MIR space station.

An **EVA airlock** allows space-suited astronauts to egress and reenter a pressurized module or vehicle. Another "… key question is whether the EVA airlock can double as the docking port between the mobile vehicle and the habitat." (Cohen, p. 13)

A **Suitport** (Fig. 5.27) could be used in combination with a rear-entry space suit. Astronauts "… *don and doff the suit through the suitport without needing to*

Fig. 5.26 **a** and **b** an inflatable airlock of Voskhod-2 spacecraft functioned well but the entry hatch was too small

decontaminate it each time" (Cohen 2000, p. 18). This concept was first proposed for NASA's lunar rover in 1993 by Wiliams. The suitport concept offers certain advantages for launch mass and volume restrictions and EVA function but pose some challenges for maintenance operations. New concepts have to be developed for the cleaning and maintenance of an attached suit, as these suits are placed "outside" and open to environmental impacts including dust collection. It is not convenient to un-dust and maintain the suits when such operations require an EVA or when a suit has to be brought inside a habitat or a rover. Such maintenance operations would expose the interior and the crew to environmental hazards.

Docking Pressure Ports connect pressurized modules and vehicles. Options that combine an EVA airlock and a docking port to connect a habitat with a vehicle have been discussed in technical reports and papers (Cohen 2010). Docking requires heavy equipment and devices that significantly increases launch mass. Combining docking functions with an airlock buys some mass and volume benefits but may complicate performing EVA's, since an airlock has to remain clear during EVA operations.

Fig. 5.27 Suitport mock-up located on a pressurized rover

5.4.7 Settlement Strategies

Eventually the goal of planetary surface exploration is to establish a permanent settlement that is independent of resupply. In particular, the following issues have to be considered when developing a settlement strategy:

- Ease of surface transportability and deployment
- Access/egress availability
- Configuration and evolution growth capacity
- Maintenance operability
- Power availability
- Research targets
- Resource availability

For future long-term missions, the design has to incorporate evolutionary site development. Geometric growth options are fundamentally determined by numbers and placements of interfaces between individual habitat elements, internal and external airlocks, and potentially, pressurized surface rovers. These interfaces determine surface geometry options, which, in turn, drive site development

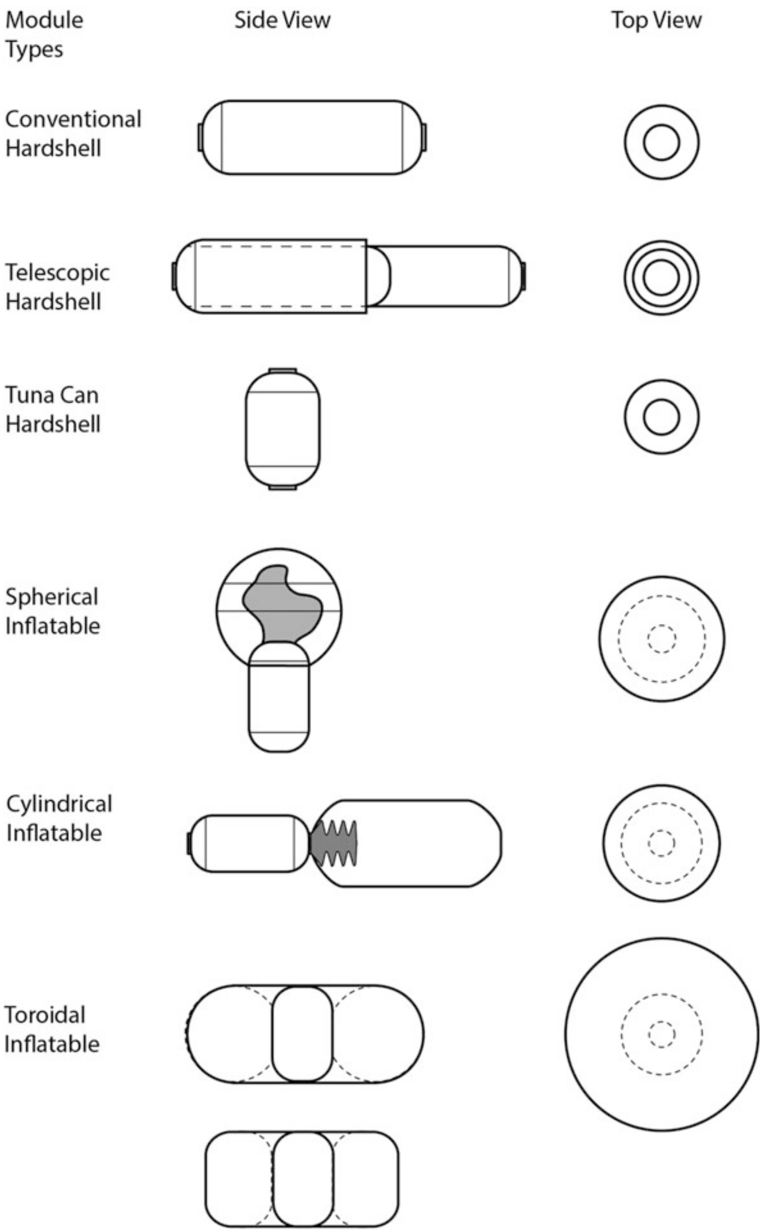

Fig. 5.28 Module shapes (authors)

strategies and establish dual egress crew safety characteristics. Different types of modules (Fig. 5.28) have to be compared and assessed in relation to those considerations.

If, for example, we compare horizontal conventional and telescopic forms with inflatable modules according to their '**Ease of surface transportability and deployment**' we may conclude that (Bannova 2007):

- Horizontal conventional modules require long carriers or wheel bases which may present difficulties on uneven/rocky surfaces.
- Horizontal telescopic modules may be similar to conventional modules but may also present deployment extension difficulties.
- Vertical conventional modules, in spite of their compact footprint, may be unstable on a rocky/hilly terrain during surface transportation.
- Vertical inflatable modules present a maneuverable, compact footprint but may still be unstable on uneven/rocky surfaces.

If we compare different types of modules according to their '**Configuration and Evolution growth capacity**' we may conclude that:

- Conventional horizontal modules can have attachment points varied according to requirements.
- Vertical modules have limited attachment possibilities and will require long transfer tunnels.
- End connections are standard for telescopic modules and axial connections can only occur at telescoping sections, which will reduce the module diameter in these areas.
- In vertically oriented inflatable modules, connections are limited to hard shell sections and will require long transfer tunnels (or additional hard modules).

Growth can occur in a variety of ways. Depending upon the habitat type (Fig. 5.28) additional modules can be added to existing ones or in situ resources can be used to expand the habitation layout. Module types as well as expansion concepts have to be compared in order to assess growth capacities and configuration opportunities for the anticipated mission.

5.4.7.1 Example: Triangular and Cruciform Layout

Although there are many geometric patterns that can be used for surface modules configurations, we use the triangular configuration and cruciform configuration as examples. The reference patterns presented in Figs. 5.29 and 5.30 show these geometric pattern approaches, both providing surface access/egress through suit-ports in the horizontal modules. Other shapes are presented in the Fig. 5.29 and can be compared on the same basis as the example used in this section.

The **triangular configuration** (Fig. 5.29) offers the following advantages and disadvantages:

- A very compact footprint around the inflatable module support bases minimizing site surface preparation requirements.
- Loop egress is achieved with three inflatable modules assembled together.

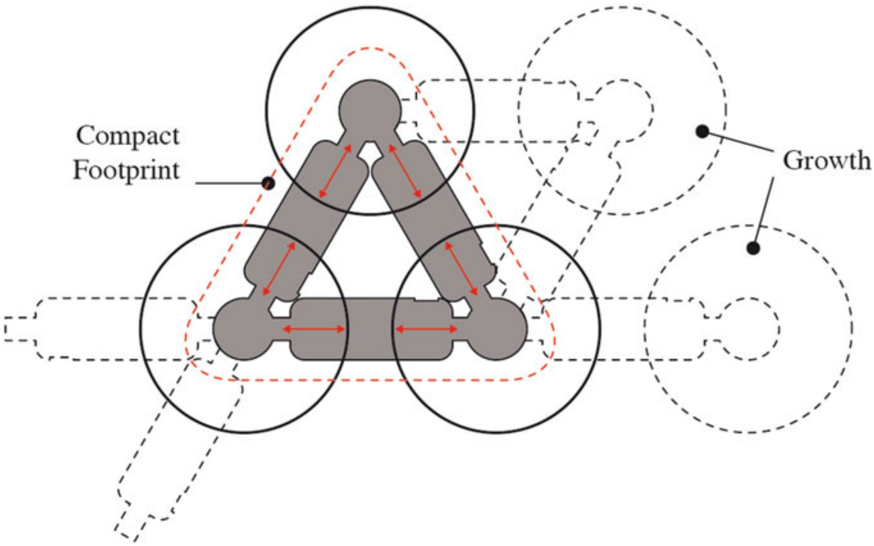

Fig. 5.29 Expansion scheme based on triangular configuration (Bannova 2007)

- This scheme may be more difficult to assemble and present limited variations.

The **cruciform** scheme (Fig. 5.30) also offers the following advantages and disadvantages:

- The deployment footprint around the horizontal module is quite small, limiting site preparation.
- The scheme can begin as a cruciform and evolve into a closed-loop plan.
- A dual egress (emergency) needs at least four modules.

If horizontal and vertical elements are combined with inflatable modules, the configuration can be optimized. Examples are as follows:

- EVA access/egress can be provided by suit ports in each horizontal module.
- The cruciform plan could later be expanded into a closed-loop racetrack.
- Inflatable modules increase crew living/working volume.
- All modules have direct connections for emergency egress.
- For module commonality this approach applies two module types, each with important functional support benefits.
- Configuration can extend linearly and possibly replicate.
- Has a small boundary for level site requirement.
- Does not impose a requirement for more than two modules/launches prior to operational configuration.
- Conventional modules with wheels are aligned to interface at a single point.
- Adjustable "feet" (module supports) for the leveling of two attached modules.

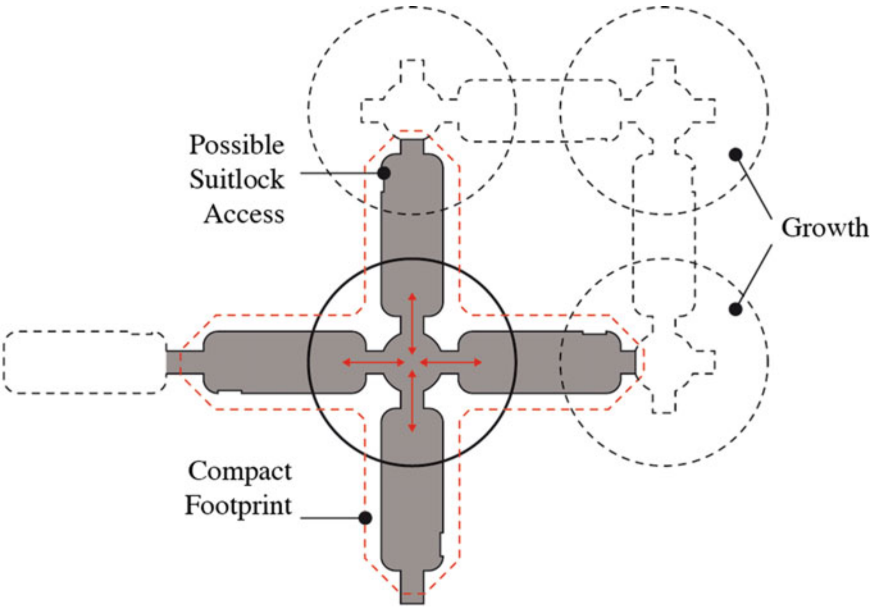

Fig. 5.30 Expansion scheme based on cruciform configuration (Bannova 2007)

5.4.7.2 Additional Required Infrastructure

In addition to habitation, other elements that correlate with each other are needed to support human health and mission success. Placement and sizing of each element depend upon the dedicated environment, mission length, launch and landing mass, and volume constraints, etc.

Infrastructure that is required to support large-scale human habitation and activity in space includes but is not limited to:

- Power supply and energy storage: Depending on power supply typology, infrastructure elements can be located in close proximity to a habitation element or in a safe distance in case the power sources are nuclear.
- Communication, control, and navigation systems have to have a high level of redundancy and may have to be located in multiple modules.
- Logistics modules have to be in close proximity to habitats and work modules and may be re-purposed after supplies are used (cf. Cargo Transfer Bags and Tanks).
- In situ resource utilization: such as 3D printing infrastructure for surface habitats.

Figure 5.31 shows NASA's concept of lunar settlement construction together with some infrastructural elements needed: photovoltaic infrastructure, the ATHLETE rover, and other surface machinery.

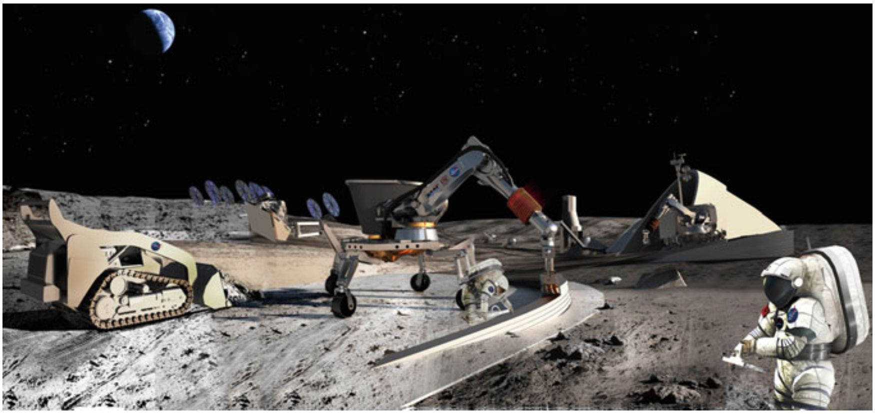

Fig. 5.31 NASA's concept of lunar settlement construction site (USC design project 'ISRU Based Robotic Construction Technologies for Lunar and Martian Infrastructure', Professors Behrokh Khoshnevis (Industrial Engineering), Anders Carlson (Architecture), Neil Leach (Architecture) and Madhu Thangavelu (Astronautics)) (NASA)

5.4.8 Discussion and Tasks

What are the differences between sortie missions and permanent settlements? Discuss the four classes of habitat design approaches and analyze the strengths and weaknesses of each. What do you think is critical for successful application of each of the described approaches and why?

5.5 Habitat Environmental Systems

Questions for Exploration
What defines a livable environment for people? What is needed to provide it for the crew during a spaceflight? Which systems are required and maintenance operations are needed?

5.5.1 Environmental Control and Life Support System

In human spaceflight, life support systems are vital for human survival. The most basic requirements for space architecture are to provide the crew with adequate environmental conditions and with the required metabolic consumables. The Environmental Control and Life Support System (ECLSS) supports humans with air, water, and food; controls interior air quality, temperature, and humidity; and balances waste products.

The minimum design requirements for space habitat environmental systems are to maintain a safe, comfortable environment, provide the crew with nutrition, and remove/recycle waste products. Critical issues for life sustaining systems include oxygen generation and CO_2 detecting and capturing systems, interior dust control, maintenance and housekeeping devices (Damon 1995).[13]

5.5.2 *Sustainability Principals and Waste Management*

Sustainability is a key term of our century, on Earth as well as beyond. Following the Brundtland Report from 1987, NASA's policy is "… to execute NASA's mission without compromising our planet's resources so that future generations can meet their needs." (NASA [Sustainability] 2014) Long-term sustainability is an important goal and requires to incorporate numerous issues, starting from conservation and recycling to maintenance, design, and construction. Enabling sustainability of a habitat in space or a surface of an extra-terrestrial body is essential for long-term space exploration missions. Accordingly, food production plus waste and life support management have to be planned and designed towards closed-loop systems.

5.5.2.1 Example: Life Support System on the ISS

The Environmental Control and Life Support System (ECLSS) of the International Space Station is a technical system consisting of various components located in the U.S. Destiny lab module and the Russian Zvezda service module that provide the habitable environment. The ECLSS (Fig. 5.32) consists of the following components: an air revitalization system, oxygen generating system, water coolant loop systems, atmosphere revitalizing pressure control system, active thermal control system, supply water and waste water system, waste collection system, temperature and humidity control, and fire detection and suppression system (NASA [ECLSS] 2008).

The main components of this interactive system are the Water Recovery System (WRS) and the Oxygen Generation System (OGS).

The **Water Recovery System** (Fig. 5.33) is designed "… *to recycle crewmember urine and wastewater for reuse as clean water. By doing so, the system*

[13]Further information: Advanced Life Support Baseline Values and Assumptions Document , August 2004 NASA/CR—2004–208941 (Anthony 2004).

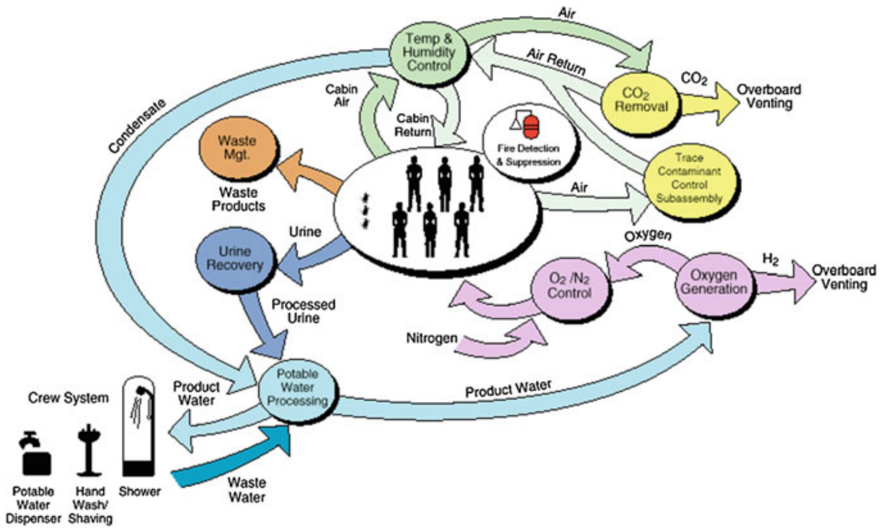

Fig. 5.32 This diagram shows the flow of recyclable ("regenerative") resources in the space station's environmental control and life support system (ECLSS) (NASA)

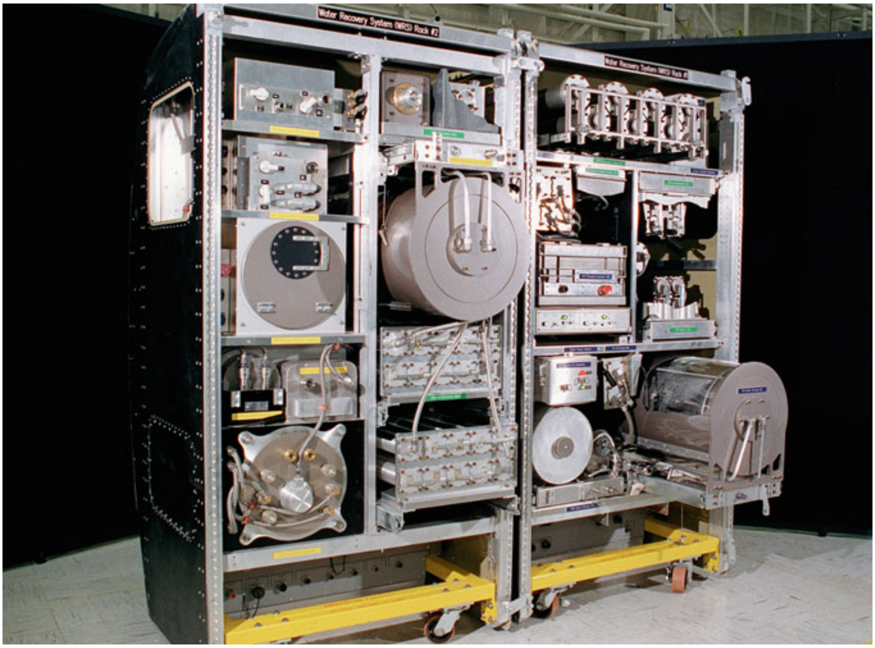

Fig. 5.33 Advanced water recovery systems of the international space station (NASA)

reduces the net mass of water and consumables that would need to be launched from Earth to support six crewmembers by 15,000 pounds (6800 kg) per year." (NASA [ECLSS] 2008)

The ISS ECLS System uses both physical and chemical processes to remove contaminants from unsanitary water, and to filter and sterilize the water before it is safe to drink. The water quality is also regularly tested to see if it meets NASA's water quality requirements and is examined for bacteria, pollutants, and proper pH (6.0–8.5).

Ideally, advanced water-processing systems require minimum power supply (up to no power required) for water recovery and purification. NASA's Exploration Life Support (ELS) Lab at Johnson Space Center in Houston is working on a biological treatment system that will refine water during future long space flights. Such system utilizes a purification process that uses microorganisms, which destroy contaminants in the water.

The **Oxygen Generation System** (OGS) is designed to supply the six-person crew with oxygen. The Oxygen Generator System converts water (wastewater, urine, and condensation) into hydrogen and oxygen (electrolysis). The Oxygen is released to the interior and the hydrogen is led to the Sabatier reactor (to create water).[14]

5.5.2.2 Example: Water Walls Life Support Architecture

The 'Water Walls Life Support Architecture' concept (Cohen 2014) is an alternative that is more efficient than the current approach used to design, build, and operate life support systems for a long duration space flight.[15]

The main goal is to achieve high reliability with increased redundancy through applying simple, inexpensive, and light components. Water Walls accomplish this goal by applying passive Forward Osmosis (FO)[16] membrane-based technology. The major advantage of using passive technology is simplicity, modularity, and low risk of mechanical failure. Water Walls Life Support Architecture offers radiation shielding capability in addition to its life support functions. All Water Walls materials have hydrogenous qualities and therefore are very effective radiation protection from highly ionizing atomic nuclei (including protons).

The key unit is the 'Forward Osmosis Bag' to perform the following life support functions: CO_2 removal and O_2 production; waste treatment for urine, wash water (gray water), and solid waste (black water); climate (temperature and humidity)

[14]More information on the Oxygen Generator System can be found in the Educator Edition of NASA: http://www.nasa.gov/pdf/570242main_OxygenGen_CHEM_ED.pdf.

[15]Further information on the Water Walls Life Support Architecture project can be found on the website of Astrotecture.

[16]Forward Osmosis is a natural process in which the osmotic potential between two fluids of differing solute/solvent concentrations equalizes by the movement of solvent from the less concentrated solution to the more concentrated solution.

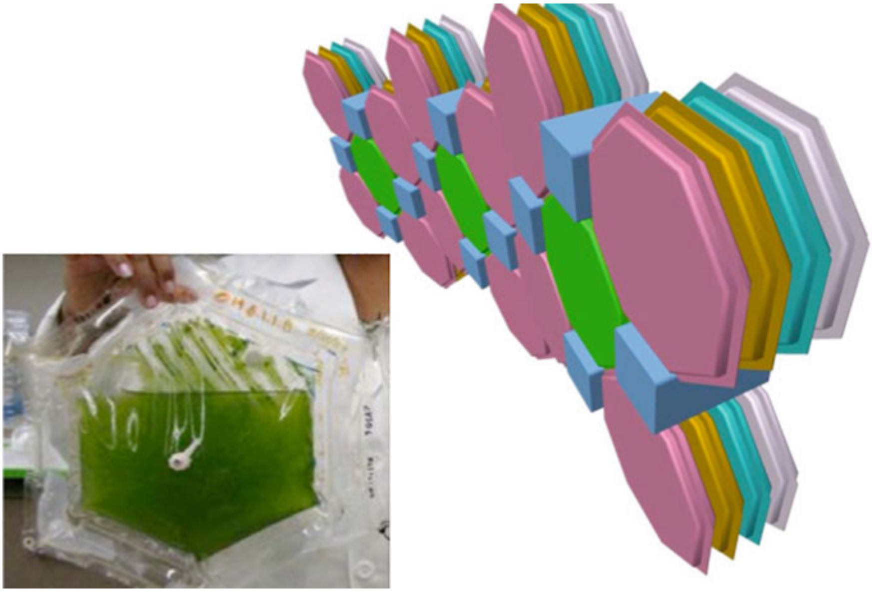

Fig. 5.34 Experimental Algae Bag with FO membrane Labyrinth (Astrotecture, Marc M. Cohen)

control, and contaminant control. An experimental Algae Growth Bag is shown in Fig. 5.34.

The algae growth containers come in a wide variety of materials, shapes, and sizes, but they all share the mandatory characteristics: Holding the algae in their aqueous environment, being translucent to admit light, and being ventilated to circulate air from which the algae can uptake carbon dioxide and can release oxygen. Used bags can be cleaned, refilled, and reused, or relocated to where their mass can add radiation shielding.

Key to designing the functional flow pattern of the operational matrix for the Water Walls module was to understand the chemistry of the system and its subsystems.[17] Figure 5.35 shows the design of the Functional Flow System the regenerative and closed-loop aspects.

"*The design process for the Water Walls Architecture involves an interaction and integration between the design of each process blocks and its subsystems and the design of the space habitat module in which it will be defined.*" This integration is shown in Fig. 5.36a, b.

The Water Walls concept can be adapted to habitats in pressurized modules of any shape, size, or dimensions.

[17]More information can be found in: Water Walls Life Support Architecture: System Overview by Marc M. Cohen, Renée L. Matossian, and Francois Lévy (ICES-2014-25), astrotecture.com.

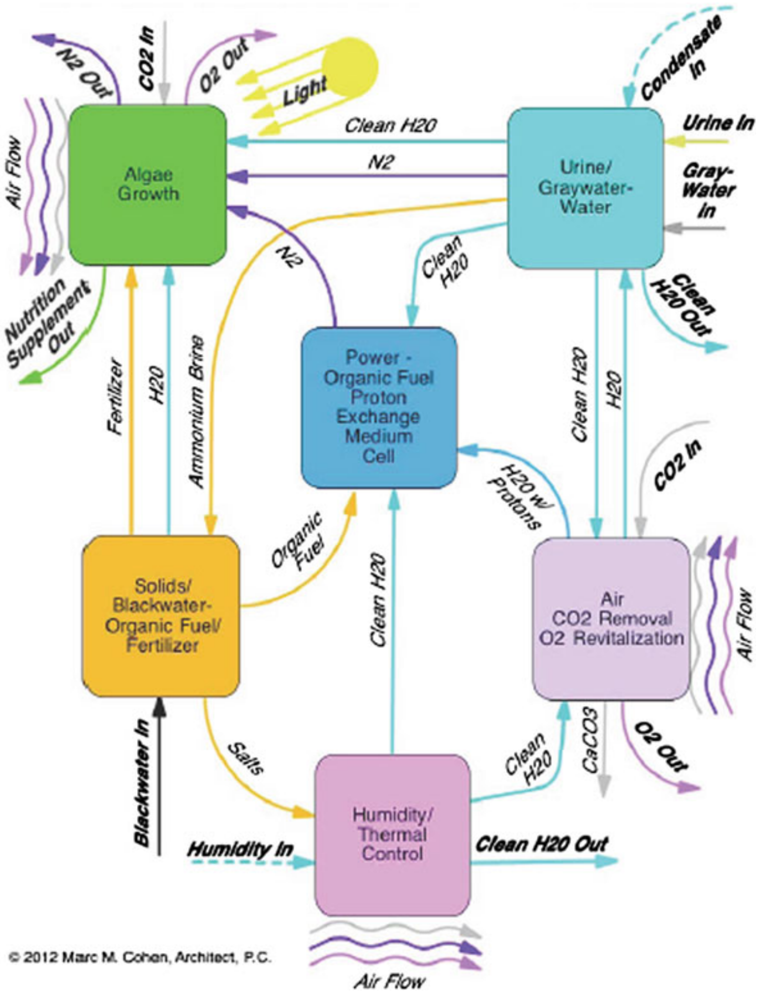

Fig. 5.35 Water walls functional flow life support system architecture. The four boxes at the corners represent four different configurations of forward osmosis bags. The box in the center represents the organic fuel cell that takes solid waste/black water and uses it to generate electricity (Astrotecture, Marc M. Cohen)

5.5.3 Greenhouses

Though the pioneers of space exploration had to survive on unpalatable food that came in tubes, astronauts today can select from an array of meals that are prepared on Earth and packaged carefully to prevent spoilage. Fresh fruits and vegetables are also sometimes available for the ISS, but they must be eaten quickly due to the lack of refrigeration systems.

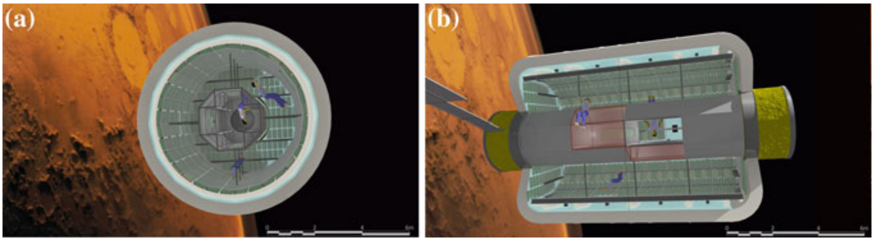

Fig. 5.36 **a** Transverse section through a Bigelow 330 (TransHab type) space habitat, showing two layers of water walls air revitalization bags installed around the inside perimeter of the cylindrical wall and the flat circular end walls of the inflatable pressure vessel. This view also shows the rigid center "axle" truss that serves as a circulation corridor and utility routing channel (François Lévy). **b** Longitudinal section through a Transhab-type module, showing the center functional core and water walls algae bags installed around the perimeter of the habitable volume (François Lévy)

Greenhouses can supplement astronauts' diets. Depending upon the location, soil-based, hydroponic, or aeroponic systems can be used. Hydroponic and aeroponic systems are advantageous for on-board space craft systems because of their minimal weight, soil-based systems offer the advantage of using in situ resources on Moon and Mars.

Aside from nutritional and life support system applications, additional benefits include sensory and spatial enhancement of the spacecraft environment, both through the plants as such and the design of their growth chambers, as well as by providing meaningful occupation through individual interaction. Examples are the psychological positive aspects of plants on crewmembers, no matter whether highly structured activities as part of experiments, or just for personal interest and health and their enhancement of the habitat (Häuplik-Meusburger et al. 2014). In view of long duration missions, plant growth facilities should not be regarded as a desirable add-on, but as an essential component of the habitat (Table 5.15).

5.5.3.1 Example: Greenhouses Used on Salyut and Mir

Experiments on growing different types of plants were conducted on Salyuts and Mir stations in 1970s, 80s and 90s (Fig. 5.37a–d). Main research objectives included to grow plants to blooming stage, producing seeds and planting seeds to grow second crop production in micro gravity conditions. Biomedical experiments helped to gain knowledge about effects of microgravity on plants cells and growth potential and identify possible ways to build a sustainable habitat with incorporated greenhouse that would support life during long duration space missions.

Table 5.15 Overview of Greenhouse facilities used in space stations (as published in Häuplik-Meusburger et al. 2014)

Small plant growth facilities onboard SALYUT (1, 4, 6, 7) and MIR	Small plant growth facilities onboard STS and ISS
Oasis 1 (Salyut 1): first plant growth system Oasis 1M (Salyut 4): improved water metering system Oasis 1AM (Salyut 6): designed for long duration missions Oasis 1A (Salyut 7): advanced lighting system Malachite (Salyut 6): ornamental plant culture system to provide psychological comfort Fiton (Salyut 6): greenhouse for onions and radishes Svetoblock (Salyut 6): plant system that could be mounted to a light in the cabin Svetoblock-M (Mir) Svetoblock-S Svetoblock-G Svet (Mir): first joint Russian-US experiment Magnetogravistat (Salyut 7, Mir): greenhouse for wheat and flax Biogravistat (Salyut 7): greenhouse for lettuce Vazon (Salyut 6, 7 and Mir): system for the cultivation of bulbous plants without artificial lighting Phyton (Salyut 7): miniature growths system, first seed to flower produced on orbit	Plant growth unit—PGU (STS): plant growth unit that fitted into a mid-deck locker on the Space Shuttle Plant growth facility—PGF (STS): improved lighting and control system Astroculture system (STS, Mir): closed chamber Advanced astroculture system (ISS): student-designed experiment and commercial payload Plant generic bioprocessing apparatus—PGBA (STS): included fluorescent lighting Biomass production system—BPS (STS): developed for long duration missions LADA (ISS): modular type system MagISStra, Veggie and AstroGarden: as described below

5.5.3.2 Example: The LADA System

The LADA System (Fig. 5.38) is used on-board the International Space Station. It is a fully automated small greenhouse garden and was developed by the Space Dynamics Laboratory at Utah State University and the Institute of Biomedical Problems in Moscow. It has been used on-board the International Space Station (in the Zvezda module) since 2002. The system is about the size of a standard suitcase and includes a control module (24.1 × 17.8 × 24.1 cm).

5.5.4 *Power Systems and Constraints*

Reliable and maintainable power systems are vital elements of a spacecraft, surface habitat, or a settlement. They have to be included in overall design and planning, sized in accordance with habitat or settlement power requirements, and located with regard to crew safety and power supply efficiency (Table 5.16).

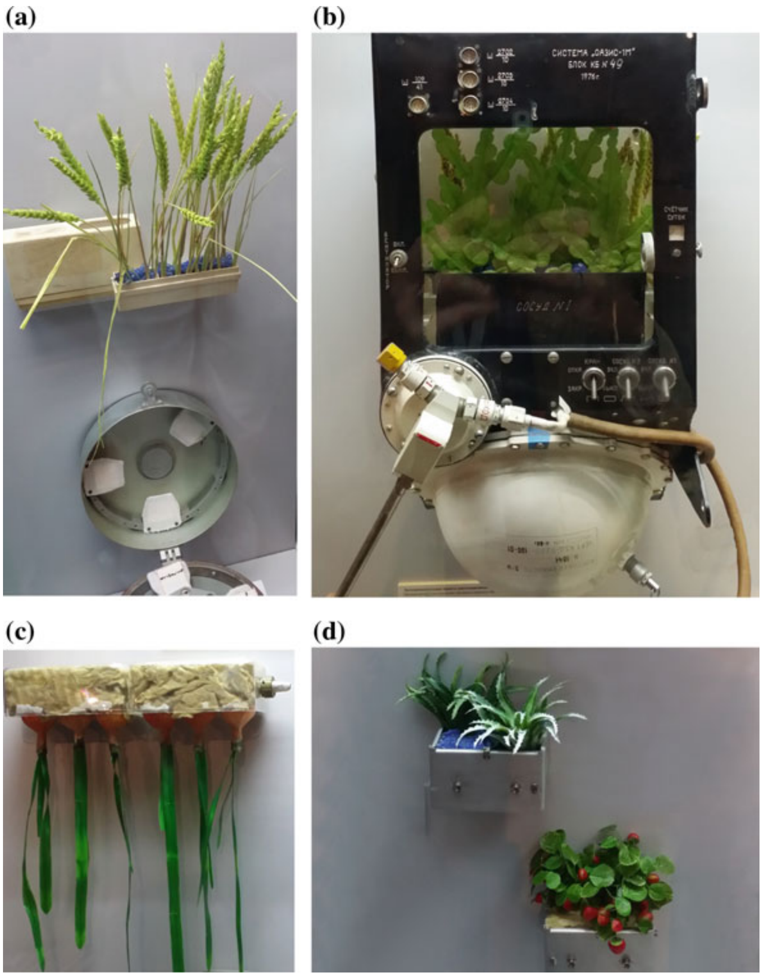

Fig. 5.37 **a**—System for wheat crops growing (Mir); **b**—system Oasis-1M (Salyut and Mir); **c**—onion growing unit (Salyut 7); **d**—strawberries and cactus growing unit (Salyut 7)

5.6 Summary: Types of Building Systems and Requirements

Tables 5.17, 5.18, 5.19, 5.20, 5.21 and 5.22[18] summarize types of building systems applications and their requirements, structures types, material considerations, structures technology drivers, and requirement definition and evaluation studies.

[18]From Haym Benaroya and Leonhard Bernold (Guest statement).

Fig. 5.38 View of Mizuna (Brassica rapa nipposinica) plant growth inside the LADA greenhouse. *Image* ISS021E030778 (NASA)

Table 5.16 Constraints and challenges for power systems

Environment	Constraints and challenges
Earth-orbit	Power system must withstand thermal cycling and be able to store energy (solar power) Exposure to atomic oxygen in low Earth orbits Exposure to the Earth's radiation belts for higher orbits
Lunar surface	353-h lunar night Dust High daytime temperatures
Mars	12.3 h night Variations in day/night cycle by season and latitude Atmospheric dust

Sources Larson and Pranke (1999, p. 646)

5.6.1 Discussion and Tasks

Discuss what resources are most valuable for short versus long missions and how they can be utilized. What is the most critical condition in space that requires the largest mass transportation? Select one of the potential resources on the Moon or Mars and propose at least 2 possible applications.

Table 5.17 Building systems: types of applications (Benaroya and Bernold 2008)

Types of applications		
Habitats	Storage facilities/shelters	Supporting infrastructure
People (living and working) agriculture Airlocks: ingress/egress Temporary storm shelters for emergencies and radiation Open volumes	Cryogenic (fuels and science) Hazardous materials General supplies Surface equipment storage Servicing and maintenance Temporary protective structures	Foundations/Roadbeds/Launch pads Communication towers and antennas Waste management/life support Power generation, conditioning and distribution Mobile systems Industrial processing facilities Conduits/Pipes

Table 5.18 Building systems: application requirements (Benaroya and Bernold 2008)

Application requirements		
Habitats	Storage facilities/shelters	Supporting infrastructure
Pressure containment Atmosphere composition/control Thermal control (active/passive) Acoustic control Radiation protection Meteoroid protection Integrated/Natural lighting Local waste management/recycling Airlocks with scrub areas Emergency systems Psychological/social factors	Refrigeration/Insulation/Cryogenic systems Pressurization/atmospheric control Thermal control (active/passive) Radiation protection Meteoroid protection Hazardous material containment Maintenance equipment/tools	All of the above Regenerative life support (physical/chemical and biological) Industrial waste management

Table 5.19 Building systems: types of structures (Benaroya and Bernold 2008)

Types of structures		
Habitats	Storage facilities/shelters	Supporting infrastructure
Landed self-contained structures Rigid modules (prefabricated/ in situ) Inflatable modules/membranes (prefabricated/in situ) Tunneling/coring Exploited caverns	Open tensile (tents/awning) “Tinker toy” Modules (rigid/inflatable) Trenches/underground Ceramic/masonry (arches/tubes) mobile Shells	Slabs (melts/compaction/additives) Trusses/frames All of the above

Table 5.20 Building systems: material considerations (Benaroya and Bernold 2008)

Material considerations		
Habitats	Operational suitability/economy	Safety
Shelf life/life cycle Resistance to space environment (UV/thermal/radiation/abrasion/vacuum) Resistance to fatigue (acoustic and machine vibration/pressurization/thermal) Resistance to acute stresses (launch loads/pressurization/impact) Resistance to penetration (meteoroids/mechanical impacts) Biological/chemical inertness Reparability (process/materials)	Availability (Lunar/planetary sources) Ease of production and use (labor/equipment/power/automation and robotics) Versatility (materials and related processes/equipment) Radiation/thermal shielding characteristics Meteoroid/debris shielding characteristics Acoustic properties launch weight/compactability (Earth sources) Transmission of visible light Pressurization leak resistance (permeability/bonding) Thermal and electrical properties (conductivity/specific heat)	Process operations (chemical/heat) Flammability/smoke/explosive potential Outgassing Toxicity

Table 5.21 Building systems: structure technology drivers (Benaroya and Bernold 2008)

Structures technology drivers	
Mission/application influences	General planning/design considerations
Mission objectives and size	Automation and robotics
Specific site—related conditions (resources/terrain features)	EVA time for assembly
Site preparation requirements (excavation/infrastructure)	Ease and safety of assembly (handling/connections)
Available equipment/tools (construction/maintenance)	Optimization of teleoperated/automated systems
Surface transportation/infrastructure	Influences of reduced gravity (anchorage/excavation/traction)
Crew size/specialization	Quality control and validation
Available power	Reliability/risk analysis
Priority given to use of lunar material and material processing	Optimization of in situ materials utilization
Evolutionary growth/reconfiguration requirements	Maintenance procedures/requirements
Resupply versus reuse strategies	Cost/availability of materials
	Flexibility for reconfiguration/expansion
	Utility interfaces (lines/structures)
	Emergency procedures/equipment
	Logistics (delivery of equipment/materials)
	Evolutionary system upgrades/change outs
	Tribology

Table 5.22 Building systems: requirements definition/evaluation (Benaroya and Bernold 2008)

Requirement definition/evaluation	
Requirement/option studies	Evaluation studies
Identify site implications (Lunar soil/geologic models)	Technology development requirements
Identify mission-driven requirements (function and purpose/staging of structures)	Cost/benefit models (early/long-term)
Identify conceptual options (site preparation/construction)	System design optimization/analysis
Identify evaluation criteria (costs/equipment/labor)	
Identify architectural program (human environmental needs)	

5.7 Guest Statement: Environmental Control and Life Support Systems, from Low Earth Orbit to Planetary Exploration (Lobascio Cesare)

5.7.1 The International Space Station Experience

Europe has provided a major contribution to the International Space Station (ISS), with permanent and logistics modules, totaling about half of the overall pressurized volume (Fig. 5.39). Each of those space modules include Environmental Control and Life Support Systems (ECLSSs) developed and integrated by European industry. As well, life science payloads have contributed to the development of know-how in life support technologies and systems. Since the early days, the

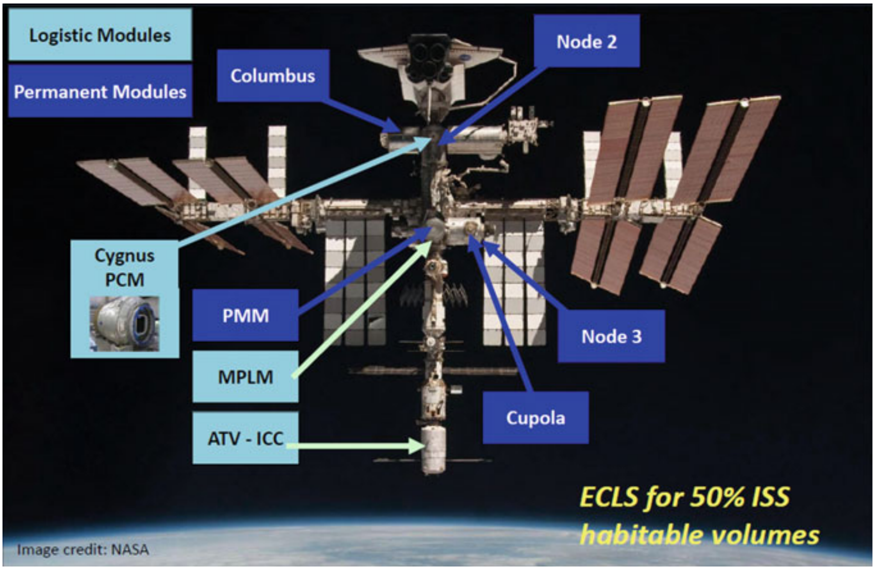

Fig. 5.39 European contributions to ISS and relevant ECLS (NASA)

primary involvement in the ISS Program has allowed mastering the design, development, assembly, integration, testing, ground and flight operations of ECLSS, with a continuous flow of experience and lessons learned in new programs.

In general, the ECLSS functions to be considered for any mission are related to controlling the environment and managing resources, with the following functional breakdown (Table 5.23).

The harsher the environmental conditions expected during a mission and the farther the source of resupply, the more complex and demanding the ECLSS will be. Ensuring a comfortable and productive human life in outer space pushes ECLSS to solve extreme design and development challenges. Absence of breathable air, extreme temperatures, modified gravity conditions, and ionizing radiation characterize the earth orbit and planetary environments. Not only do these aspects pose significant survival issues for human, animal, and plant life, but they also pose issues for the equipment operating under the burden of those environmental conditions.

The astronauts and equipment now on board the ISS rely on physico-chemical ECLSS. The ECLSS configuration for an ISS module can be quite complex and a real challenge for the architects and designers. Node 2, for example, relies on the core ISS for a subset of ECLSS functions, but the necessity to interconnect all adjacent modules dramatically increases the complexity of fluid systems configuration (Fig. 5.40). The lines are mainly routed via the so-called stand-off areas, so that the central cabin is free for crew activities.

Table 5.23 ECLS systems functional breakdown (ECSS-E-ST-34C 2008)

Maintain environment Control atmosphere total pressure and composition Control thermal comfort Control atmospheric humidity Circulate atmosphere Control airborne trace gases and odor Control airborne particulates Control micro-organisms Support ionizing radiation control	Maintain crew health Support first aid Support medical assistance on board Provide access to telemedicine services Provide medical equipment for diagnostics and treatment Provide drugs Provide means of sanitary evacuation Support gravity counter measures
Respond to environmental contingencies Respond to uncontrolled pressure changes Respond to fire Respond to radiation alarm Respond to hazardous atmosphere	Provide resources Provide dilutent atmospheric gas Provide oxygen for breathing Provide gases for specific usage Provide vacuum/venting Provide water Provide food
Manage waste Manage carbon dioxide Manage waste water Manage gas, solid, and concentrated liquid wastes	Support special operations Support extra-vehicular activity Support intra-vehicular activity

We are now mastering the conducting of environmental control operations, in terms of safely managing atmosphere pressure, composition, temperature, humidity, and contamination, under routine and contingency conditions. We know how to detect and suppress fire in microgravity.

In terms of resources, the US and Russian part of the ISS include regenerative life support systems for air and water regeneration. Node 3 hosts such technologies in dedicated racks. This reduces the amount of resources resupplied from Earth by means of the Automated Transfer Vehicle (ATV), for example. With the ATV program we have learned how to store and transport two different types of potable water safely for the astronauts. “Russian” water contains minerals such as Calcium and Magnesium, and is disinfected with Silver. “US” water has minimal minerals (less than 100 mg/l Total Dissolved Solids) and is disinfected with Iodine.

The ISS modules programs have taught us efficient ECLSS development. One of the keys to a successful ECLSS design and development is a clear and commonly agreed upon requirements baseline: program phase B aims at this major objective. This is also the phase in which a preliminary ECLSS architecture is devised, by trading-off different design solutions and performing preliminary analyses, to gain the confidence that the requirements can be met. During Phase C/D, the preliminary design conceived in Phase B is consolidated. Due to the criticality of resource management in space, mass, volume, power, and thermal budgets are established in early phases and are always maintained up to date. The main ECLSS analysis campaign activities typically include thermal and hydraulic analysis of fluid lines and loops, computational fluid dynamics analysis of ventilated cabins, fire

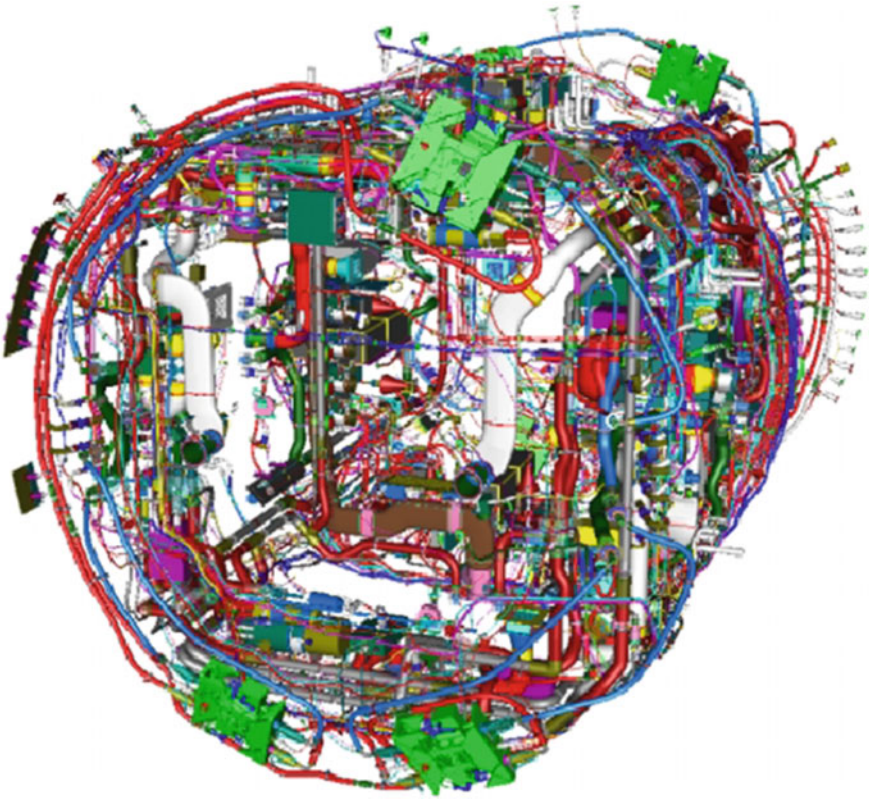

Fig. 5.40 Node 2 ECLSS and active thermal control system physical configuration, including air ducts, water, coolant, gas and trace gas sampling lines. The complexity is driven by the need to interconnect 6 adjacent modules (Thales Alenia Space—Italia)

suppressant distribution in fire compartments, and gas delivery. Indoor air quality issues relevant to trace gas, particulate and microbial contamination are tackled, employing not only the active means of ventilation and removal, but also relying on a strict selection of materials. In this respect, the designer can select, from very extensive on-line databases, materials with low off gassing release that will not support fungus growth. Typical ECLSS tests at the integrated system level include cabin ventilation, hydraulic balancing, and module off-gassing tests.

Mastering environmental control is a key for future space exploration endeavors, and with the ISS in the operational phase until 2024 we will have more lessons to learn and opportunities to exploit it as a test bed for technological developments.

5.7.2 The Challenges of Life Support for Planetary Exploration

The future is even more challenging if we consider the amount of resources necessary for sustaining human life. Figure 5.41 illustrates the typical figures for oxygen, water, and food, where about 5 kg per person per day is considered the “bare minimum” (text in red), and a pretty good reference for ISS or transfer vehicle nominal conditions. For a surface base, water demand will increase, mainly due to the presence of a shower, a commodity not present—and found quite unpractical—on orbiting stations, and clothes/dish washers, which would reduce resupply of clothing and dishware. The resulting 5.5 tons per person year deserve the attention of mission planners, giving rise to engineering tradeoffs on storage versus regenerative systems, often referred to as “open loop” and “closed loop”.

In reality the degree of “closure”, i.e. the capability and efficiency in regenerating resources, and the resulting need of resupply, must be defined on a case by case basis. Regenerative life support systems will thus differ in their architecture, technologies, and complexity depending on multiple factors, including crew size, mission duration, crew-hosting element, and mission phase under consideration. Performing such tradeoffs is a very complex design and simulation activity, requiring the definition of agreed-to metrics for performing the comparisons, dedicated models, and a set of design data for elements of the architecture which are often difficult to obtain and predict, since they might refer to technologies not yet mature or available.

The tradeoff involves system architecture elements other than the ECLSS, such as ISRU, structures, and power generation, thus extending this necessary exercise to the whole system. For example, if water will be employed for radiation protection, in particular in a crew transportation vehicle, this will affect the quantity stored and

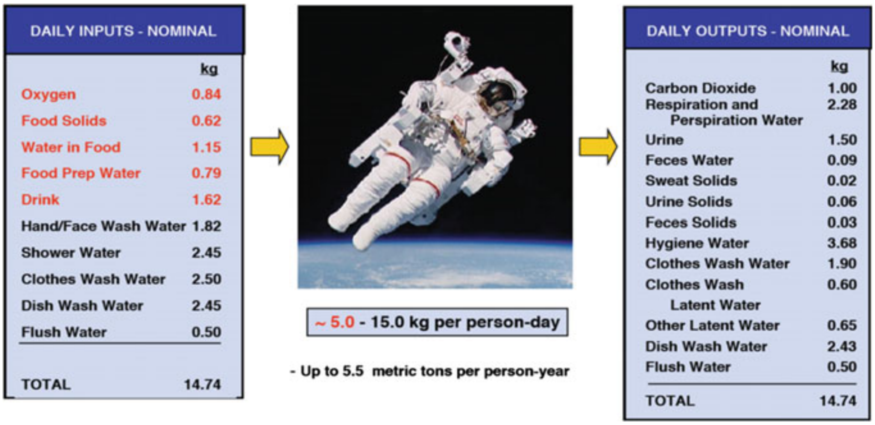

Fig. 5.41 Daily input/output life support resources for first order sizing (NASA). For complete data refer to Table 5.18

treatment technology. On Mars surface, CO_2 and N_2 could be extracted from the atmosphere, and water from soil, with evident benefits to be traded off with system complexity, and requiring the development of enabling ISRU technologies which today are at a very low TRL. When planning potential food crop production, a crucial point is energy: we need to compare natural versus artificial illumination, where natural light means adopting transparent materials, or transporting light inside with solar collectors or fiber optics, and artificial light can be obtained via many different kinds of light sources at different efficiencies…. This will have an impact on the power production system, be it solar or nuclear.

Another major factor involves systems reliability and logistics burden, with the need to define redundancies, predict components' failure rates, and thus the necessary number of spare parts and consumables (e.g. filters). For a future sustainable Mars planetary colony, the resupply of spare parts over several years will prove to be a key limiting factor, which could be mitigated by fabricating spares in situ, e.g. via additive manufacturing technologies, which today is at a very low TRL.

References such as the BVAD [2] can be of great help in retrieving necessary data for the engineering tradeoffs. The comparison of different ECLSS architectures, at increasing degrees of resources regeneration, aims at minimizing the cumulative mass (or Equivalent System Mass ESM) at launch and, depending on the launcher's capacity, the number of launches. Representing this as a function of mission duration, as qualitatively shown in Fig. 5.42, allows understanding the convenience of regenerative systems versus storage, open-loop systems and associated break-even points. Water regeneration via physico-chemical technologies is found to be the first convenient step, followed by oxygen recovery from CO_2. In fact the ISS itself hosts a complete suite of physico-chemical water and oxygen regeneration systems.

Food production will become convenient for long missions on the planetary surfaces, with higher plants providing fresh crops, O_2 regeneration from CO_2 thanks to photosynthesis, and water regeneration via leaf transpiration, as shown in Fig. 5.43.

Regeneration of organic waste from humans and inedible plants biomass into nutrients for the crops is under development for example in the bio-regenerative

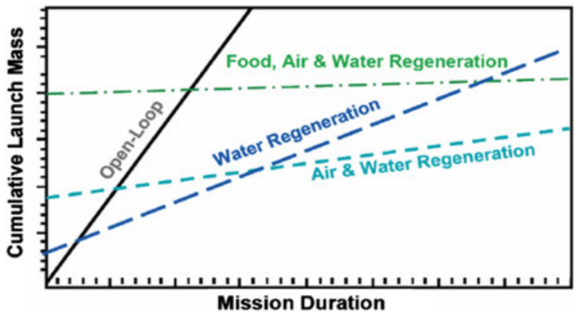

Fig. 5.42 Cumulative launch mass versus mission duration —qualitative comparison of regenerative systems (NASA)

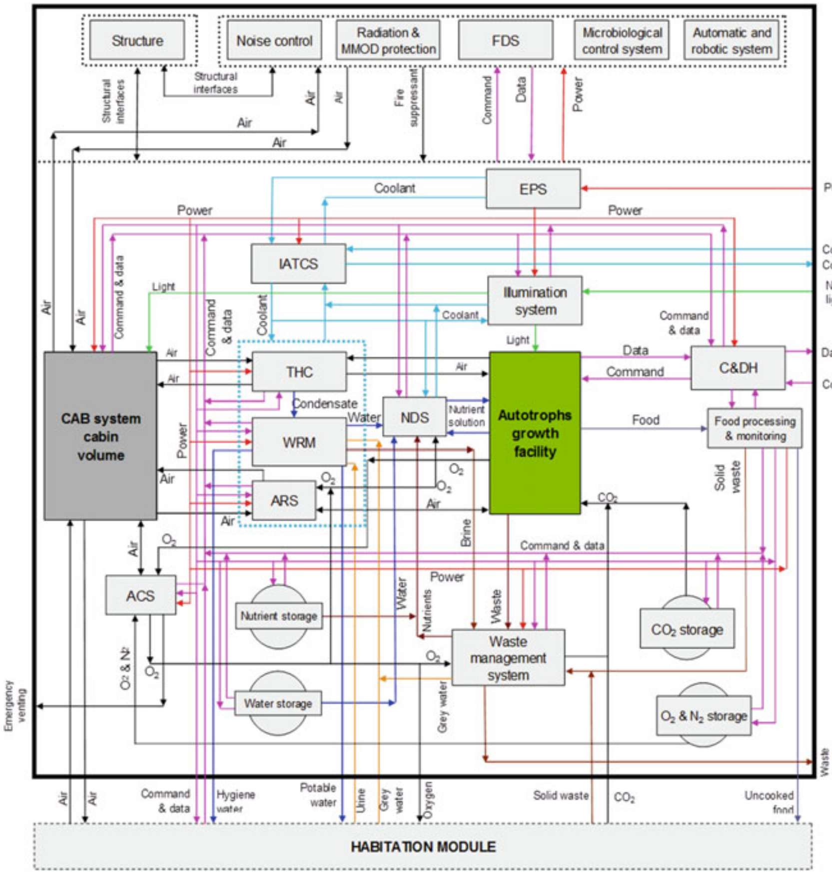

Fig. 5.43 Architecture of a plant-based regenerative system, as studied in the CAB (Controllo Ambientale Biorigenerativo) project (*Credit* Thales Alenia Space—Italia)

MELiSSA concept[19]: in such "ecological" systems micro-organisms hosted in dedicated bioreactors play a key role towards closure of Carbon and Nitrogen cycles.

In conclusion, together with radiation protection, the regeneration of life support resources and the ability of "living off the land" via ISRU can be considered key factors enabling long-term human planetary exploration. For the necessary technological developments anticipated above, exploiting the ISS and analogue environments can be of great value.

[19]Micro-Ecological Life Support System Alternative (MELiSSA) http://www.esa.int/SPECIALS/Melissa/index.html.

5.8 Guest Statement: The TransHab Design and Development—Part 1 (Kriss J. Kennedy)

5.8.1 Background

The TransHab (Transit Habitat) concept came from a Mars transportation architecture study led by Dr. William Schneider in 1997 at NASA Johnson Space Center. I was part of the tiger team to develop a habitat that would be used with the Mars Interplanetary Transit Vehicle—the transit habitat. Thus it became known as the "TransHab" hence forth. Our small team was challenged to design a habitat large enough to support a crew of six on a 560–850 day transit mission to and from Mars, based on a short-stay-time (typically 30–60 days) at Mars, NASA Mars Design Reference Mission 5.0. It had to be launched in the Shuttle Orbiter payload bay—which has volume and mass constraints. With the feasibility study design concept we were tasked to rapidly prototype its development and proof-of-concept testing. The testing of the tensile fabric structure focused on surviving micrometeoroid and orbital debris impacts, proving structural pressure test to 4x atmospheres, and demonstrating the structure could be packaged and deployed in a cold vacuum. Once we accomplished these main objectives we were tasked to develop it as an alternative to the ISS aluminum shelled Habitat—thus the ISS TransHab version matured until the project cancellation in 2001.

5.8.2 Exploration Habitats

Space and planetary habitats are pressure vessels that provide the living quarters and support systems needed by human crews engaged in space exploration missions. Structural and materials research and technology development are 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 efforts are in advanced lightweight materials, in use of inflatable structure design techniques, and in techniques for providing protection from micrometeoroids, orbital debris, and ionizing radiation.

The goal of Exploration Habitats (XHabs) 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. Three phases of XHabs have been identified to provide focus on the development of habitats and related support activities (Fig. 5.44).

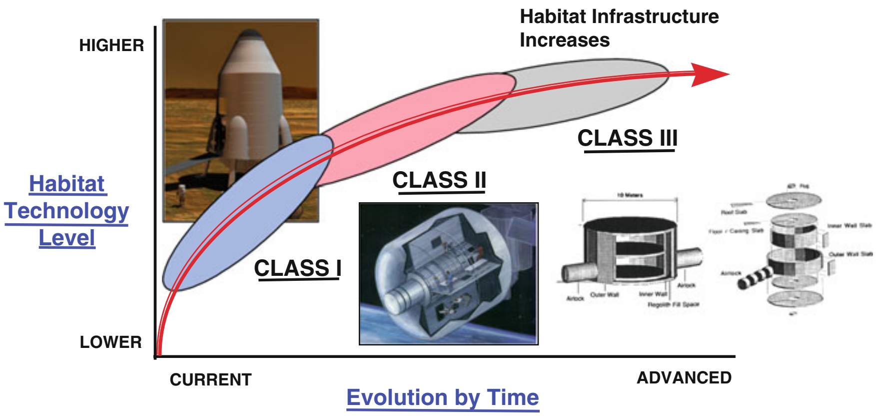

Fig. 5.44 Habitat classifications (NASA)

- CLASS I: Pre-integrated, Hard Shell Module
- CLASS II: Prefabricated, Destination Assembled
- CLASS III: In situ Resource Utilization (ISRU) Derived Structure w/Integrated Earth components

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

1. Provide technologies that significantly reduce life cycle costs and logistics reduction
2. Improve operational performance
3. Promote self-sufficiency
4. Minimize expenditure of resources for missions of long duration.

Specific goals are described in Figs. 5.45, 5.46, and 5.47.

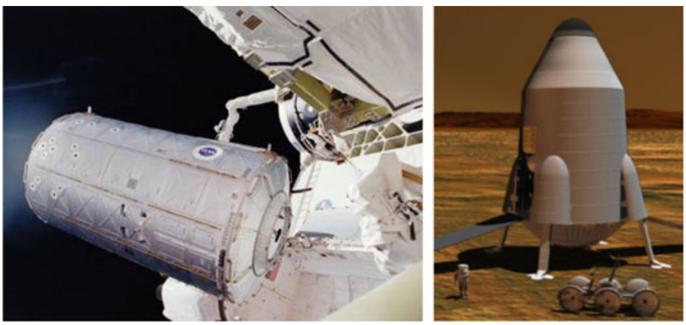

Fig. 5.45 Pre-integrated habitats: a **composite structure** that can be autonomously predeployed and operated in LEO, on the Moon or Mars surface. It would be fully integrated—ready to go. It includes the capability for Intelligent Hab for failure detection, analysis and self-repair (NASA)

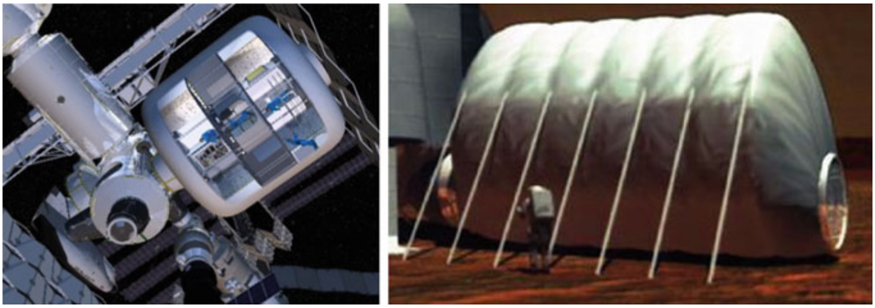

Fig. 5.46 Pre-fabricated habitats: **Inflatable structures** that can be autonomously predeployed and operated on the Moon and Mars surface. These habs are partially integrated and flexible. They include the capability for Intelligent Hab for failure detection, analysis, and self-repair (NASA)

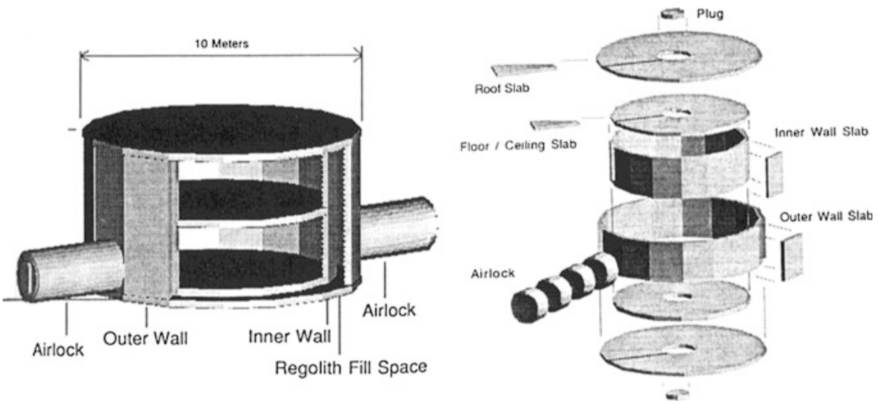

Fig. 5.47 ISRU-derived habitats: an **ISRU-derived structure** that is manufactured using indigenous resources and constructed autonomously. At the destination, it is autonomously operated and maintained utilizing an intelligent Hab operating system, including A.I. and V.R. It includes the capability for Intelligent Hab for failure detection, analysis, and self-repair (NASA)

Technical Challenges:

- develop composite structures that can be deployed and operated in space and on planetary bodies for 10–15 year life time.
- develop inflatable structures that can be packaged, deployed, and operated in space and on planetary bodies for 10–15 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 10–15 year life time.
- Integrate diagnostic and habitat health monitoring capability throughout the habitat.
- Integrated self-repairing skins for habitat structures.

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

As old as architecture itself, fabric structures have been interwoven throughout humankind's history—and now its future. The cavemen created portable housing as they became nomadic, following herds of animals in search of food. They used the animal skins stretched over bones and limbs to create shelters. Subsequently the use of these skins gave way to sewn together hides combined with erectable structures for easier deployment and break down. Over hundreds of years yarns and fabrics were developed which even further enhanced the fabric structures know as tents. Tensile fabric structures have always been at the revolutionary forefront of architecture with its dynamic shapes, sweeping boldness, and technological prowess. So it is not too surprising that a team of architects and engineers at NASA's Johnson Space Center were designing and testing this ancient architecture as a way to revolutionize habitats in space and for other planets.

NASA has considered tensile fabric structures in the past. In the late 1960s several inflatable structures were designed and tested for space applications. The Langley Research Center led efforts to develop and test a 7.32 m (24′) diameter torus space station, a Lunar Stay Time Extension Module prototype, and a large space station module nicknamed Moby Dick. All of these were successfully tested. It took many years of persistence, and a few failures, before the textile industry turned the technological corner with fibers like Kevlar, Vectran, and Polybenzoxazole (PBO).

Over the years the idea of inflatable structures for space habitats began to catch on. Several important NASA reports, such as the Synthesis Group Report, identified inflatable structures as an enabling technology that would allow NASA to accomplish lighter weight structures at a lower cost. NASA continued to refine innovative ideas and concepts preparing for an opportunity to prove an inflatable structure would live up to being an enabling technology for advanced missions. That day came when a NASA-led Tiger Team was given a design challenge: design an interplanetary vehicle habitat for a crew of six to travel to and from Mars. However, there was one major catch. Deliver this habitat to space using existing launch vehicles—which at the time was the STS Orbiter. Due to the amount of volume required per crewmember, for food, spares, etc. the logical choice was to use an inflatable structure.

TransHab pushed the technological envelope beyond Kennedy's previous design work on inflatables. The innovative architects and engineers soon shaped a revolutionary concept alternative to the hard aluminum shell. Since that early concept in 1997 TransHab has been through numerous design iterations. The latest design was a proposed habitat module for the International Space Station. It was an evolution of the Mars TransHab. A team of architects and engineers at the Johnson Space Center had been working, designing, and testing this concept to mitigate the risky technical challenges that the critics were bound to throw at them. The TransHab Project team met every challenge with vigor and determination.

Above and beyond the straight technological innovation of this vehicle—and in no small part because of it—TransHab also broke new ground in its support of the "human as a system." The process of Human Systems Integration, by which the structural design involved human engineering from its early conceptual stage and throughout its development, allowed TransHab to achieve a unique level of efficiency as a human-rated spacecraft. Its dimensioning and layout are optimized for flexibility and long-term use by a diverse crew. Because TransHab can be packaged into a smaller volume for launch and deployed on orbit to provide a much larger, more usable volume, this vehicle offers both great architectural opportunities and tremendous technical and design challenges.

Due to congressional action pertaining to ISS activities, all ISS TransHab development was canceled and the team disbanded—shut down. The systems integration and detailing of the interior elements was stopped along with an aggressive testing program at JSC, in which the technology had been consistently proven to meet and exceed existing requirements. All of these aspects of the program—its unique technology, its high level of habitability, and its outstanding testing record—attribute its success to the working of a deeply integrated project team. The team of test engineers, structure and subsystem engineers, architects, and human factors experts collaborated intensively from the project's outset with the "Human as a System" at the forefront.

5.8.3 TransHab Architecture

The architecture of TransHab provides an integrated habitable environment that creates private and social living spaces therein—which is very important for crew social and interpersonal relationships. This is especially true for the long-duration confinement of a space station or interplanetary vehicle. A functional and physical separation of the crew health care area, crew quarters, and galley/wardroom area creates a "home-like design" for the crew while they are in space, Fig. 5.48, while allowing each function to remain permanently deployed for regular use. With a larger volume and additional "floor space" TransHab provides more storage volume, two means of unobstructed egress, and permanently deployed equipment, such as a treadmill and ergometer. Some of the important design objectives of TransHab are to maintain a local vertical configuration, separate the exercise area from the dining area and to provide larger crew quarters. During the Mars interplanetary spacecraft design and the ISS design, several configurations were conceptualized. A horizontal (length of the cylinder or longitudinal section) layout was conceptualized and a vertical (baloney sliced or cross-section) layout was conceptualized. Ultimately the vertically oriented baloney-sliced layout was selected due to its efficiency of space utilization, crew traffic patterns, and functionality of spaces. TransHab has the ability to provide more storage volume, two means of unobstructed movement within the vehicle, and permanently deployed equipment in the primary activity centers. Important design objectives of TransHab are to (1) maintain a local vertical configuration, (2) separate the exercise area from the dining area and (3) to provide larger crew quarters. A central passageway in the

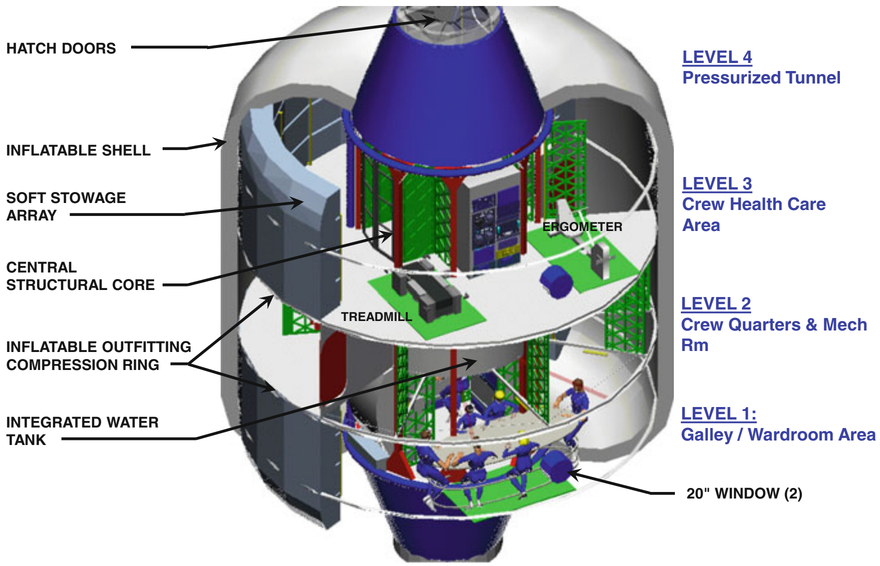

Fig. 5.48 TransHab architecture (NASA)

core and a side passage large enough to translate an ISS rack on the forward side achieves crew circulation in TransHab.

The ISS TransHab interior pressurized volume is divided into four functional levels: levels one through three are for living space and the fourth is the connecting tunnel. Providing a consistent local vertical orientation is in keeping with operational requirements established in all programs since Skylab and ISS. TransHab's architecture offers the opportunity to separate conflicting functions while enhancing the usability and privacy of each area. Level One (L-1) is the galley/wardroom and soft stowage area. Level Two (L-2) houses the crew quarters within the core's water tanks, and an enclosed mechanical room in a half-toroid of the outer area. Level Three (L-3) is the crew health care and soft stowage area. Level 4 (L-4) is the interconnecting tunnel or vestibule to ISS, Fig. 5.49.

The ISS-TransHab module was approximately 12.19 m (40 ft) long overall by 7.62 m (25 ft) internal diameter providing 342 m^3 (12,077 ft^3) of pressurized volume, Fig. 5.50. Levels 1 and 3 are 2.44 m (8 ft) tall at the Central Core and Level 2 is 2.13 m (7 ft) tall at the Core. TransHab is $\sim$7 m (23 ft) long from inside bulkhead to inside bulkhead (not including the 7-ft long Level 4 pressurized tunnel). This module was designed to be packaged and launched in the Space Shuttle Orbiter payload bay for delivery to the space station. This constraint meant it had to be packaged and folded on the ground and launched in the Obiter payload bay for delivery to the space station. The packaged central core will vent during launch to a vacuum state until TransHab is inflated.

After the Orbiter docked with ISS the TransHab would be removed from the Orbiter payload bay and berthed with the station using the space station remote

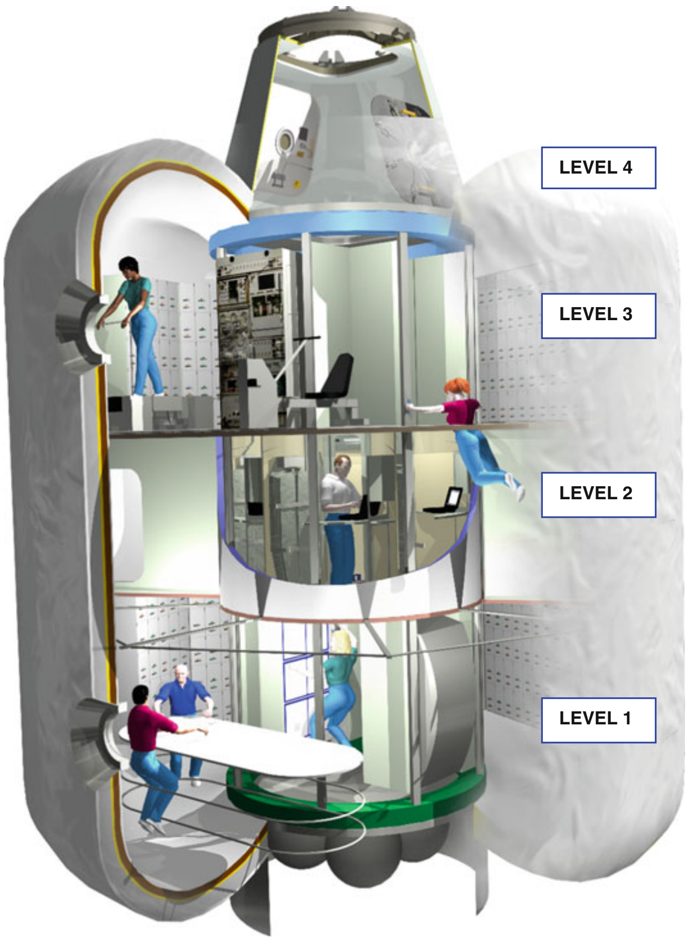

Fig. 5.49 TransHab levels (NASA)

manipulator system (SSRMS). Once captured on station the TransHab is deployed and then inflated to its internal operating pressure of 14.7 psia. During the inflation period, the air system is activated for conditioning the environment prior to crew entry and outfitting. Several days are required for the assembly crew to activate all the systems and complete preliminary outfitting and checkout of the habitat. To the extent possible all systems, utilities, and internal structures are pre-integrated into the central core.

TransHab is a unique hybrid structure that combines a hard central core integrating hard end-caps (berthing mechanism) with an inflatable exterior shell. An integrated pressurized tunnel is located at one end to provide access to the space station. An unpressurized tunnel is located on the opposite end and houses the TransHab inflation system. As such, it is differentiated from all previously

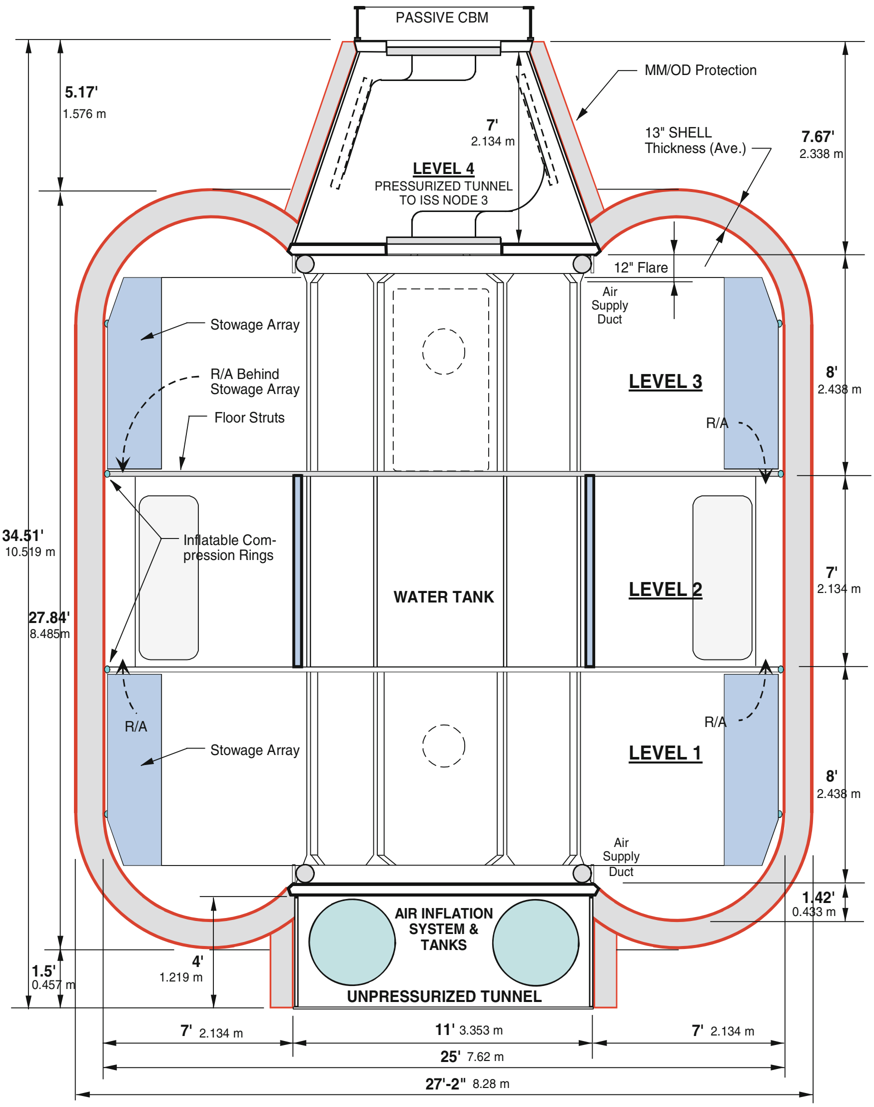

Fig. 5.50 TransHab cross section (NASA)

developed space vehicles, which traditionally utilizes an all hard external shell as both main structure and pressure vessel—such as the ISS Lab module or Nodes. Thus the TransHab vehicle's technology, revolutionary both in overall concept and in the development of each of its primary parts, represents a leap from this exoskeletal type to a new generation of endoskeletal or hybrid structural spacecraft that combine hard and fabric structures.

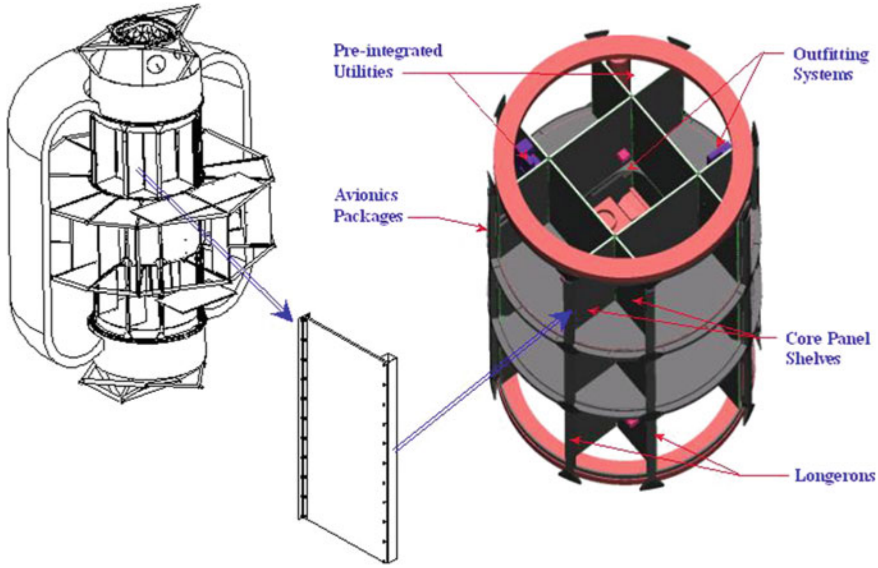

Fig. 5.51 TransHab structural concept (NASA)

The Central Core is comprised of the longerons, repositionable isogrid shelves, 2 bulkheads, a hard tunnel at each end, radiation shield water tanks, utility chaseways (2), and integrated ductwork. The launch shelves are secured into the central core for launch provided structural shear strength and rigidity, Fig. 5.51. There are 36 shelves in two different sizes: (a) 76 cm × 213.4 cm (30″ × 84″) and (b) 127 cm × 213.4 cm (50″ × 84″). About half of the shelves are repositioned once on-orbit and the others remain in place, Figs. 5.52 and 5.53.

The inflatable/expandable shell is composed of four functional layers: (1) the internal scuff barrier and pressure bladder, (2) the structural restraint layer, (3) the Micrometeoroid/orbital debris shield, and (4) the external thermal protection blanket, Fig. 5.54.

The longerons provide the primary load path through the core reacting to both pressure loads and launch loads. They are ~7 m (23 ft) long with flares at each end for attachment to the bulkheads. The crew quarters are located in Level 2 central core and are surrounded by annular water tanks. The water tanks provide a safe haven in the event of a solar flare. The water tanks are sandwiched between inner and outer shear panels that are structurally connected to the longerons. For ground operations and launch, these shelves provide structural support and lightweight equipment mounting for pre-integration. For launch they are locked into position in the central core for TransHab launch loads. Once TransHab is deployed, approximately one half of the shelves are relocated into the habitat volume to support floor beams and equipment. The shelves are designed with dual use in mind—primary and secondary structure.

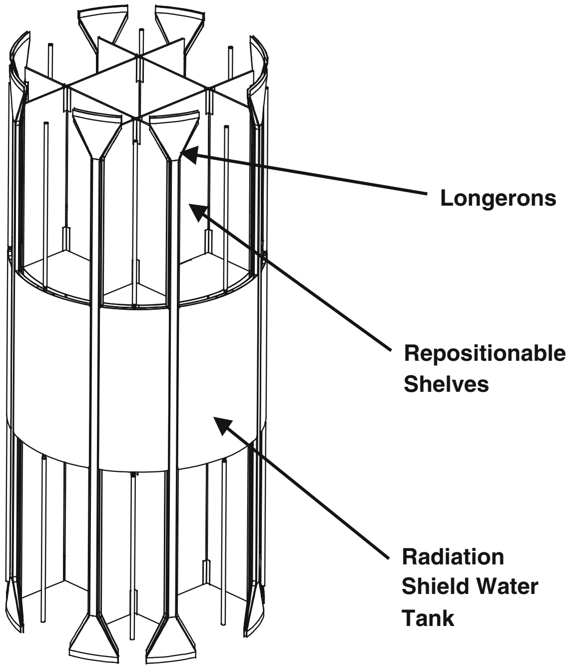

Fig. 5.52 TransHab structural core (NASA)

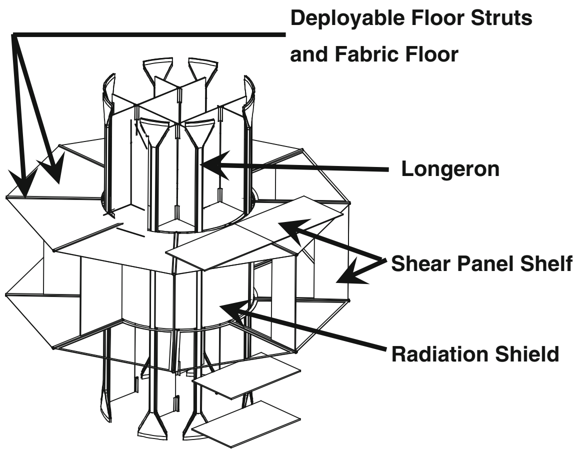

Fig. 5.53 TransHab deployed core (NASA)

“Space architects” took advantage of the added height in the first and third levels of the vehicle for easier integration of the air ducts and local-area utility distribution. Soffits attached to the core structures, both there and in the Level-2 Crew Quarters, combine the air-supply system with an enclosed utility chase-way for all power, data, and coolant runs so that each area is easily served with minimal exposure to utility connectors within the cabin, Fig. 5.55. This system also saves

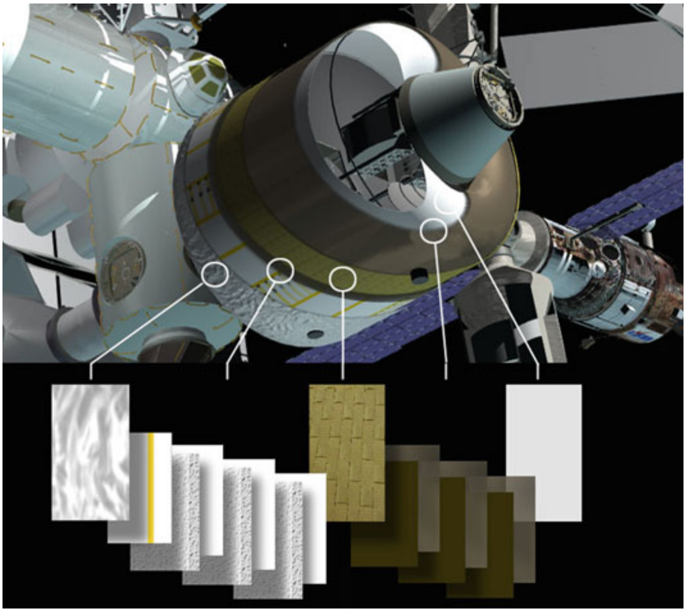

Fig. 5.54 TransHab pressure shell layers (NASA)

valuable time with on-orbit assembly and in pre-flight checkout by allowing these structures to remain fixed within the core and operate in both vehicle configurations. Another example of integrated systems architecture within the TransHab interior volume is the design of the Stowage Array to serve also as a plenum for return air flow. The Stowage Array, a subsidiary structure which attaches to the floor struts after deployment, accommodates ISS-standard stowed items in a highly usable inventory system while at the same time forming a gap between outfitting and the shell walls through which return air is channeled. This system serves an operational function at the same time that it helps TransHab to “breathe”.

5.8.3.1 Level One

Level one is the galley/wardroom and soft stowage area. It incorporates an ISS galley rack, ISS refrigerator/freezer racks, a large wardroom table, an Earth-viewing window and a soft stowage array that incorporates ISS standard cargo transfer bags (CTB), Fig. 5.56. A unique aspect about this area is that it includes a clerestory above the wardroom table area. The clerestory (two story height) was conceptualized in response to the psychological and visual creation of open space—which is very important for crew morale and productivity during long duration isolation and confinement in space.

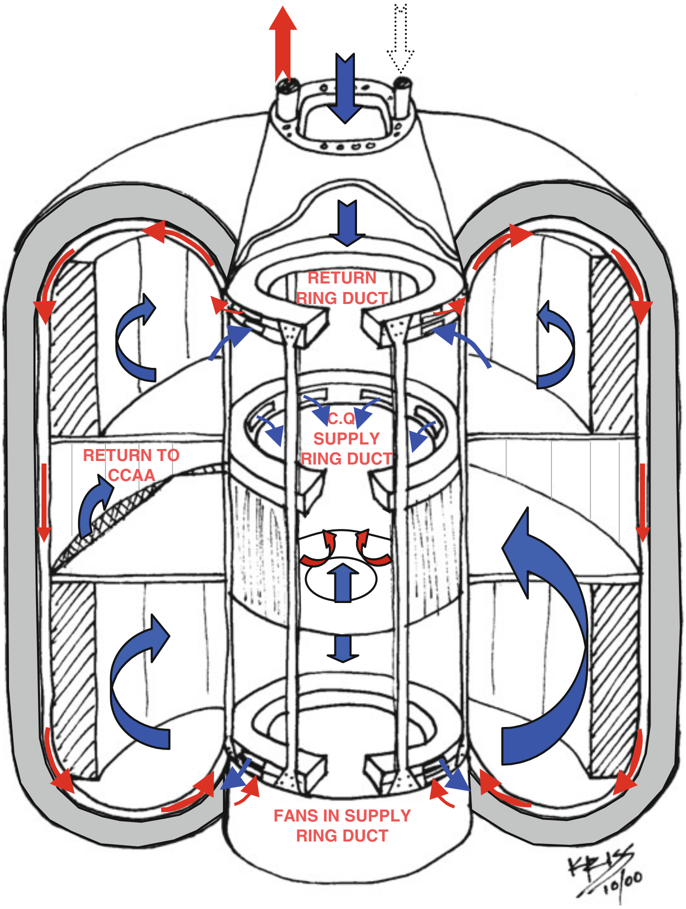

Fig. 5.55 TransHab air flow schematic (NASA)

The galley area is comprised of a rack-based ISS Galley and two rack-based ISS refrigerator/freezers (R/F). It is relocated from its ISS location and installed in TransHab once it is activated. The R/F are brought to station in a Mini Pressurized Logistics Module (MPLM). They are translated from the MPLM into TransHab and installed.

The wardroom table is design for all 12 crew members to gather during a crew change over. This wardroom table and area is also used for meetings, conferences, daily planning, public relations gatherings, and socializing. A nadir facing Earth-viewing window is located across from the wardroom table, Fig. 5.57.

The soft stowage area consists of the stowage array system and a hand-wash. The Stowage Array System (on level 1 and 3) has a total capacity of $\sim$25 m^3 ($\approx$880-ft^3) of stowage, equivalent to 475 CTBs. The Stowage Array, conceptually,

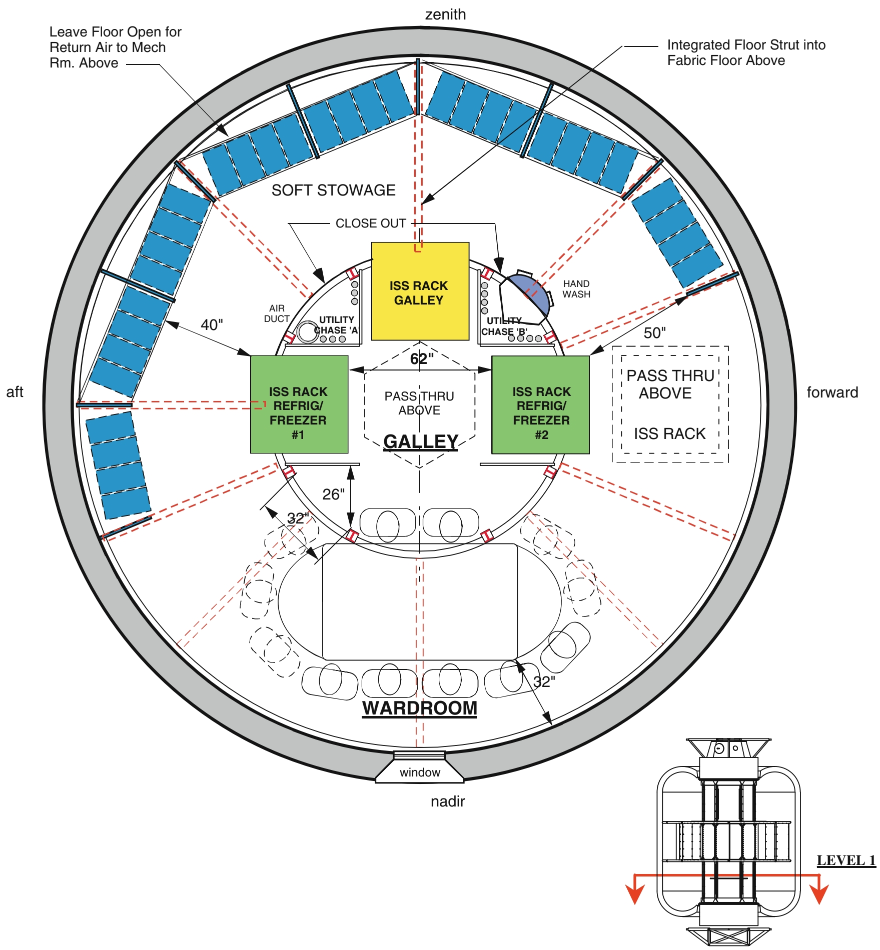

Fig. 5.56 TransHab Level 1 (NASA)

is a framework that CTBs can be placed into and utilizes the station coding and RFI bar reading system.

5.8.3.2 Level Two

Level Two is divided between the mechanical room on one side, the wardroom clearstory on the other, and the crew quarters (CQ) in the center core. Six (6) crew quarters surround a central passageway—all located within the second level central core structure and water tanks, Fig. 5.58.

The crew quarters are surrounded by ≈3″ thick (7.62 cm) water jacket-tank for radiation protection from solar flares. Access to this area is from Level 1 (below) or

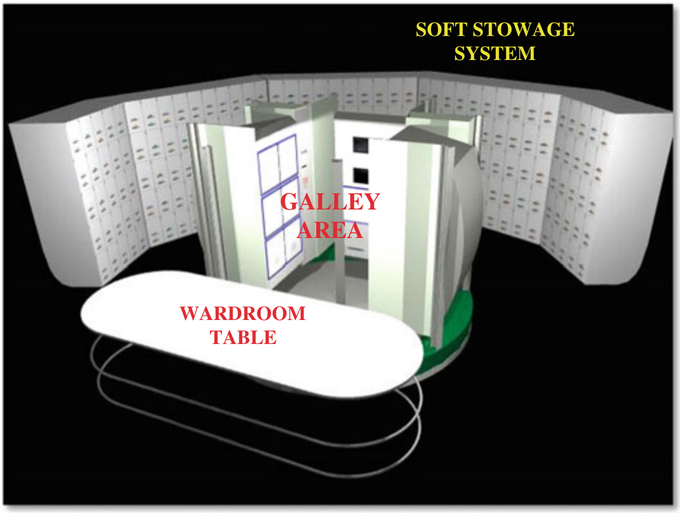

Fig. 5.57 Level 1 (NASA)

Level 3 (above), via the 42″ diameter (106.68 cm) central passageway. The CQ configuration is assembled and outfitted after TransHab's inflation. Launch shelves are used as crew quarters' partitions and the crew quarter door panel and door are installed on-orbit. Each of the crew quarters is ≈81.25-ft^3 (∼2.3 m^3) of volume (CQ 5 and 6 are less) with each having the full height of 84″ (213.36 cm). This is ≈27 % larger than the ISS Rack-based CQ (flush face), which is ≈64 c.f (without the bump-out panel).

Each CQ will have personal stowage, a personal workstation, sleep restraint, and integrated air, light, data, and power, Figs. 5.59 and 5.60. An integrated soffit at the top of the crew quarters contains the ductwork, and power and data cables that feed the work station area. The acoustic wall panels will be designed for cleaning and change out. The change out capability accommodates new crew members bringing their "personalized" panels to decorate their CQ according to personal taste. Long duration isolation and confinement studies and research have shown this concept of larger private crew quarters to have a very positive impact on crew morale and productivity.

The mechanical room is based on the architectural principle of a mezzanine level. Its function is for the placement of Environmental Control and Life Support System (ECLSS), power and avionics equipment, Fig. 5.61. This area is a "room" that is acoustically and visually isolated from the rest of TransHab. Openings in the mech. rm. floor and ceiling along the shell wall provide return airflow from Level 1 and Level 3. The mechanical room is accessible via a door on each side.

A unique aspect of this approach is equipment accessibility and design flexibility. Equipment is integrated onto the shelves that are placed into the core for

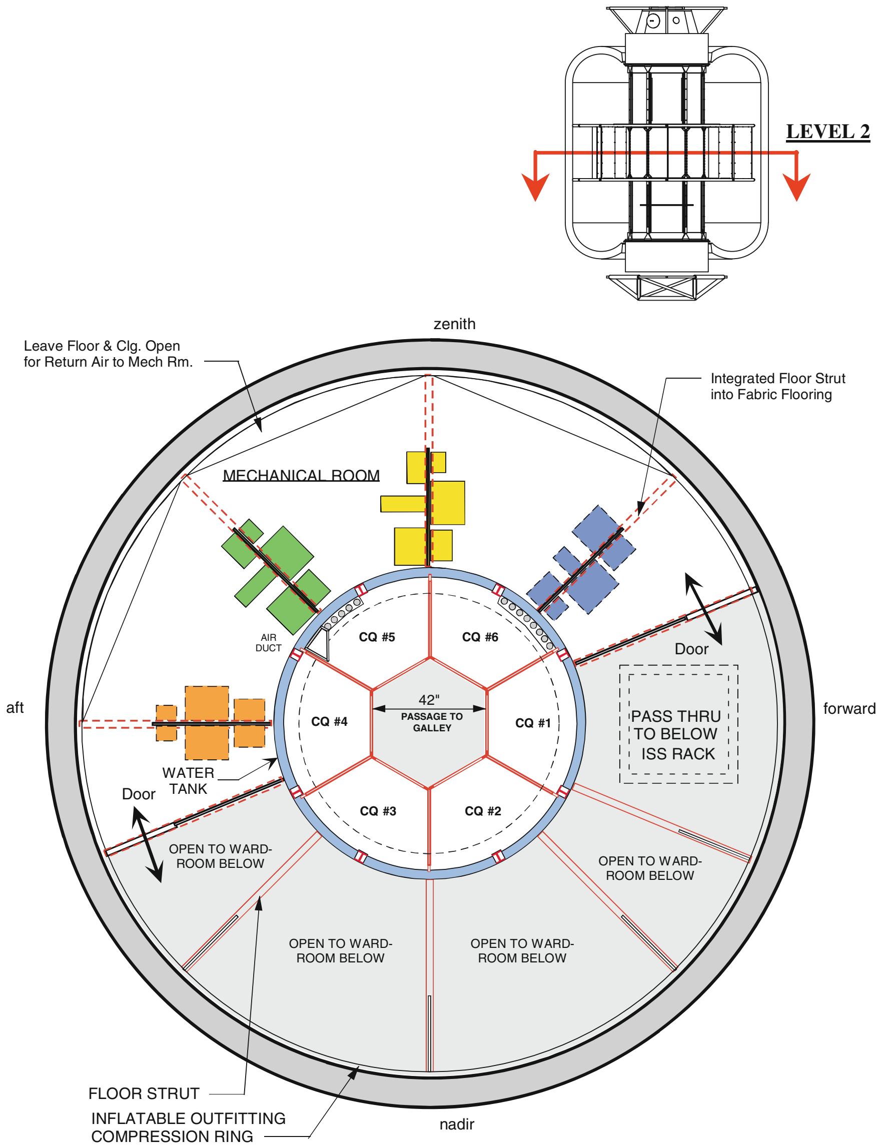

Fig. 5.58 TransHab Level 2 (NASA)

launch and then the shelves with equipment are moved to their final location once TransHab is inflated. An example of this shelf use is for the Air System. A Common Cabin Air Assembly (CCAA) is pre-integrated onto a shelf during assembly on Earth. The entire shelf with pre-integrated hardware is installed into the central core for launch and then relocated into mechanical room post inflation.

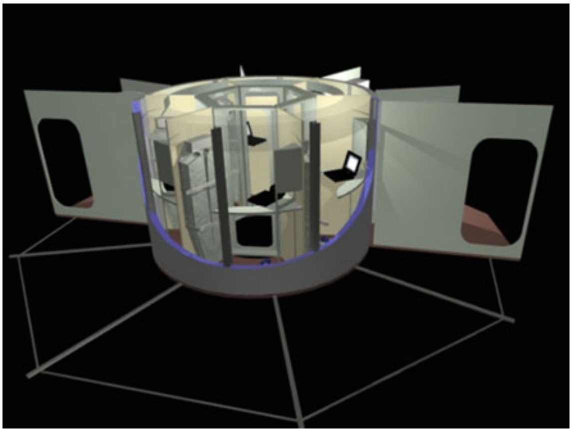

Fig. 5.59 Level 2 crew quarters (NASA)

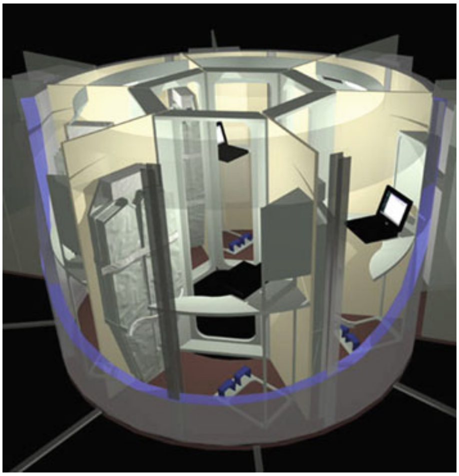

Fig. 5.60 Level 2 crew quarters (NASA)

5.8.3.3 Level Three

Level Three is the crew health care and soft stowage area. The crew health care area incorporates an Earth-viewing window, two ISS Crew Health Care System (CHeCS) racks, a Full Body Cleansing Compartment (FBBC), changing area, exercise equipment (treadmill and ergometer), a partitionable area for private medical exams and conferencing, Fig. 5.62. Also included on this level is a soft stowage area identical to level one. The exercise equipment is permanently mounted in their deployed position. This saves crew time in the deployment and stowage of exercise equipment on a daily basis. Placement of the exercise equipment is synthesized with the window location to allow the crew Earth viewing during exercise. Two launch shelves are placed on the floor struts as exercise equipment mounting platforms and structural integration, Fig. 5.63. Four movable

Fig. 5.61 Mechanical room (NASA)

partitions provide visual screening of crew members for (a) pre and post full body cleansing activities, and (b) private medical exams at the CHeCS rack.

5.8.3.4 Level Four

Level Four is the pressurized tunnel area. It has two station standard hatches, avionics, and power equipment. Its function is to (1) provide a "transition" between Node 3 and TransHab; (2) house critical equipment required during inflation; and (3) provide structural connection to space station. It is the only pressurized volume in TransHab during launch. Once TransHab is berthed and bolted to the ISS Node, Level 4 provides immediate access to the vestibule area between the Node and TransHab, Fig. 5.64. This will allow the critical power and data vestibule connections to enable initiation of the deployment and inflation operations.

5.8.4 Summary

With the successful completion of the demonstration testing and inflatable shell development, the TransHab project proved that the inflatable structure technology is real. The project also opened up a new space architectural alternative to the ISS type Class I type of modules. TransHab made great strides to prove inflatable structures technology are ready to be applied as habitats for space applications. TransHab's design met or exceeded habitation requirements for space. It has put the "living"

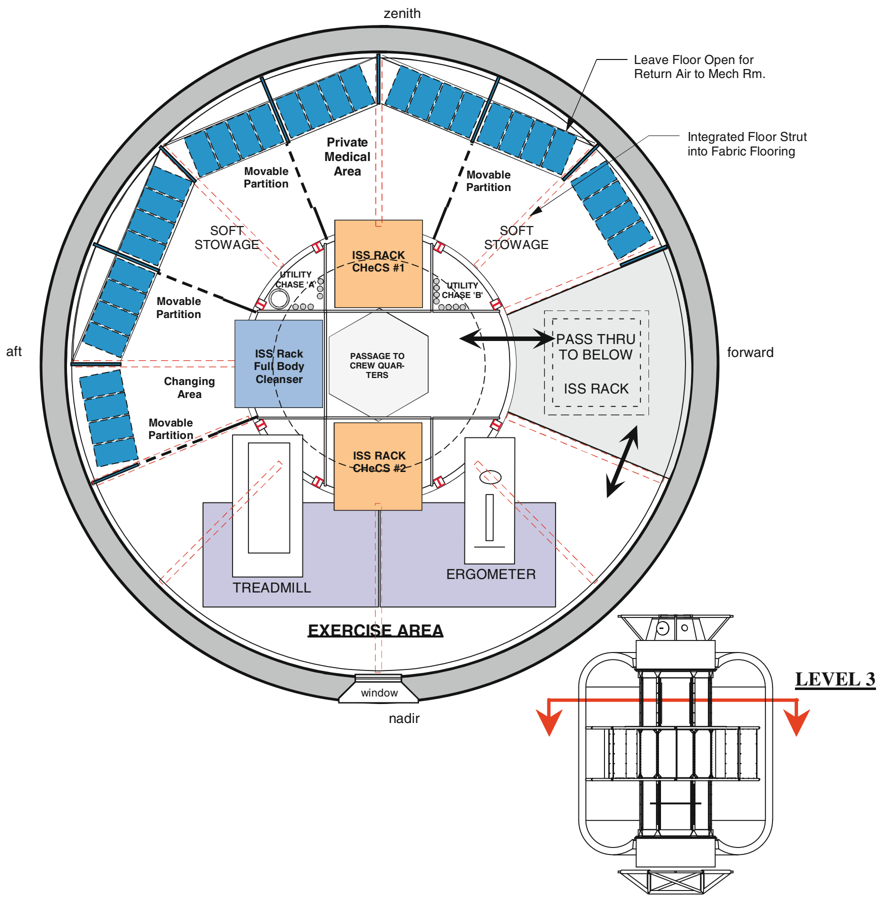

Fig. 5.62 TransHab Level 3 (NASA)

back into "living and working in space." The TransHab design provides facilities for sleeping, eating, cooking, personal hygiene, exercise, entertainment, storage, and a radiation storm shelter. TransHab also helped to develop, test and prove technologies necessary for long duration interplanetary missions—back in 1997–2000 (Fig. 5.65).

TransHab has already contributed many technical and management lessons to the aerospace field. It has broken the volumetric barrier of the exoskeleton spacecraft type by innovating an entirely new, endoskeletal typology; it has demonstrated the advantages of combining human system integration and engineering with aggressive structural innovation and testing at the conceptual rapid prototyping stage. The integrated effort by which this spacecraft was conceived and developed has proven its virtue in meeting tremendous challenges by combining innovative

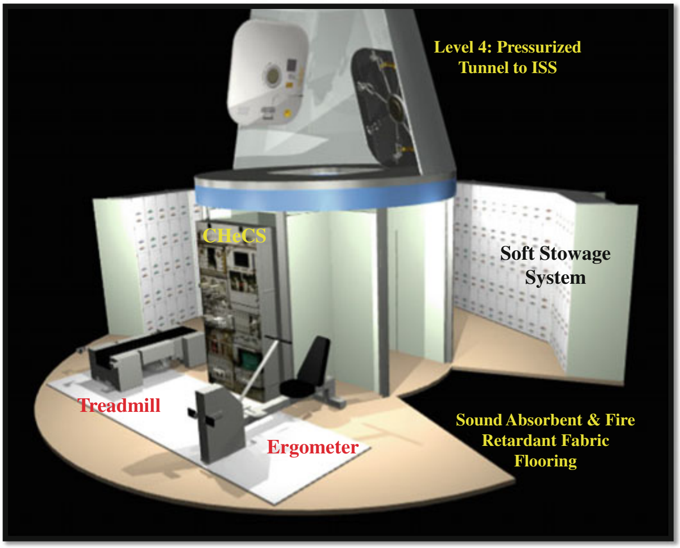

Fig. 5.63 Level 3 exercise area (NASA)

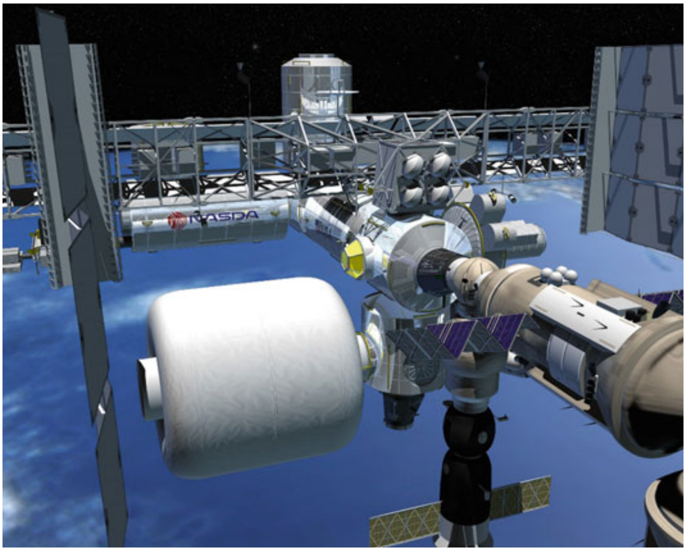

Fig. 5.64 TransHab conceptually installed on ISS (NASA)

design with cutting-edge technologies, both of which are appropriate for in-space and planetary surface habitats, with multiple applications for both on-Earth and beyond.

Fig. 5.65 Kriss J. Kennedy, space architect, ~1999 (NASA)

The TransHab concept, rapid prototyping, and testing will prove to be a disruptive technology that has and will change the architectural revolution of spacecraft, habitats, and space systems for decades to come.

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5.9 Guest Statement: Engineering and Construction of Lunar Bases (Haym Benaroya and Leonhard Bernold)

5.9.1 Introduction

How do we begin to expand our civilization to the Moon? What are the technical issues that infra-structural engineers, in particular, must address? Can we create an economic justification for the large investments needed to involve private companies? This essay reviews some of the key aspects of the lunar environment that critically affect how surface and then subterranean structures are designed and constructed for habitation.

Concepts for lunar base structures have been proposed since long before the dawn of the space age. For a review of the lunar structural literature and preliminary ideas, see, for example, reference list papers.[20] For an early example of the gearing up of R&D efforts that took place during Apollo, see the US Army Corps of Engineers study (Department of the Army 1963). During the decade between the late eighties to mid-nineties, these studies intensified, both within NASA and outside the Government in industry and academe. Numerous other references discuss science on the Moon, the economics of lunar development, and human physiology in space and on planetary bodies (Connors et al. 1999). An equally large literature exists about related policy issues. These topics are outside our scope here, but should be viewed as equally important to the implementation of permanent manned settlements on the Moon and beyond. Human physiological and psychological issues are better understood but as yet unresolved.

The emphasis below is on structures for human habitation, a technically challenging fraction of the total number of structures likely to comprise the lunar settlement. The test for any proposed lunar base structure is how it meets certain basic, as well as special, requirements. On the lunar surface, numerous constraints must be satisfied by all designs, constraints very different from those for terrestrial structures. A number of structural types have been proposed for lunar base structures. These include concrete structures, metal frame structures, pneumatic construction, and hybrid structures. In addition, options exist for subsurface architectures and the use of natural features such as lava tubes. Each of these approaches can, in principle, satisfy the various and numerous constraints, but differently. Problems related to constructing "man-made" structures in a totally new environment for which we don't have any ASTM or building standards are issues that are still not well understood.

Numerous reasons are given for the creation of a lunar settlement. These include: much more effective lunar science and astronomy, a stimulus to space and spin-off technologies and as a test bed for the technologies required to place humans on Mars and beyond, the utilization of lunar resources, space tourism, nationalism, and to stimulate interest in science and engineering, as well as the beginning of a

[20]Benaroya, H. 1993. Rigid tension structures for a lunar base, special issue: The applied mechanics of a lunar base. Applied Mechanics Reviews 46(5): 326–335. Benaroya, H. 1994. Reliability of structures for the moon. Structural Safety 15(1): 67–84. Benaroya, H., and M. Ettouney. 1992a. Framework for the evaluation of lunar base structural concepts. Aerospace Engineering 5(2): 187–198. Benaroya H., and M. Ettouney. 1992b. Design and construction considerations for a lunar outpost—utility of earth design codes. Aerospace Engineering 5(3): 261–273. Benaroya, H., L. Bernold, and K.-M. Chua. 2002. Engineering, design and construction of lunar bases. Journal of Aerospace Engineering 15(2): 33–45. Bernold L.E. 1994a. Compaction of lunar-type soil, ASCE. Journal of Aerospace Engineering 7(2): 175–187. Ettouney M., and H. Benaroya. 1992. Regolith mechanics, dynamics and foundations. Journal of Aerospace Engineering 5(2): 214–229. Ettouney M., Benaroya H., and Agassi, N. 1992. Cabled lunar structures. Journal of Aerospace Engineering 5(3): 297–310. Duke, M., and H. Benaroya. 1993. Lunar exploration and development, special issue: The applied mechanics of a lunar base. Applied Mechanics Reviews 46(5): 272–277

long-range program to ensure the survival of the species (Ruess et al. 2006). As important, it can be said, is the fulfillment of the human spirit in its quest for knowledge, understanding, and exploration.

5.9.2 The Environment

The design of a structure for construction on the lunar surface has to consider its constructability while, at this point, we have no experiences and no standards that an earthbound engineer depends on. For example, we don't know how to excavate and move the "dangerous" lunar soil, referred to as regolith, as almost 50 % of it consists of pure dust. Apollo 17 astronaut Gene Cernan predicted that "... *dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust*." (Crotts 2014, p. 334)

There are severe lunar temperature cycles and temperature differentials between different sections of the same component, possible out-gassing for exposed steels and other effects of high vacuum on steel, alloys, and advanced materials, plus ambiguity of reliability and risk. The question is whether it will be economically feasible to ship construction material at all, while ignoring the potentials of the in situ resources. How will lunar concrete made of processed soil behave? Why not use the carbon rich soil to produce plastic or nano-tubes?

Any lunar structure will have to be designed for and built with the following prime considerations:

Safety and Reliability. Human safety and the minimization of risk to "acceptable" levels are always at the top of the list of considerations for any engineering project. Minimization of risk implies, in particular, structural redundancy or fire protection, and when all else fails, easy escape for the inhabitants. The key word is "acceptable." It is a subjective consideration, deeply rooted in economics. What is an acceptable level of safety and reliability for a lunar site, one that must be considered highly hazardous? Such questions go beyond engineering considerations and must include policy considerations: *Can we afford to fail?*

1/6-g gravity. A structure will have, in gross terms, six times the weight bearing capacity on the Moon as on the Earth. Or, to support a certain loading condition, one-sixth the load bearing strength is required on the Moon as on the Earth. In order to maximize the utility of concepts developed for lunar structural design, mass-based rather than weight-based criteria should be the approach of lunar structural engineers. All of NASA's calculations have been done in *kg-force* rather than *Newtons*. Calculations are always without the gravity component; use kgf/cm^2 as pressure, for example. The magnitude of the vastly different distributions of pressures and forces during construction will depend on the methods that will be selected for construction. Whatever will be selected, it will be without precedence for humans, thus lacking the long history of construction technologies. There will have to be a quick learning curve requiring new approaches to execute tests providing data reliable enough to be used as design standards that would be considered safe and insurable by insurance companies.

In the area of foundation design, most classical analytical approaches are based on the limit state condition. That means that the design is based on the limit of loading on a wall or footing at the point when a total collapse occurs, that is, the plastic limit. Since many of the structures on the Moon require accurate pointing capabilities for astronomy and communications, for example, a settlement-based design method would be more useful.

Internal Air Pressurization. The lunar structure will have to be a life-supporting, closed environment consisting of a volume with an internal pressure of 6.9×10^4 to 10.3×10^4 Pa. The enclosure structure must contain this pressure, and must be designed to be "fail-safe" against catastrophic and other decompression caused by accidental and natural impacts. Internal pressurization offers challenges to all lunar structures, but especially the inflatable concept. Placing inflatables inside lava tubes or under large concrete arch structures would eliminate many associated risks.

Shielding. Living without the protection of an atmosphere creates many different hazards for the human body. A prime design consideration is that any structure must be able to shield against the types of hazards found on the lunar surface: continuous solar/cosmic radiation, meteorite impacts, and extreme variations in temperature and radiation. If a layer of regolith is placed atop the structure for shielding, the added weight would only partially (in the range of 10–20 %) balance the forces on the structure due to internal pressurization mentioned above. By erecting stand-alone concrete arches using box type modules and glass-fiber tension cables "Made in Moon" shielding could be easily incorporated. In addition to general shielding, special radiation shelters will be needed during periods of increased solar activity. Underground mines or lava tubes will provide such protection but need to be sufficiently close to be reached on time.

Shielding against micrometeorite impacts is most probably done by using the abundant regolith that is able to absorb the kinetic energy. As mentioned earlier, the handling of the lunar dust has its own inherent risks. For this reason, lunar rocks would be safer than regolith as they also provide fracture toughness. But rocks are more difficult to obtain and much more difficult to place atop surface structures. Some suggest that for shielding purposes alone, it is better to design and place human rated structures underground. This may be so, but it is then necessary to factor in the added costs and difficulties of subsurface work.

Much effort has been devoted to determining the damage effects on human beings and electronics resulting from nuclear weapon detonation and little is being done to determine long-term sustained low-level radiation effects, such as those that would be encountered on the Moon. During the times of low solar activity, the annual dose-equivalent on humans on the exposed lunar surface may be about 0.3 Sv and the dose-equivalent over an 11-year solar cycle is about 10 Sv, with most of the particles arriving in one or two gigantic flares lasting one to two days. It appears that at least 2.5 m of regolith cover would be required to keep the annual dose of radiation at 0.05 Sv, which is the allowable level for radiation workers

(0.005 Sv for the general public). A shallower cover may be inadequate to protect against the primary radiation and a thicker cover may cause the secondary radiation, which consists of electrons and other radiation as a result of the primary radiation hitting atoms along its path. Again, a sufficiently thick arch structure (in 1/6 g) made of lunar concrete and glass fibers seems to provide an elegant and cost efficient solution.

Vacuum. A hard vacuum surrounds the Moon. This will preclude the use of certain materials that may not be chemically or molecularly stable under such conditions. This is another issue to be researched. Construction in a vacuum would be another first for humans. Can we fabricate machines and tools that don't have a risk of out-gassing oil, vapors, and lubricants? The out-gassing is detrimental to astronomical mirrors, solar panels, and any other moving machine parts. The ever-present dust will require specially designed seals, joints, gears, etc. Still another requirement is the prevention of surface-to-surface contact as they may easily fuse or cold weld. This is, of course, aggravated by the fact that the vacuum is a bad conductor of heat. The increase in abrasiveness at interfaces also increases friction on all moving parts, for example, wheels.

Explosives are not only a safe way to separate rocket parts in space but also represent excellent means to release large amount of energy on the moon. In fact, Bernold (1991) reported that small explosives have been buried in lunar soil simulants to test its effectiveness in reducing the high density of the soil before excavation. He has since abandoned that concept to be used for general excavation because of the risk to create large "dust-clouds" covering the Moon. When the explosive in a blast hole is fired, it is transformed into a gas, the pressure of which may sometimes exceed 100,000 terrestrial atmospheres. The experiences of lunar lander of Apollo 12 "sand-blasting" of Surveyor 3 with regolith will certainly require the landing areas that are "stabilized".

Dust. As mentioned earlier, the lunar surface has a layer of fine particles that are disturbed and placed into suspension easily. These particles cling to all surfaces and pose serious challenges for the utility of construction equipment, air locks, and all exposed surfaces. Lunar dust consists of pulverized regolith and appears to be charged. The charge may be from the fractured crystalline structure of the material or it may be of a superficial nature, for example, charged particles from the solar wind attaching themselves to the dust particles. Any activities that involve interaction with the regolith need special study.

Constructability. The remoteness of the lunar site, in conjunction with the high costs associated with launches from Earth, suggests that lunar structures be designed for semi-automated construction so that it can be controlled from Earth prior to the arrival of astronauts. Construction methods must be simple and, in a sense, modular. The goal would be to make all the heavy parts using in situ resources on site while special parts and elements can be shipped from Earth as fitting components. Some ideas will be provided in a subsequent section on construction.

Use of ISRU (In Situ Resource Utilization). Considering the history of human expansion on Earth (e.g., settling of Sydney) "living off the land" will emerge as a key rule of design. It has to be expected that private companies participating in the Lunar Google X-Prize will be mining the moon robotically before the first humans will arrive. Undoubtedly, the initial robotic mining activities on the Moon will provide opportunities to test various uses of the ISRU, even to make plastic from the carbon-rich soil or mining pressurizable underground caverns. The continuing evolution of advanced manufacturing technologies, in particular 3D printing, holds the promise of autonomous construction utilizing local materials. This capability is viewed as one Holy Grail of human exploration and settlement of the Solar System. Realistically, however, while the infrastructure is initially being constructed, ISRU/3D printing does not appear to be economically or logistically feasible. See the monograph by Rapp (2013).

It appears that there may be significant amounts of water-ice in some craters near the poles of the Moon. This is the most significant resource found on the Moon, in addition to the other resources that exist in quantities that can eventually be extracted as part of the creation of an industrial infrastructure.

5.9.3 Developing Construction Technologies for the "New World"

It is a general misconception by engineers lacking expertise in general construction that building on the Moon is simply a scaling of similar operations on Earth. One needs to consider that today's construction methods, equipment, technologies, and materials have evolved over the last 4000 years mostly through trial and error that caused large numbers of humans to loose life and limbs. Astonishingly, despite uncountable numbers of building standards, design codes, and materials testing methods, construction is still the riskiest industry for workers and structures still collapse. In contrast, not a single building standard or design norm exists for a lunar structure today. How can we make up for 4000 years of trial and error so that we will be able to design and construct high quality and safe habitats? There is no doubt that this has to be a collaborative and synergistic effort that takes advantage of every visit to validate critical elements that have been built in a simulated lunar environment on Earth.

The following section provides two examples of first experiments as a stepping-stone to design exploratory experiments of key components to be executed in the lunar environment, eventually leading to establishing design standards.

5.9.3.1 Digging and Moving Regolith to Build and Mine

Excavation, transportation, and processing of soil are the most common activities of terrestrial construction and mining. Most likely, this will be true in the "New World" even though roads will be replaced with a much more efficient cable based transportation system (Bernold 1994b). Due to many Earth-specific factors, 95 % of "earth" removal methods rely on mechanical means of cutting, scraping, scarring, dozing, etc. All of them depend on gravity forces to create traction and on ample combustion power. One exception is gold miners who use pressurized water to loosen and erode away the soil to be guided into sluices. A major factor that makes the earthbound methods work is the relatively low density of naturally deposited soil compared to the 95 % relative density of lunar regolith below a depth of 28 cm. But let's also remember Apollo 17 astronaut Gene Cernan's warning about lunar dust. Any of the most efficient methods of removing soil will create dust or will require water, which is not available in vacuum.

The risks of elevating dust, as well as the high density of lunar soil, are critical drivers to look for alternatives. Why not get out of our "Earth bound prejudices" and try to think like a "Moon bound engineer"? In this case, a lunar solution needs to synergize the various unique factors into a new system. For example, a lunar solution needs to take advantage of the highly densified fine-grained basaltic regolith, the 0 % water content, low gravity, and the ample availability of SiO_2 to make glass with the unique capabilities of airflow within an artificial closed "atmosphere."

Why not replace the power intensive mechanical cutting with aerodynamic forces able to remove and transport dry and dense fine-grained sand in the many terrestrial deserts? Fig. 5.66 depicts a closed-cycle system that relies on a pressurized gas flowing from a high to a low pressure zone creating a velocity sufficient to move the lightweight and dry soil particles eroded at one end to a separator at the desired location (Bernold 2013).

The presented system acts like open pneumatic systems on Earth that utilize air pressure gradients to move containers with documents or even heavy material within a pressurized piping system at rapid speed. In fact, the reduced gravity on the

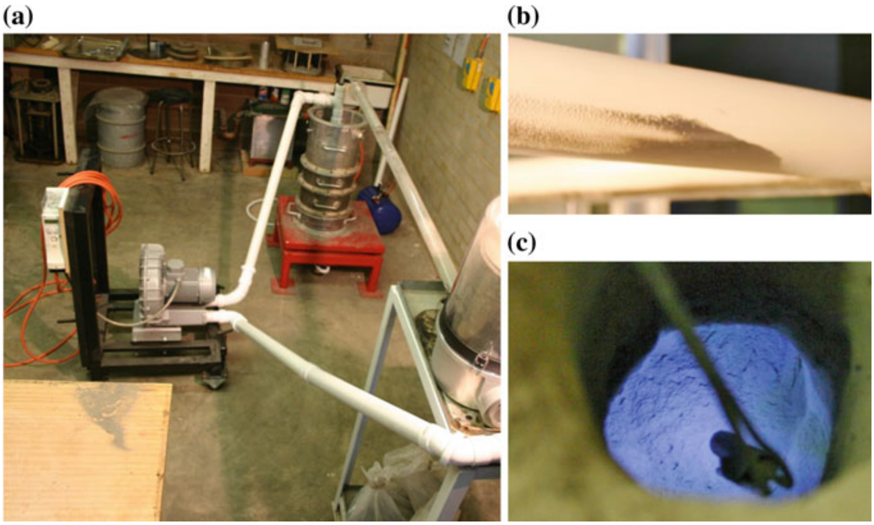

Fig. 5.66 **a–c** Earth-based facility to test pneumatic lunar excavation and mining. **a** Closed system pneumatic system built with ISRU glass pipes; **b** soil deposit pattern after a 90° elbow; **c** inspection of excavated deep cavern (Benaroya, Bernold)

moon will make such a concept even more effective while easily produced gas will be recycled within the piping network. The energy needs for the blower are also easily met. Finally, the aerodynamics of turbulent and laminar gas-flows are controlled without difficulty. It will serve as an efficient medium to erode, elevate, transport, and separate the soil without creating any surface dust.

Figure 5.66c presents the view from the surface into a cavern that was excavated deep inside a basaltic lunar soil simulant that had been compacted to a density equivalent to lunar conditions (90 % relative density). A specialized remote controlled nozzle mechanism was used to extend the cavern horizontally in a circular mode. The intake can be modified easily to be used for surface excavation. Pneumatic transportation efficiency over long distances and variable elevations are supported by intermediate accelerators utilizing so called “air lances” fed from the central blower.

5.9.3.2 Glass Fiber Reinforced Sulfur Concrete to Build Protective Arches

One of the factors that makes lumber and also concrete such a successful construction material is that the main ingredients, trees, stones, and water, are locally available. Of these, only concrete as a mix of cheap local material held together by a binder seems to be applicable to the Moon. However, a direct copy of Earth-based concrete falls apart because of lack of cheap water and the difficulty to fabricate the needed reinforcing steel. But there are ISRU binders on the Moon and other materials to be used to reinforce a lunar concrete that might also serve as a radiation shield.

Silicon dioxide (SiO_2) is the predominant chemical compound found in lunar regolith at a composition of 46 %. Also known as silica, it is the base material for many important products on Earth including microchips, glass, glass fibers, and even fiber optic cables. In addition, glass fibers have excellent tension characteristics and can be used to fabricate strong strings as well.

One material to be used as a binder for lunar concrete, also used on Earth, is the chemical element sulfur (S). Different than the cement based concrete, sulfur concrete can be created by mixing sulfur with sand/gravel without the need of water. The binding of the stone particles occurs by melting the sulfur with heat energy to approximate 110 °C. The brittleness is controlled by small amounts of additives to create a compound that has high compressive strengths of 77 MPa or more. Here on Earth, sulfur concrete is commercially well established especially in corrosive environments. Figure 5.67 a–c shows the casting of sulfur concrete, with various sulfur percentages, into different configurations that were reinforced with glass fiber-meshes to “absorb” tension and shear forces.

5.9.3.3 Advancing the Roman Arch for Lunar Applications

It is well understood that the Romans did not invent the arch structure but they enhanced the construction method that led to wider spans, while concrete and steel

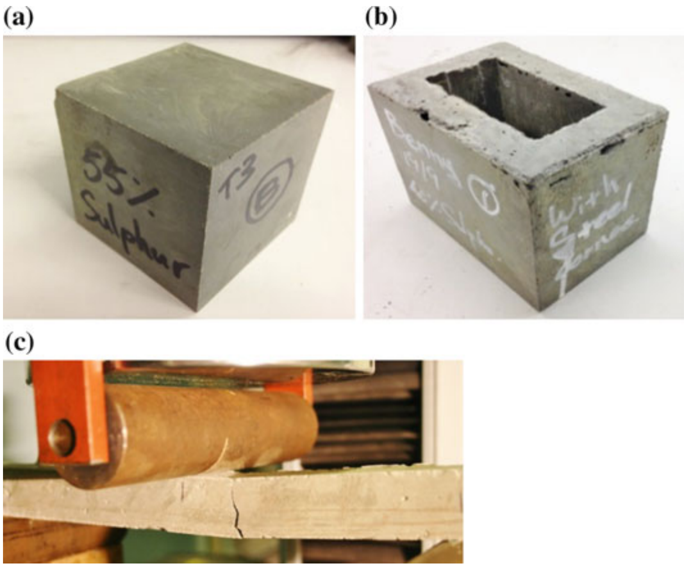

Fig. 5.67 **a–c** Testing glass-mesh reinforced sulfur concrete building elements. **a** Sample cube with 55 % sulfur; **b** reinforced hollow box 40 % sulfur; **c** tension test of glass fiber reinforced beam (Benaroya and Bernold)

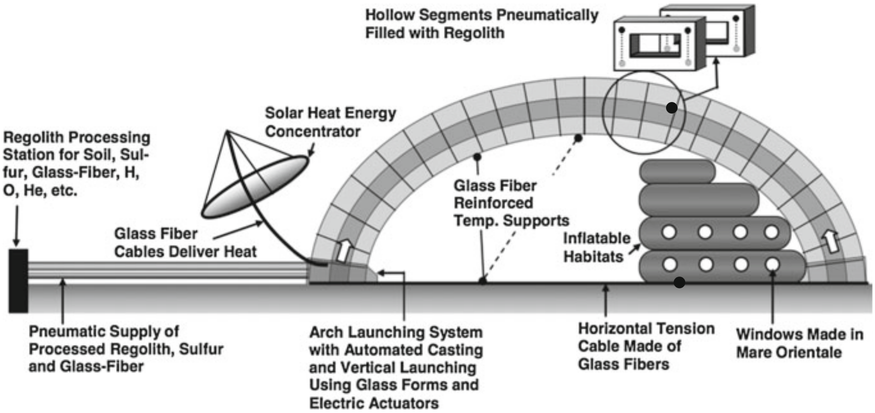

Fig. 5.68 Concept of ISRU "Heavy" construction of arch structure to shelter humans and equipment (Benaroya and Bernold 2008)

cables added yet another dimension during the last 100 years. Without a doubt, arches built in the lower lunar gravity will extend the use of this ancient design. Figure 5.68 depicts a concept that synergizes many ISRU's that were addressed above with the effectiveness of the arch to create versatile shelters, mixing it with other basic principles that have already been successfully tested on Earth.

It should be apparent that the arch structure concept builds on the principles discussed above. The heavy reliance on ISRU will result in a minimal weight of supplies that need to be shipped from Earth, mostly consisting of electric motors, seals, sensors, and other specialized systems. Of course, multipurpose robotic manipulators need be able to prepare the building site, install the piping system, set up the arch launching facility, and the solar heat concentrator. A simple production facility is necessary to make glass fiber and pipes from the available silica. Naturally, such a facility could serve other needs as well including the casting of furniture, windows for the inflatables, and truss-towers, all “Made in Mare Orientale.”

5.9.4 Concluding Thoughts

In closing the chapter on lunar structures and construction, the reader needs to be reminded again that conceptual designs, such as the one presented in Fig. 5. 68, will stay pipedreams until there exists a large set of tested and globally approved standards and norms for designing safe structures that can be built and maintained on the lunar surface with the maximum use of ISRUs. The Holy Grail of space exploration and settlement is the marriage of robotics and ISRU-3D printing technologies. But, learning from history, this process will take many decades even if the interested “Earthlings” get together to make it happen. Gathering the political will might well be the most difficult obstacle to achieve this dream before even the youngest reader is able to witness it happen. Fortunately, the private sector has made significant inroads in space, so, with enough time, they and not the governments will be the primary actors on the space stage.

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Chapter 6
Validation, Demonstration and Testing

Abstract The chapter describes verification and testing approaches and examples. Verification of accepted solutions and testing methods are related to the last five Technology Readiness Levels and Habitation Readiness Levels. The chapter introduces several existing and recently used analog facilities from NASA, RSA, ESA, and lists testbed facilities around the world. Descriptions of verification methods include their aims, requirements for selection of appropriate analogs and mock-ups, and gaps in human related risks.

6.1 Introduction and Chapter Structure

This chapter describes verification of accepted solutions and testing methods that correlate with the final set of Technology Readiness Levels and Habitation Readiness Levels: from 5 to 9 (Table 6.1).

The chapter discusses mission assessment strategies using comparison of habitation schemes as an example, verification and testing methods, risk of an incompatible habitat design, analog habitats and environments, and aims of verification methods. Examples used in the chapter include reduced scale models and full-scale mock-ups evaluations and technology and habitability testing onboard of the International Space Station.

The guest statement by Kriss Kennedy[1] discusses the testing of technology, design solutions, and technology operations of the TransHab project.

[1]NASA Johnson Space Center, Commercial Crew Program-Health & Medical Partner Integration Team.

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Table 6.1 Definition of the habitation readiness levels 5–9 in relation to technical readiness levels 6–9 (Connolly et al. 2006, p. 5; ESA [TRL] 2008)

HRL	Definition of the habitation readiness levels 5–9	TRL	Definition of the technical readiness levels 6–8
Demonstration of the technology			
5	Full-scale, high-fidelity mockups, human testing and occupancy evaluations An HRL Level 5 Habitation System is at a stage where the individual technologies required for the habitat have reached the level that has a system/subsystem model or prototype demonstration in a relevant environment, attaining a **TRL 6** for all systems or subsystems. Mockup fidelity is at a high level such that most habitat subsystems are functional. At this level, human testing using the active systems can be performed. Any redesign necessary for the systems is performed and testing is repeated as required	>6	System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space) Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application
6	Habitat and deployment field testing An HRL Level 6 Habitation System is at a stage where an operational habitation system is taken into a relevant field environment for full-scale, integrated activation and testing at an Earth-ambient internal pressure	>7	System prototyping demonstration in an operational environment (ground or space) System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available
	Testing of the Technology and Technology Operations		
7	Pressurized habitat prototype testing An HRL Level 7 Habitation System is at a stage where a fully operational integrated prototype habitation system is tested at the internal pressures required for the mission application	>8	Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space) End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed
8	Actual systems completed and "flight qualified" through test and demonstration An HRL Level 8 Habitation System is at a stage where the integrated habitation system is the actual "flight qualified" system that has completed qualification testing. Compliance to the habitation system requirements	>8	

(continued)

Table 6.1 (continued)

HRL	Definition of the habitation readiness levels 5–9	TRL	Definition of the technical readiness levels 6–8
	and standards has been verified by test, analysis, or a combination thereof		
9	Actual system "flight proven" through successful mission operations. An HRL Level 9 Habitation System is at a stage where the habitation system has been flown, deployed and made operational. It has demonstrated that it has met mission objectives. Post mission-debrief data will assist in defining any aspect of the habitation system that requires improvement, and changes in the collection of technologies and their overall integration and configuration can be addressed and applied as lessons learned	>8	

6.2 Mission Assessment Strategies

Prior to planning an analog mission, potential analog approaches and missions have to be evaluated. This process can be compared to an evaluation process of a space mission. Mission evaluation strategies are based on defining mission attributes and are directly linked to corresponding TRLs and HRLs. In order to compare performances of devices, systems, or methods, the Figures of Merit (FOM) format is commonly used (Fig. 6.1). FOM is frequently applied by the National Aeronautics and Space Administration (NASA) centers as a "*practical and efficient way to characterize and compare project's attributes and to evaluate them.*" (Schrader and Rickman 2010) Application of this method to results of research and concept development stages precedes testing and evaluation stage of proposed design solutions. Figures of Merit, along with other tools for comparison and evaluation (assessment tables and matrixes), are an effective methodology for quantitative analysis of design considerations.[2] Those tools can be applied for all design elements and at every stage of the design development of a habitat, an overall settlement, and other facilities and structures. Non-quantitative attributes can be translated into programmatic and physical attributes. These attributes can then be evaluated for example:

[2]Further Reading: Cohen, Marc M.; Houk, Paul C. (2010 September). Framework for a Crew Productivity Figure of Merit for Human Exploration (AIAA 2010-8846). AIAA Space 2010 Conference and Exposition, Anaheim, California, USA, 30 August–2 September 2010. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

- affordable level of redundancy (launch constraints)
- level of complexity (sub-systems)
- level of relevance to crew physical safety (critical elements)
- level of relevance to mission success (achieving mission goals and performance requirements)

Note: Preliminary assumptions can be made based on 'common sense' and experience from previous analog missions on Earth and human space missions.

6.2.1 Example: Comparison of Habitation Schemes

In the frame of a study on the Minimal Functionality Habitation Element (MFHE) for Lunar Surface Systems Concepts, various options were developed.[3] Figure 6.1 presents a FOM assessment on general and priority features of four generic MFHE configurations for preliminary lunar habitation concepts. Priority applications rate each scheme for potential evolutionary uses.

Limitations and benefits are visually comparable. The category 'Priority Applications' indicates which concepts have the potential to be used for Mars missions. In this case, scheme 3 and 4 scored best for further development. This example of a FOM considers prospective benefits and limitations of various generic module configurations to serve evolutionary needs leading from early lunar habitation to outposts and settlements. Possible lessons and applications for human exploration of Mars had to be taken into account. An objective of such analysis was to postulate resourceful growth paths that build upon an inventory of versatile, upgradable assets.

Instead of putting values such as good, fair, poor, etc., numbers can be used and sums can be scored. An assessment table for a student space architecture project for the areas: Concept, Representation, and Space Architecture is shown in Sect. 2.4.

6.2.2 Discussion and Tasks

Identify goals and major requirements for planning a Mars manned fly-by mission with a crew of four and list them according to a level of complexity and relevance to crew safety. What are the major drivers for your assumptions?

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[3]More information on the NASA Lunar Surface Systems Concepts along with the presentations of the MFHE can be found at: http://www.nasa.gov/exploration/library/lss_systems_concepts_workshop_prt.htm.

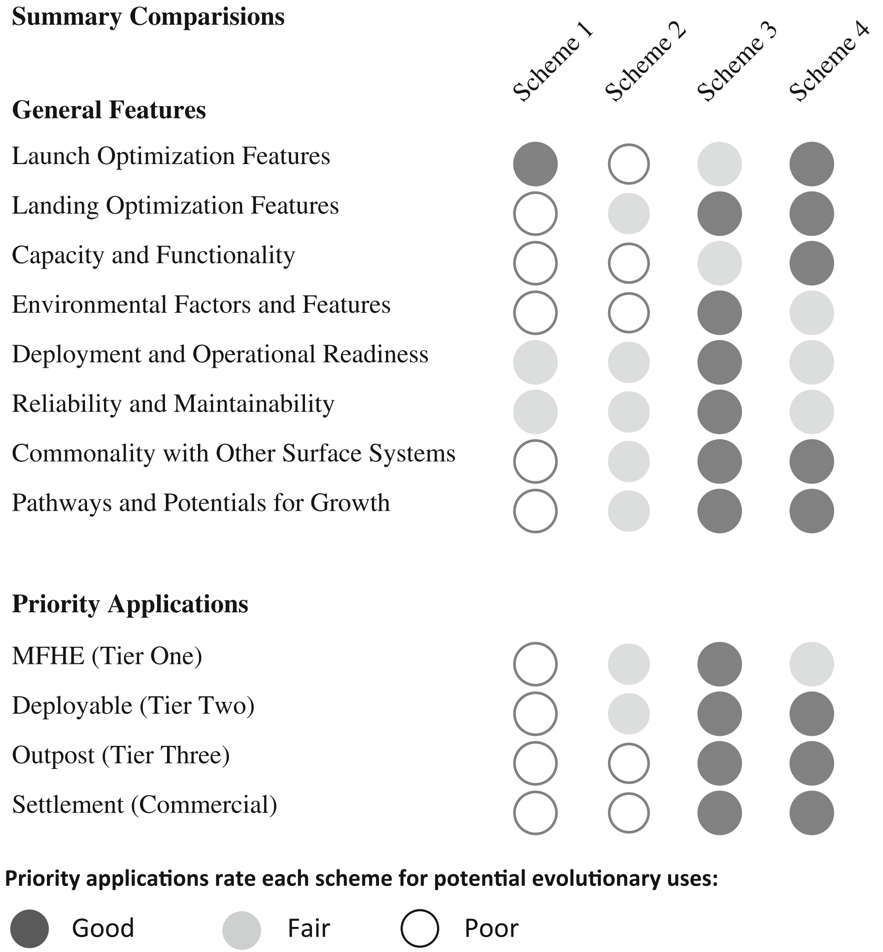

Fig. 6.1 Summary comparison of FOM assessments relating general features of the four generic MFHE configurations (MFHE study, SICSA, 2009. Bannova and Bell 2011)

6.3 Verification and Testing Methods

> **Questions for Exploration**
> Why do we need verification methods? What can and cannot be tested in Earth conditions? What is the goal of testing habitats and their systems and elements?

The verification process for design solutions requires extensive preparation work, time, and material resources. Verification can be applied to different aspects of design solutions: from mechanisms and units to mission and operational schedules.

With significant improvement of Virtual Reality (VR) technology, many of spaceflight related issues can be simulated in an artificial reality. The aerospace manufacturer Thales Alenia Space Italia uses VR in support of the design and validation phases. In the VR-LAB they simulate, for example, the following (Basso et al. 2012, p. 1):

- Assembly Integration Test (AIT) phases: Are the planned AIT procedures feasible?
- The Human presence in some elements: What is the habitability of a module?
- Regular EVA and IVA activities: What is the reachability of a particular area? What is the operability of the tools?
- Maintenance of elements: What are the maintenance procedures if a failure occurs? (or to prevent a failure)
- Design: What is the best design for the Human-Machine-Interface?

However, VR methods can only be applied to a limited number of tests and are still considered low-fidelity.

Full-scale mockups and analogs offer a wider range of advanced testing capabilities. Usually elements and sub-systems or systems have already been verified before a full-scale mockup is tested in an appropriate environment. Table 6.2 shows Mock-up and simulator attributes in relation to TRLs. The goal is to perform human

Table 6.2 Technology readiness levels (TRLs) in relation to mock-up/simulator attributes (adapted from Cohen, M.)

TRL	General description	Mock-up/Simulator specific attributes	Simulation facility needed
1	Basic principles observed	Conceptual Design to show that X can exist with attributes Y&Z	No, scale models, usually work as well as full-scale mockups
2	Concept formulation, modeling, and simulation	Control design variables for dimensions	Architectural Experiments
3	Proof of concept	Form, fit, function, mechanical operations	Engineering integration phase
4	Component/Subsystem test in a laboratory environment	Functional and operational research	Includes part task flight simulator
5	Subsystem test in a relevant environment	Partial habitable living and working environment simulation	Includes motion-based flight simulator
6	System test in a relevant environment	Full habitable living and working environment simulation	Includes high fidelity mission simulator

testing of all (or almost all) systems including the habitat itself in an environment closest to the mission conditions before launch. Such an ‘analog mission’ demands similar planning efforts as planning a future space mission (cf. Deems and Baroff 2008; Cohen 2012).

Space agencies have performed multiple analog missions since the beginning of human space exploration. They continue developing analog missions that are aligned with new space exploration roadmaps. An overview of past and present simulators and simulation missions is given below (Deems and Baroff 2008; Mohanty et al. 2008).

Past Simulators and Simulation Missions:

- Regenerative Life Support Study by NASA Langley Research Center
- Apollo Ground-based Tests
- Skylab Medical Experiments Altitude Test (SMEAT)
- Skylab Mobile Laboratory (SML)
- Ben Franklin Underwater Research Laboratory
- Tektite I and II Underwater Research Laboratories
- BIO-Plex (Bioregenerative Planetary Life Support Systems Test Complex)
- BIOS-3 (Institute of Biophysics, Krasnoyarsk, Russia)
- Biosphere-2
- Lunar Mars Life Support Test Project (LMLSTP)
- Closed Ecology Experiment Facilities (CEEF)
- Mars 500 (RSA and ESA)

Current and Planned Simulators and Simulation Missions (as of 2015):

- Aquarius and NASA Extreme Environment Mission Operations (NEEMO)
- Mars Desert Research Station (MDRS)
- Flashline Mars Arctic Research Station (FMARS)
- Concordia research station in Antarctica
- NASA Fast Track Horizontal and Vertical Mock-Ups for lunar habitation
- Facility for Integrated Planetary Exploration Simulation (FIPES)
- Environmental Habitat (EnviHab)
- European Mars Analog Research Station (EuroMARS)
- Australian Mars Research Station (MARS-Oz)
- Virtual Simulators located at Industries, such as TAS-I VR Lab
- HI-SEAS Hawaii Space Exploration Analog and Simulation

The selection of an appropriate mission analog depends on many factors. All space missions require the development of a combination of several analogs and test-beds in order to approve mission objectives. The goal is to replicate configurations’ experiences in microgravity and partial gravity environments. However, it is important to remember that not all conditions can be tested in analogs on Earth. For example, zero or microgravity conditions can only be imitated under-water and during 30 s free-falls during a parabolic flight. Partial gravity can be simulated with the help of mechanical devices that are limited by lab environments and capabilities (e.g. for space suit testing[4]). Therefore, surface conditions of Mars or the Moon can only be simulated to certain degree of resemblance, including creating simulations of regolith or Mars soil compositions (Benaroya 2010; Schrunk et al. 2008).

6.3.1 *Risk of an Incompatible Habitat Design*

The 'risk of incompatible vehicle or habitat design' has been identified by NASA as recognized risk to human health and performance in space (NASA [Risk] 2013, p. 3). Mockups and simulators are seen as appropriate measures to represent and to understand the strengths and weaknesses of layout configurations (Fig. 6.2a, b). The fidelity of the mock-up is strongly related to the TRLs as showcased in the guest chapter by Marc M. Cohen (Sect. 3.5).

Key contributing factors are listed in Table 6.3 along with examples of evidence that appropriate design can reduce injuries, mistakes, or even failures.

6.3.2 *Analog Habitat and Environments*

Prior to the lunar landing for the Apollo program, NASA used terrestrial analogue sites for understanding planetary features, for testing equipment, and for training astronauts to perform scientific tasks. In general, analogue studies are driven by the need to understand processes and to optimize exploration requirements and strategies for future planned human missions.

Past and present mission simulators include analog habitats, such as Desert Research and Technology Studies (Desert RATS) field test series, NASA Extreme Environment Mission Operations (NEEMO) underwater expeditions, Human Exploration Research Analog (HERA) testing (Fig. 6.3), and the HI-SEAS Hawaiian mission. These tests are supported by a vast number of studies, which also can be used for further research (Fig. 6.4).[5]

Sources for further research:

- ESA HUMEX Study: A study on the survivability and adaptation of humans to long-duration exploratory missions (2003). This study includes risk assessments for human missions to Mars.
- ESA REGLISSE Study: Review of European Ground Laboratories and Infrastructures for Sciences and Support of Exploration (2002). This study includes a survey of existing facilities.

[4]The spacesuit simulator Aouda by the Austrian Space Forum (OEWF) replicates the weight to strength ratio present on Mars through the Hard-Upper-Torso and an adjustable exoskeleton.
[5]NASA Human Research Program: http://www.nasa.gov/hrp/research.

Fig. 6.2 **a** Mir station mock-up in Star City (Zvezdny). **b** Skylab back-up station in the Smithonian, Washington D.C.

Table 6.3 Key contributing factors to habitat design (NASA [Risk] 2013)

Key contributing factors	Example of evidence
Anthropometric and biomechanical limitations	A number of crew-activities (stowing equipment, translating, eating, etc.) have caused in-flight musculoskeletal injuries
Motor skill/coordination or timing	A microgravity environment leads to distortion of orientation and posture; the ability to avoid moving objects is impaired
Space and lunar visual environments	Improperly lit displays and controls may lead to mistakes and confusion
Vibration and g-forces	Vibration can cause injuries and also impairment to equipment
Noise interference	The detrimental effect on face-face speech communication at high noise levels has been reported
Seating, restraints, and personal equipment	Lower back discomfort and numbing of feet and legs has been reported
Visibility/Window design and placement	Window watching (without a handle) was listed as probable cause for the leak of a flex hose used as a handle
Vehicle/Habitat volume/layout	Insufficient habitable volume and inappropriate functional layout can decrease productivity and habitability

Fig. 6.3 Human exploration research analog (HERA) mockup at NASA Johnson Space Center

- Integrated High-Fidelity Planetary Mission Simulators: A Toolkit for Fidelity Evaluation by Mohanty (2010). This work includes a survey of past, present and planned Human Space Simulators.
- NASA Human Research Program: Integrated Research Plan (HRP-47065, 2015). The Integrated Research Plan (IRP) defines Human Research Program (HRP) research and technology tasks. The IRP goal is to present strategy and

Fig. 6.4 The HI-SEAS habitat on Mauna Loa, Hawaii (NASA Astrobiology Institute)

tactical plan for research development in order to meet requirements outlined by the Human Research Program.

Each isolated, confined, and extreme environment (ICE) has its own limitations and strengths as an analogue environment for the development of future habitats. Some will be introduced in the following:

Polar Research Stations

Polar (Arctic and Antarctic) areas are terrestrial locations to test human factors during winter-over operations and technological remote operations.

Challenges for overwintering crews that have great similarities to space missions include the following (ESA [Concordia] 2013, p. 6):

- Prolonged isolation and confinement.
- Hostile natural environment (extreme low outside temperatures, chronic hypobaric hypoxia).
- Autonomy: the crew needs to be totally self-dependent especially from February to November where no access to and from Concordia station is possible.

Fig. 6.5 Inflatable habitat deployed in McMurdo station, Antarctica (NASA)

- Life in a small multicultural setting (different languages and behavioral customs).
- Limited mobility outside of the station buildings, especially during winter.
- Under stimulation, boredom.
- Night/Daylight variations.
- Change in atmospheric pressure at the beginning of the stay.

In Europe the Concordia station is used in cooperation with ESA for preparatory activities related to a future human exploration mission to the Moon or Mars. Every year researchers in medicine, physiology, and psychology commit to do research at the Concordia station.

One of the most recent habitat analogue facilities was jointly developed by NASA, ILC Dover, and NSF in McMurdo station in Antarctica in 2009. An inflatable module was deployed there to test technology and capability to remotely control (from the Johnson Space Center in Houston) the sensors installed inside the module and other equipment (Fig. 6.5).

Underwater Analog Habitats

Underwater conditions are very similar to conditions in space, on an asteroid, or the Moon. Both environments: space and underwater, demand substantial planning and very complex technologies (Fig. 6.6a, b). Such conditions include the necessity of having a pressurized habitat to protect the crew from the external environment, requirements for EVA operations, dependence on life support systems, and psychological constrains of living in a confined and isolated space. Underwater facilities offer means for testing technologies, systems, tools, and operations of the habitat and EVA-related activities. Specifically they can test vehicles and crew operations in 0-gravity conditions. In addition, the underwater environment allows simulating different gravity conditions.

An example of an underwater analog facility is the NASA Extreme Environment Mission Operations project (NEEMO) Aquarius research station located underwater off the coast of Florida (Fig. 6.6a, b). Underwater facilities such as NEEMO are used to test EVA equipment and operations.

Isolation Chambers

Missions using confined environment analogs, such as isolation chambers, usually focus on psychological aspects of a long-term space flight and operational procedures including EVA operations (see more information on isolation chambers in Marc Cohen's Guest Statement in Sect. 3.5). Other purposes include, but are not limited to (Mars 500):

- Evaluation of new technologies, systems, and tools for life support and emergency situations;
- Investigating how confined conditions of a space habitat influence human health and work performance;
- Organization and testing communications between the crew and mission control;
- Testing and verification of habitat technologies;
- EVA procedures simulations;
- Testing and verification of medical and health monitoring procedures;
- Verification of means and methods of telemedicine for distant control over the state of human health;
- Verification of methods and procedures for psychological and physical health support; and
- Testing and evaluating data collecting procedures and methods.

An example of a terrestrial analog mission in preparation for a human mission to Mars was the Mars 500 experiment (IMBP RAS 2011), a collaborative project between Russian Space Agency (RSA) and European Space Agency (ESA). It was organized and planned through the Moscow Institute of Biomedical Problems (IMBP) of the Russian Academy of Sciences (RAS) and included a number of experiments starting in 2007 with completion of the program in 2011 (Fig. 6.7).

The crew was comprised of three Russian members, two from the European Space Agency, and a Chinese participant. The crew performed tasks planned according to a long-term mission timeframe with specified dates of experiments conduction. Considerations taken into account included labor intensity, complexity of required methodologies, crew members' specialties, and possibility of experiments to cross-reference and influence each other, and observation if some special conditions are present during an experiment's implementation.

Stages of the experiments included a 14-day isolation (completed in November 2007); a 105-day isolation (completed in July 2009), and a 520-day isolation (April 2010–October 2011).

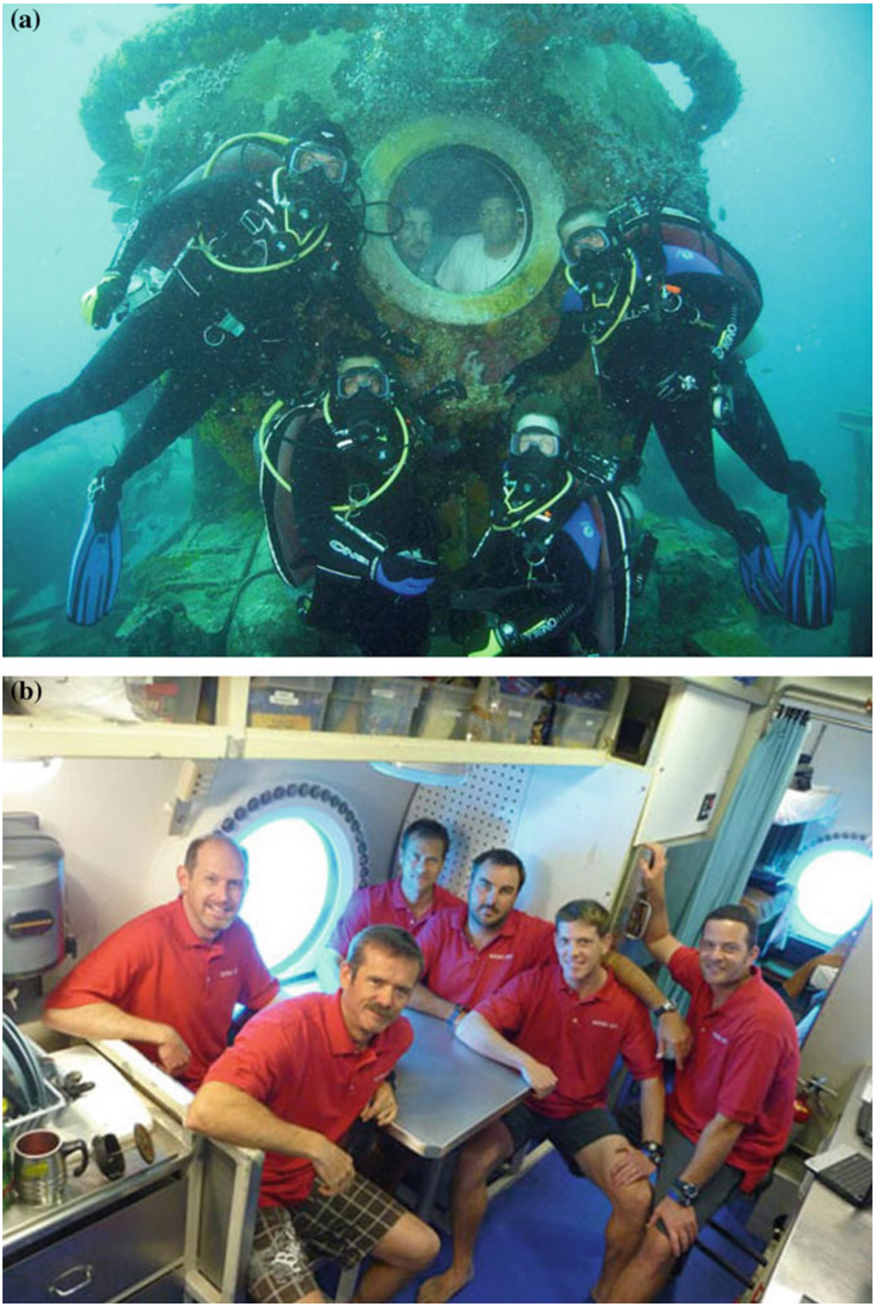

Fig. 6.6 **a** The NEEMO 12 crew (May 7–18, 2007) pose for a group photo at their undersea Aquarius habitat (NASA). **b** The NEEMO 14 crew (May 10–24, 2010) consisting of two astronauts, a veteran undersea engineer and an experienced scientist and two NURC hab techs, inside Aquarius (NASA)

Fig. 6.7 Interior of the Mars 500 (Mars 500) habitat (IMBP RAS) (Programs and simulators: “Mars-500” http://zvezdniygorodok.ru/tours/mars500/ (Rus))

6.3.3 Experience from Past Space Habitats

In addition to space simulators on Earth, past space habitats can be considered as analogs for future missions as well. In particular, a lot of research has been done and published about the habitability studies during the Skylab missions.[6] NASA has evaluated the safety record, operations, and human factors of the Mir station.[7] In ‘Architecture for Astronauts’ (Häuplik-Meusburger 2011), a cross-program comparison and analysis of all major inhabited human spacecraft and space habitats was made from a human perspective as a basis for the systematic assessment of existing and future living and working environments in space.

6.3.3.1 Example: Moving in Microgravity

The ‘real’ microgravity research started during the Skylab missions in 1973. The Skylab space stations provided the largest habitable volume within one volume (with an approximately 6.6 m diameter). Despite of previous astronauts’ experiences in microgravity, Skylab was the first station where astronauts could experience relatively free moving in microgravity.

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[6]Further Reading: The Skylab Experience Bulletins, NASA (1973).

[7]Further Reading: 1985 Space Station Crew Safety: Results from Mir by Marilyn Dudley-Rowley, Marc M. Cohen, Pablo Flores (2004).

A Skylab's objective was to test a long-term living and working environment. That included a number of special designs related to microgravity research. Many of them became redundant very soon, e.g. specially designed triangle soleplate shoes that were meant to assist astronauts in stabilizing and moving around the station; chair-type body restraints and a 'fireman' pole (cf. NASA Bulletins). However, much of the research is still valid today and presents a foundation for diverse biological studies and research related to micro-gravity technology. One example is a widely used reference to the 'Neutral Body Posture' (Fig. 4.2) that is based on measurements made by the Skylab 4 crew (cf. Häuplik-Meusburger, p. 18) (Fig. 6.8).

6.3.3.2 Example: Technical Greenhouses

Growing your own food and incorporating greenhouses into space station's structure is a compelling idea of enabling sustainability into astronauts and cosmonauts everyday life in space. Long before the first manned spacecraft left the surface of Earth in 1961, Tsiolkovsky was already certain that human space exploration will require development of space agriculture, and plants should be an essential component of sustainable space habitat. To ensure such habitats can be built in the future, multiple biomedical experiments were conducted on early Soviet and US stations. Several biological experiments to grow flowers and crops run on Salyut stations in late 1970s and through 1980s, cosmonauts on those missions reported that plants become very important in their orbital life and greenhouses should be part of habitats for long-term space missions (Fig. 6.9a, b). After working with biological experiments on Salyut station Cosmonaut Lebedev said: "*While taking care of plants, fixing and improving biological units, we realized that long duration space flights will be impossible without plants*." (Technika molodeghi, 4, 1983, p. 7).

6.3.4 Aims of Verification Methods

The goal of a rigorous design process is to develop and evaluate approaches and methodologies for validating human factors models for vehicles and habitats. Methodologies should be developed through a series of iterative tests, including several key classes of modeling tools.

Goals of verification methods include (NASA [Research] 2015):

- Understand how vehicle/habitat architecture, acoustics, vibration, and lighting may affect crew performance and how those aspects can be accommodated in internal vehicle/habitat design.
- Analyze characteristics of human physical capabilities and limitations (e.g., body size and shape, movement range) that may change for selected mission aspects, and how internal vehicle/habitat design can be adapted for those changes.

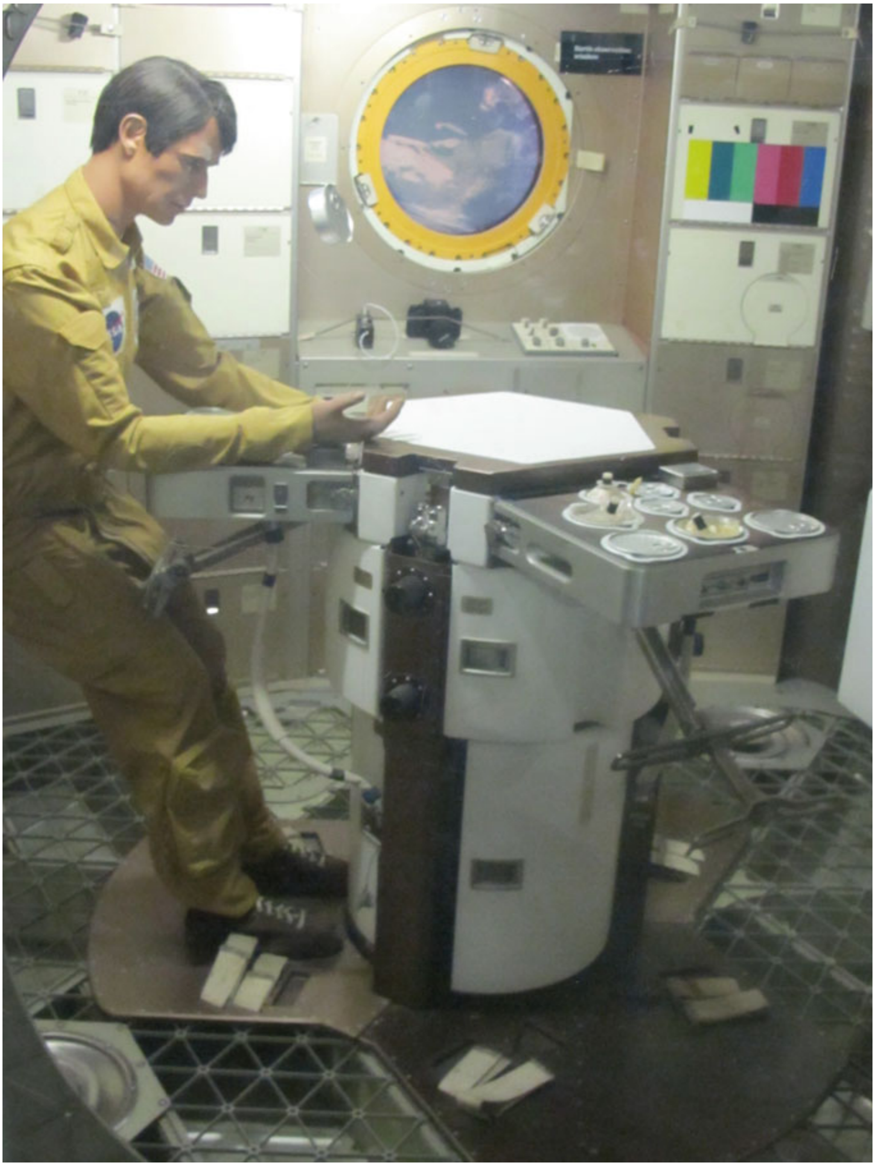

Fig. 6.8 Galley of the Backup Skylab station, showing the triangular grid floor and the restraints for the dining table (chair-type body restraints, slip-in foot restraints)

- Develop design guidelines for adequate habitable volume and design configurations for selected mission aspects.
- Define the Risk of Incompatible Vehicle/Habitat Design, and the acceptable level of risk due to inadequate internal vehicle/habitat design.

Fig. 6.9 A biological experiments on Soviet space stations: **a** Trapetsiya (Mir). **b** Malakhit (Salyut 7 and Mir)

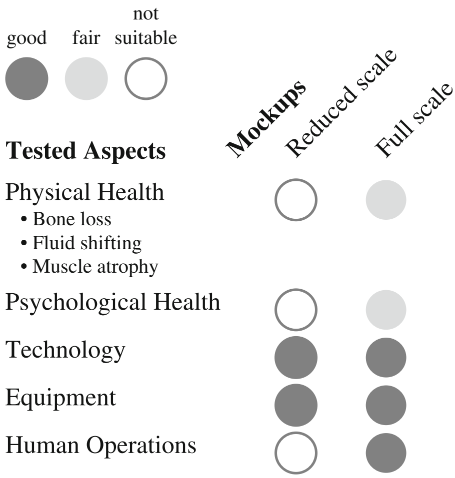

Fig. 6.10 Comparison table between reduced scale and full scale models

- Identify technologies, tools, and methods for data collection, modeling, and analysis (e.g., net habitable volume, layout, and usage) and for refinement and validation of level of acceptable risk.

Vehicle, habitat, and other facilities designs should adapt to various conditions of spaceflight and adjust to related changes in human physical and psychological characteristics. Duration of future space missions will be greater than past missions, which increases risks of acute and chronic ergonomic-related disorders. This can result in human errors and inefficiencies, a failed mission and program objectives, and an increase in the potential for crew injuries.

6.3.4.1 Example: Reduced Scale Models and Full-Scale Low Fidelity Mock-up Evaluations

Using FOM to evaluate mock-ups to test applicability for different characteristics of space mission aspects is presented in Fig. 6.10. Some technology related capabilities can be tested in reduced scale mockups while human factors related issues can only be tested in full scale mockup modules.

6.3.4.2 Example: Using ISS for Technology and Habitability Testing

The International Space Station is the best testing environment for space mission preparation, where most aspects of space flight conditions can be examined, but it still has its limitations due to a close distance to Earth and relatively quick and regular transportation capabilities.

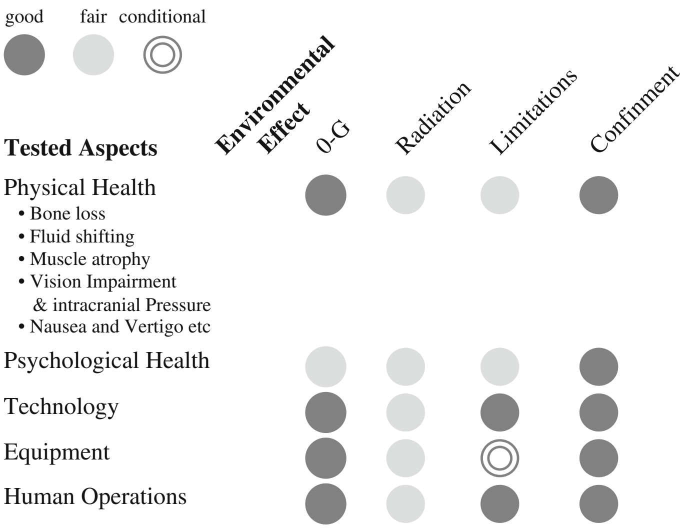

Fig. 6.11 Comparison table of environmental effects

Figure 6.11 presents an evaluation of testing some aspects of human spaceflight on the ISS.

6.4 Guest Statement: The TransHab Project—Testing and Evaluation—Part 2 (Kriss J. Kennedy)[8]

6.4.1 Background

The TransHab (Transit Habitat) concept was born from a Mars transportation architecture study led by Dr. William Schneider, NASA Johnson Space Center in 1997. I was part of the tiger team to design and develop an exploration habitat that would be used in conjunction with the Mars Interplanetary Transit Vehicle—a transit habitat. I started calling it the TransHab and then it became known as the "TransHab" hence forth. Our small team was challenged to design a habitat large enough to support a crew of six (6) on a 560–850 days transit mission to and from Mars, based on a short-stay-time (typically 30–60 days) at Mars, NASA Mars Design Reference Mission 5.0. At the time, this habitat had to be launched in the Shuttle Orbiter payload bay—which has volume and mass constraints. With the feasibility study design concept in hand, we were tasked to rapidly prototype its development and proof-of-concept demonstration testing. The testing of the tensile

[8]NASA Johnson Space Center.

fabric pressure vessel structure focused on surviving micrometeoroid and orbital debris impacts; demonstrating structural pressure integrity on this large a diameter structure—to 4× atmospheres; and demonstrating that the structure could be folded, packaged to 14′-6″ diameter (Orbiter payload bay), and deployed in a cold vacuum. Once we accomplished these main objectives, we were tasked to develop TransHab as an alternative to the ISS aluminum shelled Habitat—thus the ISS TransHab version matured until the project cancellation by Congress in 2001.

6.4.2 TransHab's Technologies

The TransHab transit habitat, concept represents a technology breakthrough in several areas: (1) in the development of flexible, high-load tensile composite structures; (2) in the development of an optimized independent inflatable pressure-shell of flexible fabric and integrated micrometeoroid and orbital debris (MM/OD) shielding technologies; and (3) in the application of both systems in a single reconfigurable habitat. This hybrid structure combines the packaging and mass efficiencies of a flexible inflatable structure with the advantages of a load carrying hard structure, Fig. 6.12.

The structural hard core is essentially a multi-component spindle (column) element that bears the principal shear loading in launch configuration. The core can be reduced to its role as a tensile stabilizer during on-orbit assembly by removal of its internal truss work and reuse of the truss' subcomponents (shear panels) as

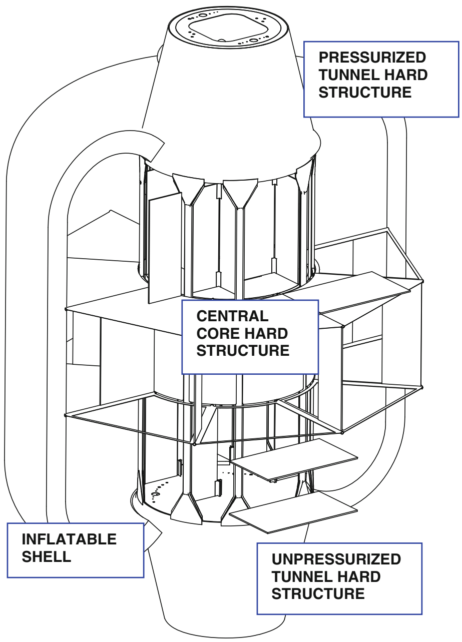

Fig. 6.12 TransHab hybrid structure (NASA)

interior framing and outfitting elements. In order to make this possible, the core's truss work is made up of modularized shear panel "shelf" units with a universal system for attachment to one another and to other core elements. Thus, the hard structures of the vehicle are part of a modular system, which allow them to respond efficiently to two very different loading conditions.

All of these structural core elements are made from a standard set of graphite-composite forms. The structure is remarkably low in weight relative to the capability that it gives the vehicle. In fact, some 50 % of the vehicle's total weight is contributed by the pressure-shell, a combination of robust inflatable restraints and high-performance debris and thermal shielding.

The inflatable shell is a separate system from the TransHab's primary structure, and thus can be optimized in its function as a pressure vessel shell. Folded and compressed around the core for launch, the shell is deployed and inflated on-orbit. It is composed of four functional layers: the internal scuff barrier and pressure bladder, the structural restraint layer, the Micrometeoroid/orbital debris shield, and the external thermal protection blanket. Woven from 1″ wide Kevlar or Veteran straps, the restraint layer is designed to contain four (4) atmospheres of 14.9 psia air pressure. Each shell restraint area is structurally optimized for that area's load. In order to accomplish this, strap seams were developed achieving over 90 % seam efficiency. Particles hitting at hyper velocity expend energy and disintegrate on successive Nextel layers, spaced by open cell foam. Backing layers of Kevlar add an additional degree of protection—a considerable amount of the shell mass is attributed to the MM/OD protective layers. An inner liner of Nomex provides fire retardant and abrasion protection. Three Combitherm bladders form redundant air seals. A felt layer provides a vacuum evacuation between bladder layers (necessary for launch packaging). The TransHab shell, Fig. 6.13, shows to the far left the Multilayered Insulation, followed by four layers of bullet-proof materials separated by open-cell foam; to the right of this is the webbing of the main restraint layer. Inside (to the right of) the restraint layer are the redundant bladder layers and, on the far right, the interior "wall" or scuff barrier.

6.4.3 Demonstration of Inflatable Shell

TransHab's whole design concept was based on a relatively unproven—at the time—space inflatable pressure vessel structural technology. The team had to prove this technology would work and was safe. There were three important prototyping demonstration goals set for the team to prove that an inflatable structure is a feasible structural technology for human-rating in space:

1. Demonstrate how to protect an inflatable structure from being ruptured by micrometeoroid and orbital debris impacts of the LEO environment.
2. Demonstrate a large diameter fabric inflatable pressure vessel structure can hold one atmosphere pressure in the vacuum of space. However, being a fabric

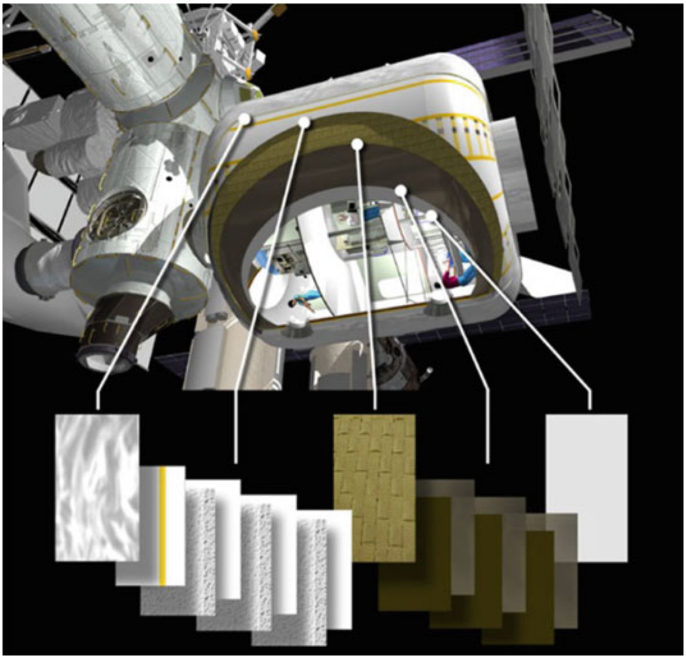

Fig. 6.13 TransHab shell layers (NASA JSC S99-05362)

structure the terrestrial industry standard is a safety factor of 4—thus 4× atmospheric pressure.

3. Demonstrate TransHab core and shell—including the MM/OD shield—could be folded, packaged and then deployed in the vacuum of space.

6.4.4 Demonstration Goal One—Protect the Shell from MM/OD

The first demonstration goal was achieved by building a typical inflatable MM/OD shell layup and performing Hyper Velocity Impact testing at JSC and the White Sands Test Facility. The TransHab goal is to have a minimum of 0.9820 Probability of No Penetration (PNP), Fig. 6.14. MM/OD impact analysis was performed taking into account the location of TransHab on ISS and its size. Both of which affect the PNP calculations, Fig. 6.15. Numerous one-foot (12″) thick orbital debris shield coupons were made and tested. Small representative MM/OD particles were initially used with the debris shield taking shot after shot and kept passing—exceeding all expectations. The TransHab MM/OD shell survived a 1.7-cm Aluminum sphere at hypervelocity of 7 km/s (15,600 mph), Figs. 6.16, 6.17 and 6.18. With the

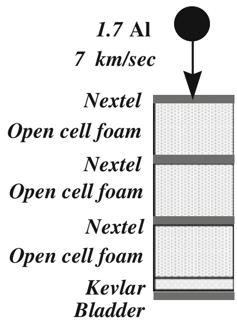

Fig. 6.14 TransHab shell MM/OD design

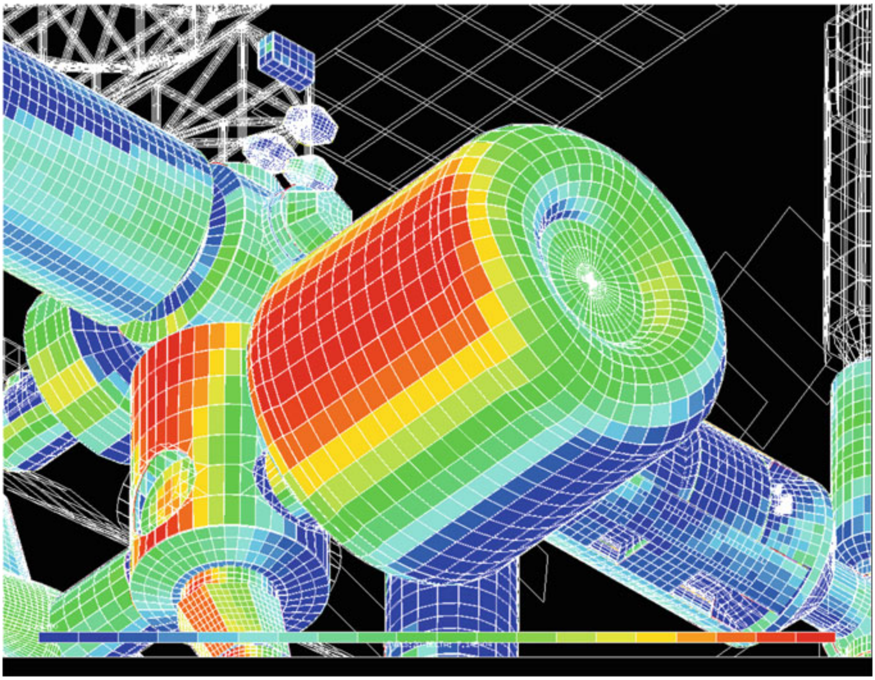

Fig. 6.15 TransHab shell MM/OD PNP analysis (NASA)

successful completion of the Hyper Velocity Impact testing and inflatable shell development tests, TransHab was on its way to proving that the inflatable structure technology was ready for the space age.

Building a typical shell lay-up and performing Hyper Velocity Impact testing at JSC and the White Sands Test Facility achieved the first goal. These series of tests proved to be very important. If the debris shield could not stop the particle, then TransHab had no chance of surviving—technically or politically.

Fig. 6.16 TransHab shell MM/OD hypervelocity impact test (NASA)

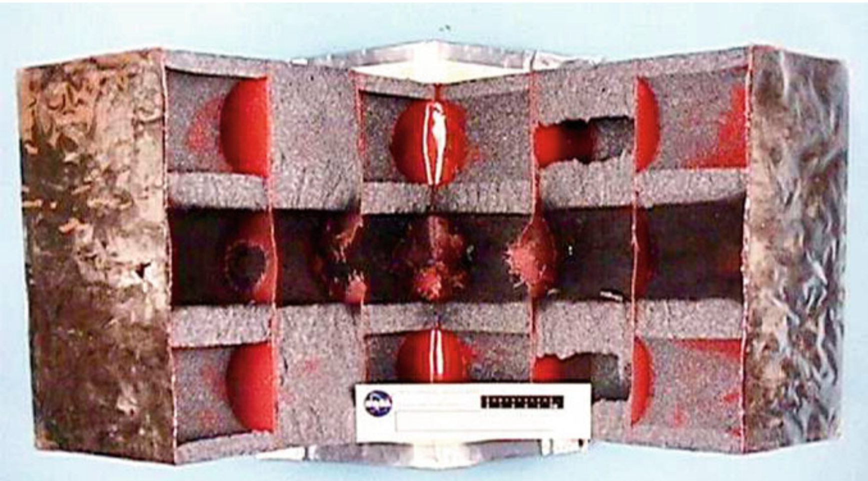

Fig. 6.17 TransHab shell MM/OD hypervelocity impact test (NASA)

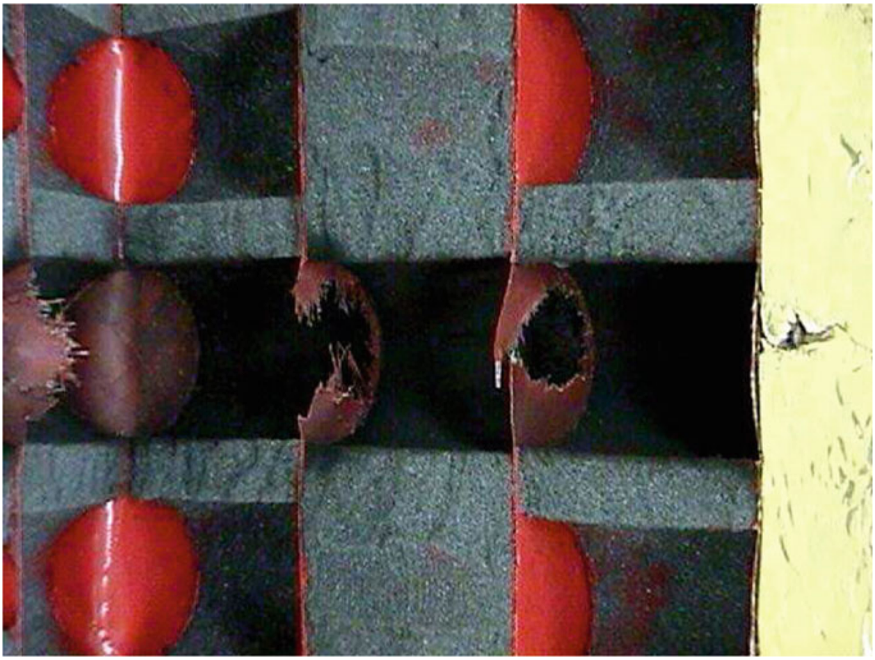

Fig. 6.18 TransHab shell MM/OD hypervelocity impact test (NASA)

The test engineers who set up the shot like to blow stuff up with their hypervelocity gun(s). At first they were disappointed that they were not failing the target, but then they got real excited when they realized the breakthrough they were now a part of. This turned out to be so important that Scientific America Frontier with Alan Alda included these shots as part of a series on Mars mission technologies, Fig. 6.19. TransHab made great strides to prove inflatable structures technology is ready to be applied as habitats for space applications.

6.4.5 Demonstration Goal Two—Full Scale Diameter Hydrostatic Test

Two (2) shell development structural test articles (units) were built and tested at JSC to prove the second and third goal. The first test article was to prove the inflatable restraint design would hold to the 14.7 psia operating environment for the crew to live in. This unit was 23 ft ($\sim$7 m) in diameter by 10 ft tall. Since we were testing the hoop stress, it did not have to be the full TransHab height. Using the aviation recommended safety factor of four (4) for tensile fabric structures used in airships and blimps, NASA used this as a basis for its test. This test soon became

Fig. 6.19 TransHab shell MM/OD hypervelocity impact test results (NASA)

known as the 4.0 test. This meant the restraint layer had to withstand the equivalent stress of four (4) atmospheres. The only safe way and place to perform such a potentially dangerous test was to perform a hydrostatic test in the Neutral Buoyancy Lab at JSC, Fig. 6.20. This test was completed in September 1998 marking yet another historical milestone for inflatable habitat structures. Figure 6.21 shows the first full scale diameter structural test article being lowered into the NASA Neutral Buoyancy pool. It failed—ruptured during the test. We had to redesign some of the stitching to strengthen the seams.

Figure 6.22 shows the second full scale diameter structural test article being lowered into the NASA Neutral Buoyancy Laboratory (NBL) pool. NASA built a second unit in a month and successfully retested this unit to ~4 atmospheres, approximately 58.8 psid (Fig. 6.23).

6.4.6 Demonstration Goal Three—Shell Deployment in a Vacuum

The second structural test article was to prove the inflatable shell design could be folded, packaged around the core, and deployed in a vacuum environment. This structural test article reused the hydrostatic test article bulkheads and rebuilt a full height inflatable restraint layer, Figs. 6.24 and 6.25. Also included in this test was the orbital debris shield that was proven in goal 1. The one-foot thick debris shield is vacuum packed from 12″ (~30.5 cm) to a few inches to reduce its thickness for folding to enable the module to fit into the Orbiter payload bay, Fig. 6.26. Once on orbit, TransHab is deployed with the debris shield being released to its desired

Fig. 6.20 TransHab full scale diameter structural test article (NASA)

thickness. Figures 6.27 and 6.28 shows two technicians performing a final inspection of the test unit before folding the unit. TransHab was successfully folded and deployed in the vacuum environment of Chamber A in December 1998, proving the third goal, Figs. 6.29 and 6.30. With the successful completion of the Hyper Velocity Impact testing and inflatable shell development tests, TransHab has proven that the inflatable structure technology is ready for the space age.

TransHab made great strides to “prove” or demonstrate that inflatable structures technology is ready to be applied as habitats for space applications. ISS TransHab’s design met or exceeded the habitation requirements for space station. TransHab put the “Living” into “living and working in space.” This basic design and technology are appropriate for LEO commercial development, deep space exploration, and for planetary surface habitats. Technologies developed by the TransHab project have multiple spin-off applications for uses both on-Earth and in-space.

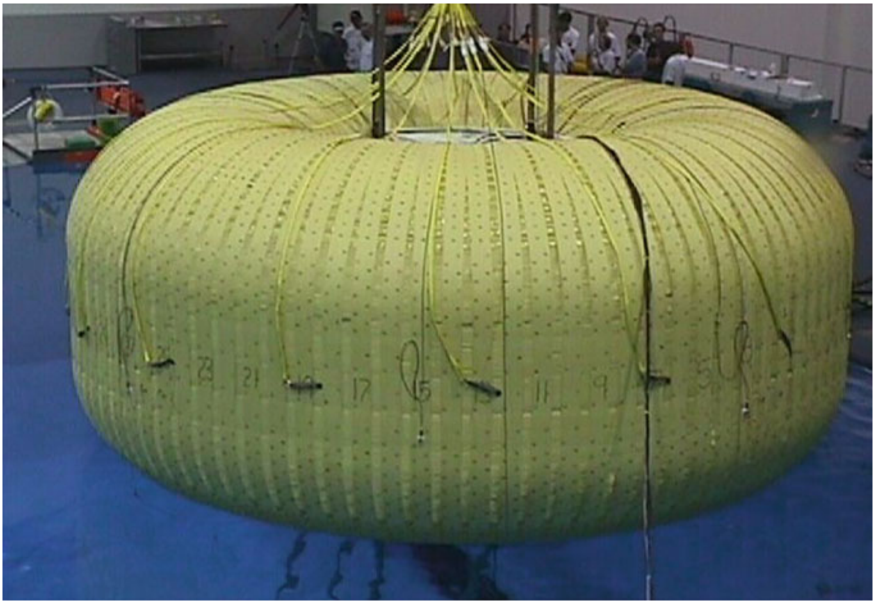

Fig. 6.21 TransHab hydrostatic test #1 ~30 psid (NASA)

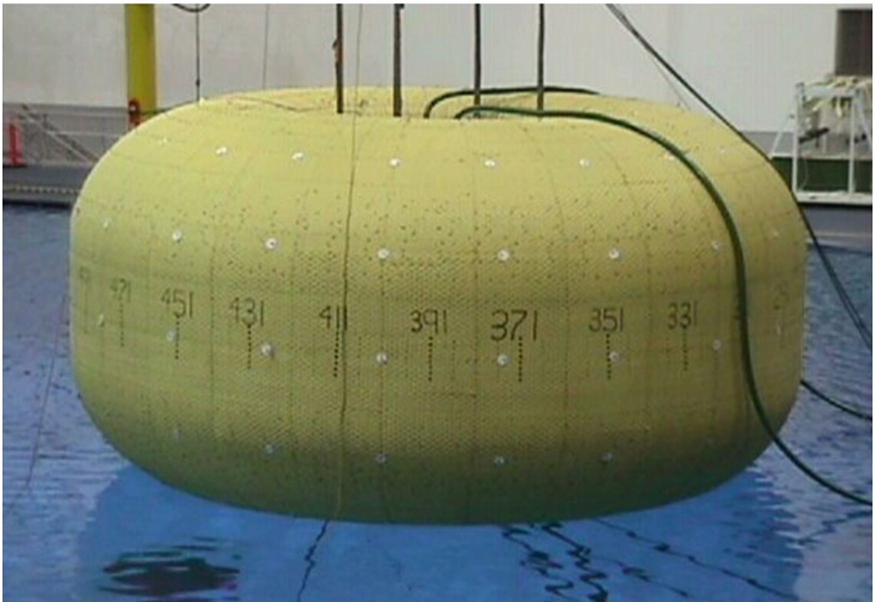

Fig. 6.22 TransHab hydrostatic test #2 ~60 psid (NASA)

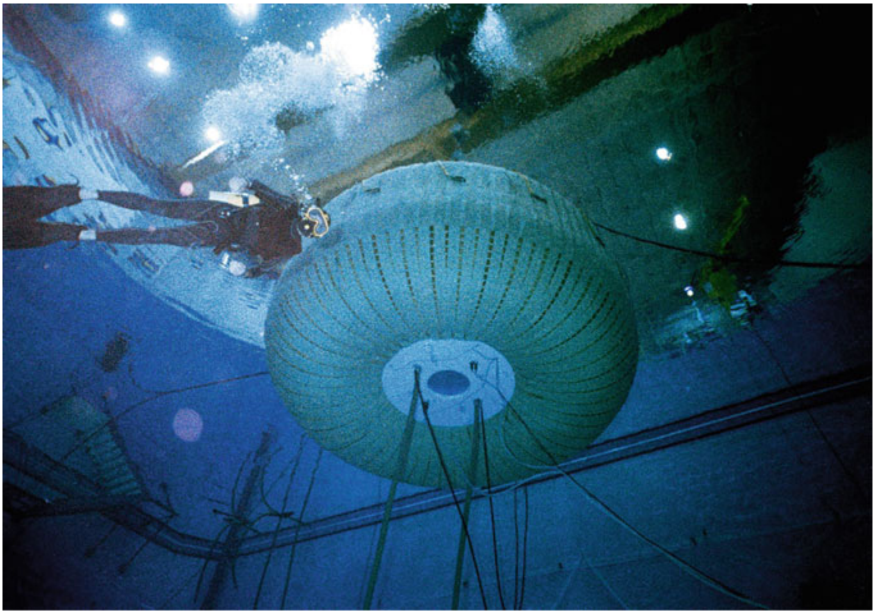

Fig. 6.23 TransHab full scale diameter STA in the NASA NBL (NASA)

Fig. 6.24 TransHab Full Scale Demonstration Unit Restraint Layer Assembly (NASA)

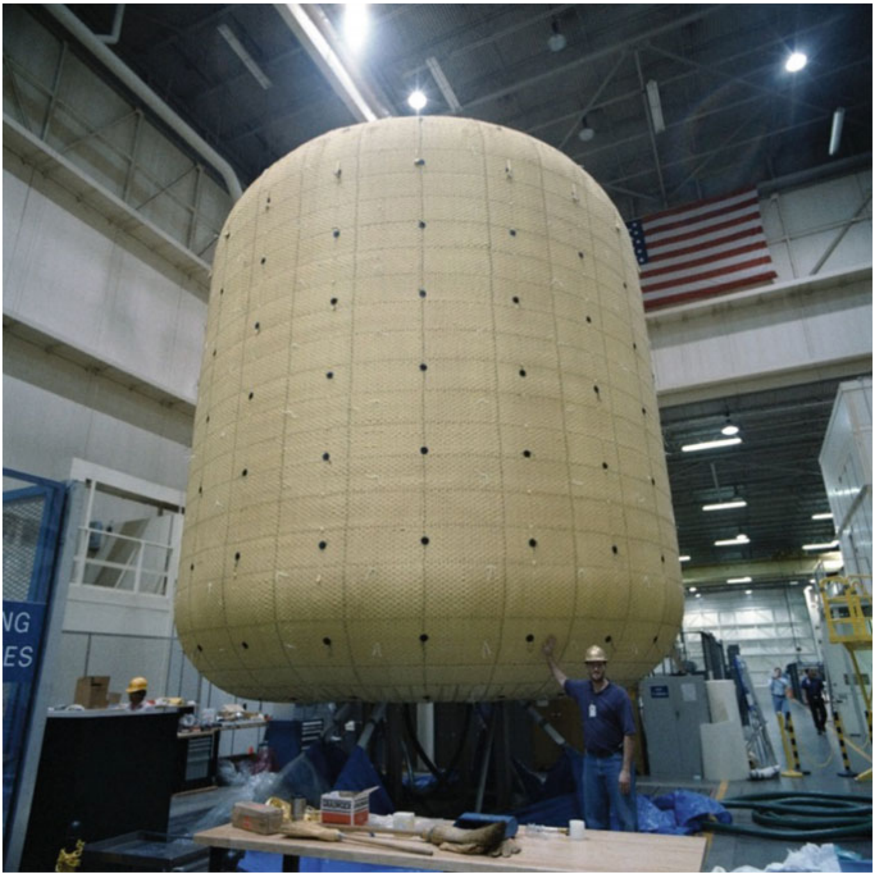

Fig. 6.25 TransHab Full Scale Demonstration Unit (NASA)

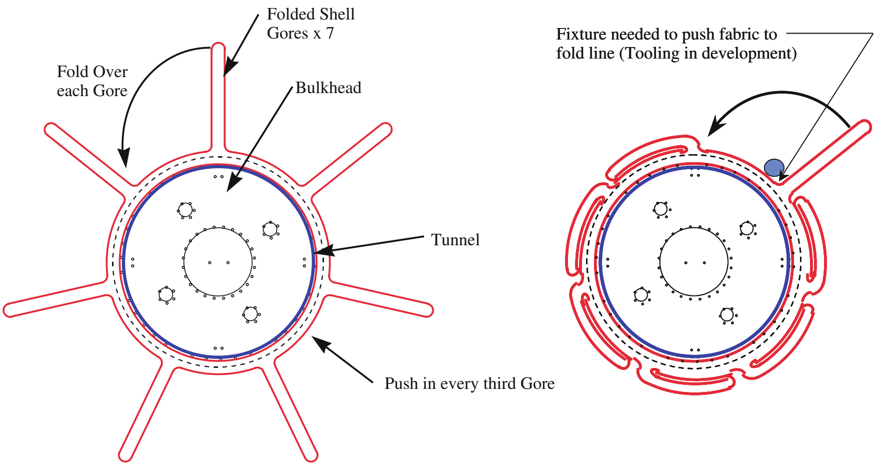

Fig. 6.26 TransHab folding concept (NASA)

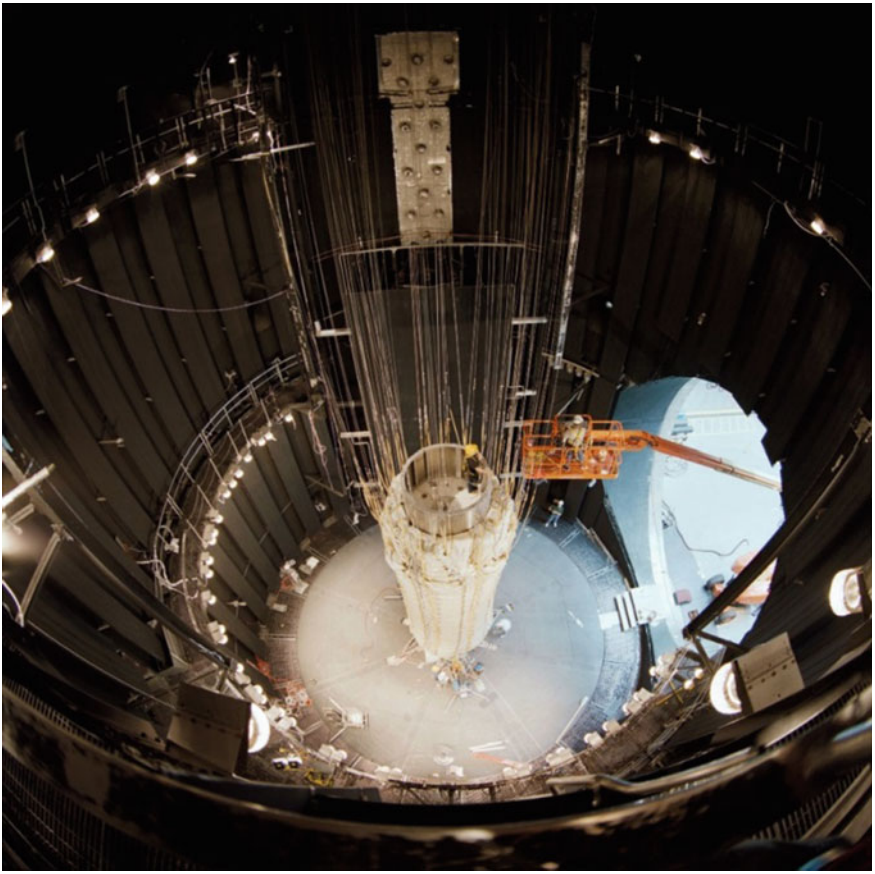

Fig. 6.27 TransHab vacuum deployment test (NASA)

6.4.7 Lessons Learned

There are many lessons from my TransHab Project experience. One of the most important lessons I can think of is to keep the project focused on the technology development and rapid prototyping. TransHab moved too quickly out of pure technology development trying to become a replacement for the ISS aluminium Habitat. This allowed for congressional scrutiny and subsequent cancellation. A similar fate that occurred with the X-38. From a technical perspective, the approach of build a little, test a little, evaluate, and learn was of great value technically and managerially—building momentum and advocacy along the way. It

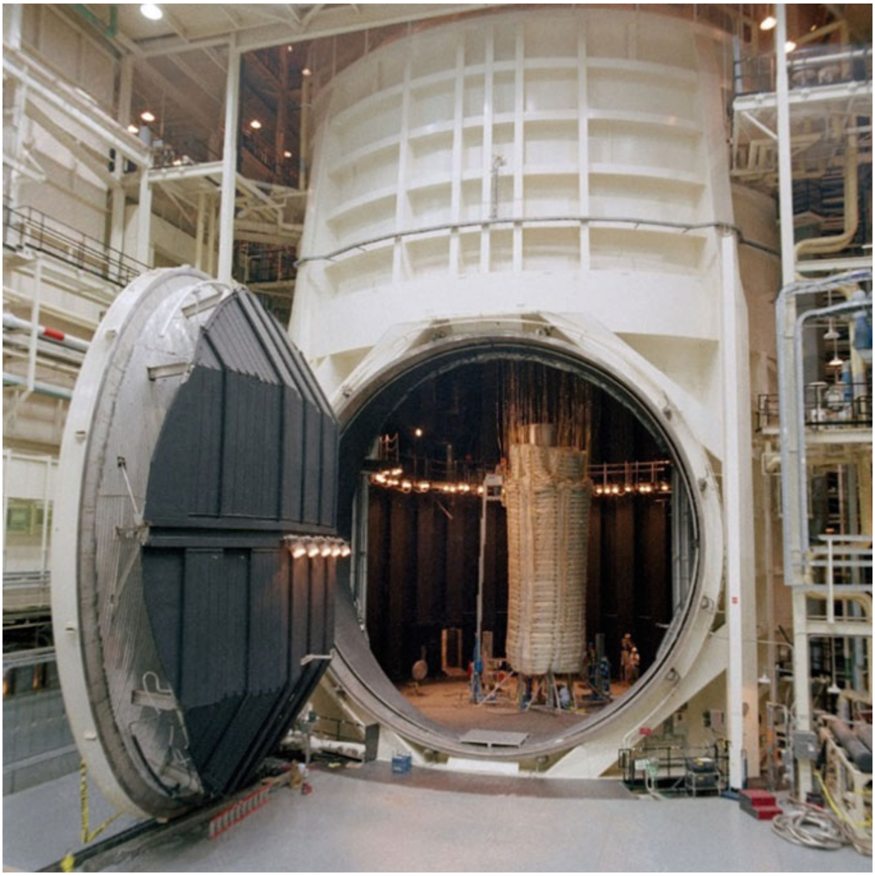

Fig. 6.28 TransHab packaged for the vacuum deployment test (NASA)

allowed us to incorporate what you learn as the design matures. It is often referred to as the spiral approach to engineering. Below is a summation of the lessons learned from my perspective.

Technical Lessons:

1. Build a little, test a little, evaluate, and learn. Incorporate what you learn as the design matures. Spiral approach to engineering.
2. Rapid prototyping brings focus to the project. It also creates successes, builds momentum, and builds advocacy.
3. It's okay to fail as long as you fail forward. Learn from the failures during this stage of rapid development and testing.

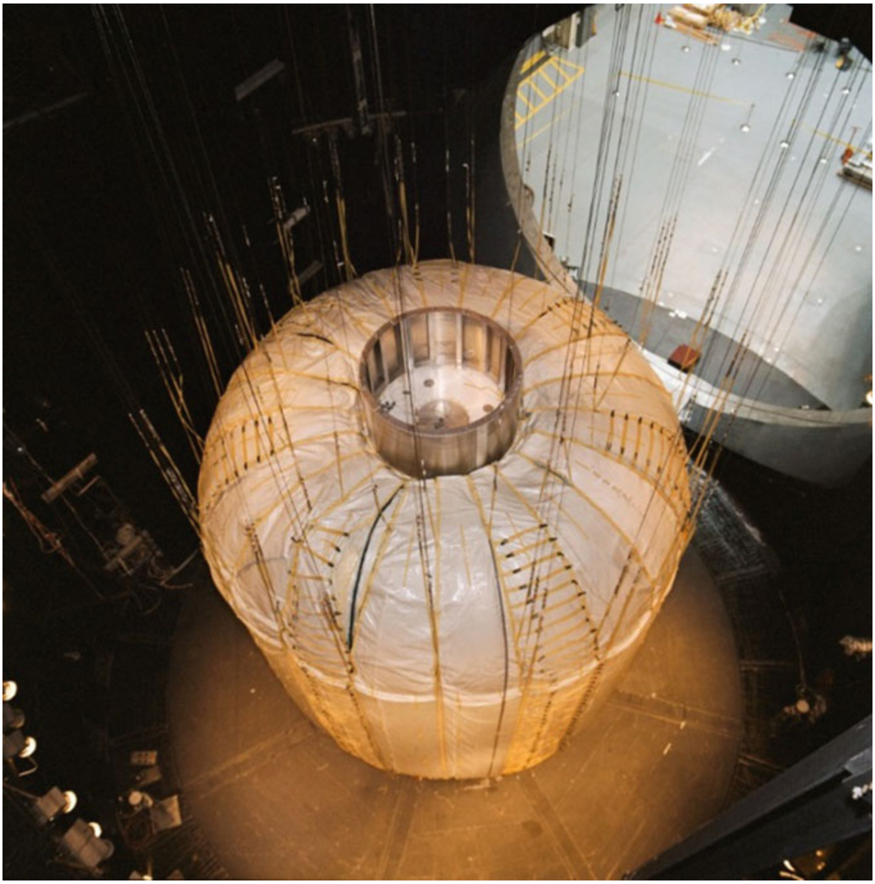

Fig. 6.29 TransHab vacuum deployment test (NASA)

4. Technology development needs a real focus—hard requirements and schedule.
5. The tiger team technical leads need to sit together—co-located. Improves performance and communication.
6. Trust the other leads and each other. Let the team do its job and believe in it.
7. Be technically honest—technical truth. If you can't do something—say so. Don't hide or skew the results.
8. Build test articles early and often. Build on small successes. Build momentum.
9. Build full-scale mockups early.
10. Keep the team focused. Let them focus on the technical job at hand.

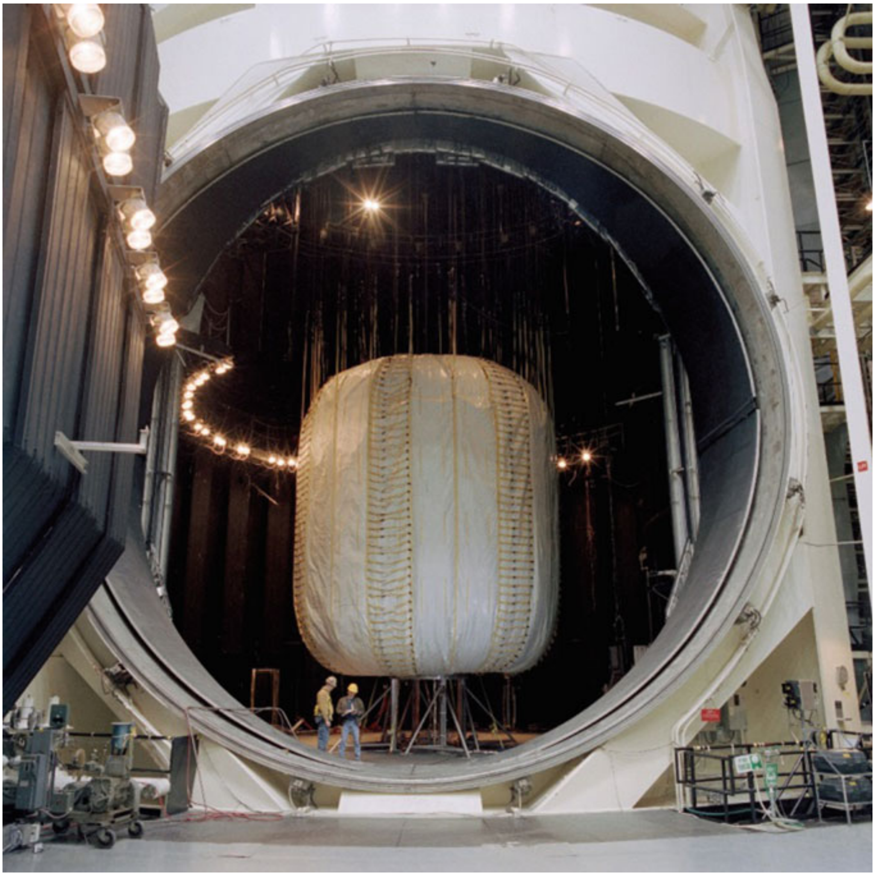

Fig. 6.30 TransHab vacuum deployment test (NASA)

6.4.8 Summary

With the successful completion of the demonstration testing and inflatable shell development, the TransHab project proved that the inflatable structure technology is real. The project also opens up a new space architecture alternative to the ISS type Class I type of modules. TransHab made great strides to prove inflatable structures technology is ready to be applied to habitats for space applications. TransHab's design met or exceeded habitation requirements for space. It has put the "Living" back into "living and working in space." The TransHab design provides facilities for sleeping, eating, cooking, personal hygiene, exercise, entertainment, storage,

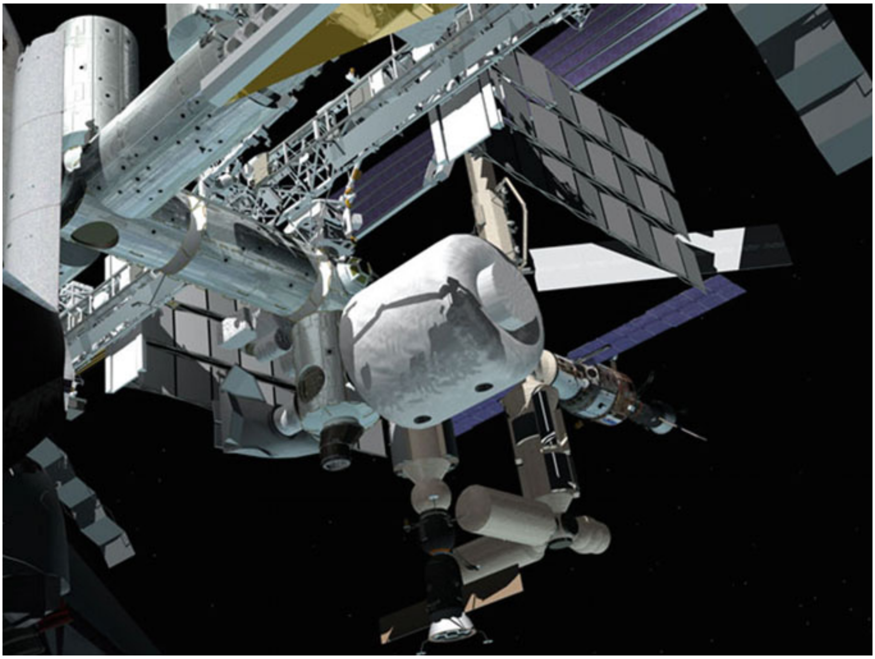

Fig. 6.31 TransHab as proposed for ISS (NASA)

and a radiation storm shelter for ISS, Figs. 6.31 and 6.32. TransHab also helped to develop, test, and prove technologies necessary for long duration interplanetary missions—back in 1997–2000.

TransHab has already contributed many technical and management lessons to the aerospace field. It has broken the volumetric barrier of the exoskeleton spacecraft type by innovating an entirely new, endoskeletal typology; it has demonstrated the advantages of combining human system integration and engineering with aggressive structural innovation and testing at the conceptual rapid prototyping stage. The integrated effort by which this spacecraft was conceived and developed has proven its virtue in meeting tremendous challenges by combining innovative design with cutting-edge technologies, both of which are appropriate for in-space and planetary surface habitats, with multiple applications for on-Earth and beyond.

The TransHab concept, rapid prototyping, and testing will prove to be a disruptive technology that has and will change the architectural revolution of spacecraft, habitats, and space systems for decades to come.

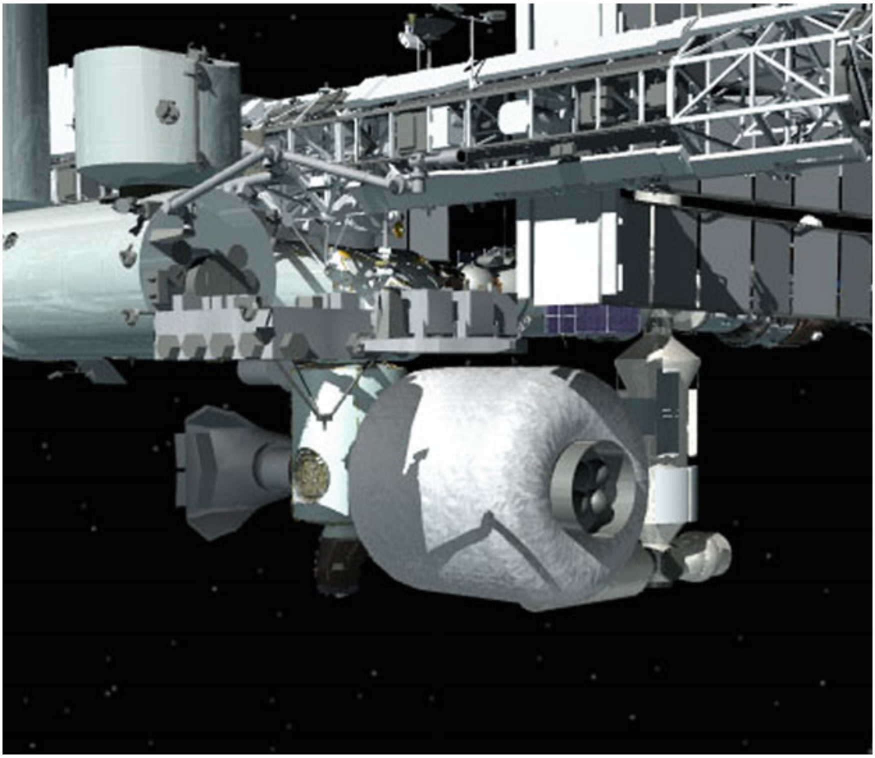

Fig. 6.32 TransHab as proposed for ISS (NASA)

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Appendix

A.1 Hints and Literature Research

This book has been prepared for students to assist in their own research. In the footnotes and references of each chapter a number of additional resources for further research can be found.

It is extremely important to do a thorough literature search prior to and also during working on a project. A lot of empirical and practical information is already available. Yet students should exercise an open and also a skeptical mind. Sources have to be examined, compared with others, and/or questioned on their content.

In Sect. A.2 Brand Griffin talks about the role of the space architect.

In addition, the following links may help students to start their research:

Space Architecture Technical Committee (SATC) Website
http://spacearchitect.org/resources/
Here students can find a vast collection of links to educational and research resources as well as publications by the members of the AIAA[1] Space Architecture Technical Committee.

NASA Technical Reports Server (NRTS)
http://www.sti.nasa.gov/
This site contains multiple technical reports and articles.

Curriculum for Aerospace Architects, with Emphasis on Lunar Base and Habitat Studies, by Donna P. Duerk, NASA/CR-2004-212820
http://spacearchitect.org/pubs/NASA-CR-2004-212820.pdf

SICSA Lecture Series
http://www.uh.edu/sicsa/library
Data sheets referring to an interdisciplinary "system of systems" perspective that encompasses broad aspects of mission planning, spacecraft and habitat

[1]American Institute of Aeronautics and Astronautics https://www.aiaa.org/.

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S. Häuplik-Meusburger and O. Bannova, *Space Architecture Education for Engineers and Architects*, Space and Society,
DOI 10.1007/978-3-319-19279-6

elements/design, planetary surface mobility and construction equipment, operations and logistics, and other important topics.

Living Aloft—Human Requirements for Extended Spaceflight by Mary M. Connors, Albert A. Harrison & Faren R. Akins (1985) Ames Research Center, Washington, NASA
http://hdl.handle.net/2060/19850024459.
Please also refer to our Facebook site where we put recent information on Space Architecture Education: https://www.facebook.com/SpaceArchitectureEducation.

A.2 Possibilities to Study Space Architecture

Possibilities to study space architecture are rare. Only a few universities offer regular programs or classes. Also courses may vary during an academic year and not be offered on a regular basis. The following schools and universities offer Space Architecture courses at the time of this writing:

A.2.1 Undergraduate in the US

Cal Poly Pomona has a regular architecture program, and a space architecture studio with Professor Michael Fox.
http://www.csupomona.edu

A.2.2 Graduate in the US

Colorado School of Mines. This university offers several engineering-based courses for space architecture with Paul Van Susante.
http://www.mines.edu

Columbia University Graduate School of Architecture, Planning and Preservation. Every spring semester since 2006, the school has been offering a graduate level advanced architecture studio that focuses on space architecture. The studio was established and led by Yoshiko Sato until her passing in 2012 and is headed by her husband Michael Morris. Every year the studio visits Johnson Space Center, Houston, where the students present their work to NASA engineers.
http://gsas.columbia.edu/

Oklahoma State University. This university is currently offering an interdisciplinary design course in connection to the NASA X-Hab competition. The course is under mentorship of Dr. Scott Howe.
http://go.okstate.edu/

Sasakawa International Center for Space Architecture (SICSA). SICSA is an interdisciplinary program within the University of Houston. It is a full-time space architecture program for those who already have an undergraduate degree in architecture or engineering and offers the world's only Master of Science in Space Architecture degree. Courses are taught by Olga Bannova.
www.uh.edu/sicsa

University of Southern California. The graduate Space Exploration Architectures Concept Synthesis Studio is offered by the Department of Astronautical Engineering and guided by Madhu Thangavelu.
astronautics.usc.edu/student-projects/space-exploration-studio

University of Maryland. The university has a well-established engineering based Space Systems Laboratory directed by Dr. David Akin.

A.2.3 Schools in Europe

The International Space University (France). ISU hosts a one-year Master's program and a two-month Space Studies program. Its curriculum covers many disciplines that related to space industry and enterprises, space science, space engineering, systems engineering, space policy and law, business and management, and space and society. Programs include an intense student research Team Project offering graduate students and young space professionals an opportunity to work on complex problems in the intercultural team environment.
www.isunet.edu

Vienna University of Technology (Austria). The school offers design courses in space architecture and a regular course on *Emerging Fields in Architecture* that includes lecture series on Extreme Architecture during every winter semester. Courses are taught by Dr. Sandra Häuplik-Meusburger.
www.hb2.tuwien.ac.at/www.ar.tuwien.ac.at.

School of Architecture, Lund University (Sweden). The school offers a one-semester Industrial Design course and a graduate level, also one-semester architectural course on "Extreme Environments: Space Architecture". Both classes include two weeks visit to NASA JSC in connection with Space and Terra Architecture & Design (STAR Design) program. The STAR is a NASA educational outreach program at the Johnson Space Center in Houston. The goal of the program is to expand the developmental knowledge of design in extreme environments. (http://www.ide.lth.se/courses/industrial-design-project-iii-iden25/). The architectural class is taught by Tina-Henriette Kristiansen and industrial design by Per Liljeqvist.
http://www.lunduniversity.lu.se/

A.2.4 Other Design studies

Other design studies related to space architecture for further reference are listed below.

Robert A. Heinlein Prize. The prize was established in 1988 to reward teams and individuals for outstanding contributions and achievements to spaceflight activities and commercialization of space. The Heinlein Prize® honors the memory of Robert A. Heinlein™, renowned American author. The purpose of the Heinlein Prize is to encourage and reward progress in commercial space activities that advances Robert and his wife Virginia's dream of humanity's future in space.
http://www.heinleinprize.com/#sthash.60JK8Cwi.dpuf

Space Development Theory and Practice (SDTP) summer program at the Bauman Moscow State Technical University (BMSTU), Russia.
Project-oriented two-week program engages international students together with BMSTU students from its Youth Space Center to work on a team project and present it to a formal jury of distinguished guests. Graduates of the program receive Certificates of Completion.
http://ysc.sm.bmstu.ru/eng/sdtp/back.htm

Cornell University. College of Agriculture and Life Sciences, Department of Biological and Environmental Engineering.
Professor Jean Hunter's research group is working on design of food processing and waste management systems for long-term space colonies. She teaches engineering principles and their application to identifying and solving problems involving biological systems.
http://bee.cals.cornell.edu/

University of Colorado, Aerospace Engineering Sciences Department.
Master's curriculum 'Bioastronautics'
A series of courses address human spacecraft design, including characterization of space environment, definitions of vehicle systems, and physiological and psychological stressors. A master's curriculum 'Bioastronautics' is offered by David M. Klaus.
http://www.colorado.edu/aerospace/

A.3 Current Launch and Transfer Vehicles

A candidate vehicle system has to be selected depending upon requirements (e.g. Payload mass and spacecraft dimension) and constraints (e.g. economic and political). Selection of a launch vehicle and propulsion system depends on mission characteristics and objectives (e.g. manned vs. unmanned missions—see Mission Planning chapter) (Table A.1).

Table A.1 A selection of current and near-term possible launch systems and space vehicles

Launch vehicles[a]	Characteristics	Remarks
Ariane-5	FD: 4.57 m FL: 10.35 m	Arianespace operates two versions of the Ariane 5 (ECA and ES), ensuring high-quality vehicles that are standardized and repeatable in production, and delivered ready for launch
	LEO 18 t/GTO 6.8 t	
Proton-M	FD: 4.1 m/FL: 10.8 m	The Proton Rocket Family is one of the most successful heavy-lift boosters in the history of spaceflight
	LEO: 22 t/GTO 6 t	
Delta IV	FD: 5 m/FL: 25.9 m	The Delta IV launch system is available in five configurations: the Delta IV Medium (Delta IV M), three variants of the Delta IV Medium-Plus (Delta IV M+), and the Delta IV Heavy (Delta IV H)
	LEO 13.36 t/GTO 7 t	
Atlas V	FD: 5.4 m/FL: 23.4 m	Atlas 5 is available in several variants, built around a LOX/RP-1
	LEO 20.5 t/GTO 8.67 t	Common Core Booster (CCB) first stage and a LOX/LH2 Centaur second stage powered by one or two RL10 engines. Up to five solid rocket boosters (SRBs) can augment first stage thrust
Falcon 9	FD: 5.2 m/FL: 13.1 m	Falcon 9 is a two-stage rocket designed and manufactured by SpaceX for the reliable and safe transport of satellites and the Dragon spacecraft into orbit
	LEO 13 t/GTO 4.85 t	
SLS	FD: 8 m/FL: 25 m	NASA's Space Launch System is under development and is expected to be in operation in 2018
	LEO 100 t/TLI 45 t	

Sources Larson, Human Spaceflight, p. 800
[a]Launchers that can transport humans or heavy loads (*FD* fairing diameter, *FL* fairing length)

A.4 Degrees of Chamber Closure

In Sect. 3.5 Marc M. Cohen talks about Mockups and Simulators related to the Chamber Classes. This chapter and in particular Table A.2 give an overview of chambers for human occupancy, as described by Marc M. Cohen in his paper: Mockups 101: Code and Standard Research for Space Habitat Analogue (Cohen 2012).

"The two standards that apply to the design of chambers used as pressure vessels and simulators are the *ANSI/ASME PVHO-1-2012 Pressure Vessels for Human Occupancy* and the *ANSI/NFPA 99B Hypobaric Facilities*. The key properties of simulation chambers and pressure vessels include the degree of closure, the atmospheric regime including ventilation or life support, electrical isolation and grounding, and fire protection. The PVHO presents a rating scale A to F that covers

Table A.2 Overview of environmental chambers/pressure vessels for human occupancy (Cohen 2012)

Class	Door/Hatch	Pressure	Gas mix	Ventilation	Electrical	Example
A	Open door	1 ATM	Normal	Natural	Standard	JSC Altair Mockups
B	Open door	1 ATM	Normal	Mechanical	Standard	Ames Space Station
						Prox-Ops Simulator
C	Closed door	1 ATM	Normal or life support	Mechanical	GFI if water is present	IBMP ESA-Mars 500, Lunar Electric Rover
D	Press-sealed	Reduced in altitude mode	Constant gas mix, normal or life support	Mechanical	GFI if water is present	JSC LCMLSTP in 20 Foot Altitude Chamber
				May include air revitalization		
E	Press-sealed	Reduced in hypobaric mode	Increased O_2	Mechanical w/air revitalization	Explosion-proof w/isolated ground/GFI	EVA Suit, Ames Controlled Environment Research Chamber (CERC)
			Partial pressure			
F	Press-sealed	Reduced in hypobaric mode	Increased O_2 partial pressure, artificial buffer gas, Halon	Mechanical w/air revitalization	Explosion-proof w/isolated ground/GFI	Ames CERC for Human Exploration
						Demo Project

the range from open cardboard mockups to sealed hypobaric chambers with an artificial buffer gas. Table A.2 presents some of these characteristics as they apply to space habitat analogues. Air circulation can be passive, through open "windows" in the shell, through a system of active ventilation, or through full life support. The atmospheric gas mix can vary from ambient air to variations in the concentration of oxygen and buffer gas. If water is present, the electrical system requires ground fault interrupt (GFI) circuits. If the concentration of oxygen is elevated, the electrical system requires high quality isolation from the building ground and explosion-proof fixtures. Fire protection requirements bring into play fireproof or fire-retardant materials, and active fire suppression system such as water sprinklers or Halon. These requirements from the applicable standards can lead to important interactions. Each of these subsystems demands careful design and integration into the experimental chamber." (Cohen 2012, p. 7)

A.5 Volume and Area Allocations

In Sect. 4.4.2 we talk about system sizing and early volume considerations. Table A.3 gives examples of minimum dimensions related to human activities. For more information read the full paper of Adams (1999).

A.6 Space Architecture and Aerospace Engineering Glossary

Several major terms that are used throughout this book are listed below. Sometimes more than one definition exists. The Authors present the most commonly used meaning.

Artificial gravity—"*Artificial gravity is the inertial reaction to acceleration due to the electromagnetic interaction between atoms" (See* Sect. 4.5*on Artificial Gravity by T.W. Hall). It is* often proposed for long term space missions as a countermeasure for microgravity conditions of a spaceflight. It can be achieved in a rotating environment using centripetal forces or without rotation with constant linear acceleration.

Architecture—the art or practice of designing and constructing buildings and structures, also a complex or system of related structures. See also **Space Architect.**

Coriolis Effect (Coriolis cross-coupled angular accelerations)—the effect of the **Coriolis force** that appears when an object is moving within a rotating environment. The path of the object seems to curve although in reality it does not, but it appears to do so because of the coordinate system rotation.

EVA—"*EVA is any activity performed by a pressure-suited crewmember in unpressurized or space environments. EVA begins with depressurization of the airlock or space module, and ends with repressurization of the space module or airlock after crewmember ingress. This includes any internal activities where a pressure-suited crewmember may be operating in normal modes of operation (e.g., airlocks, passageways, unpressurized work areas, donning/doffing areas) and abnormal modes of operation (e.g., unpressurized modules).*"[2]

Evaluation—testable by TRLs&HRLs. "*Equipment and or process evaluation involves experimental or pilot facility testing of the process or equipment identified in the selection process. Although selection identified those processes and equipment that most closely meet design requirements, it is not uncommon for evaluation of those selected processes and equipment to identify areas where the process or*

[2]Man-Systems Integration Standards, Volume 1, Section 14: Extravehicular Activity) http://msis.jsc.nasa.gov/sections/section14.htm.

Table A.3 Summary of general allocations of volume and area

Function	Notes	Dimensions in cm (in.)	Minimum volume
Translation	Translation path between activity stations	H: 215 [84″] W: 825 cm [32″]	
Translation (vertical)	Stairs for surface habitats Storey H: 215 cm [7 ft] Step L × H: 28 × 19 cm Landing 85 cm	W: 85 [33″] L: 308 [121″] H: 420 [165″]	14 m^3 [494.4 f^3]
Dining	Accommodates crew of 6 Width/Crew member: 70 cm [28″]	H: >215 [84″] L: 300 [118″] W: 254 [100″]	for a crew of 6: 16.4 m^3 [579.1 f^3]
Sleeping Partial G and Full G	Volume orientation must be horizontal to the local vertical Human envelope W: 85 cm [33″] D: 85 cm [33″] Exclusive of access area	H: 85 [33″] L: 215 [84″] W: 85 [33″]	1.55 m^3 [54.4 f^3]
Crew quarter Micro-G	Sleeping + stowage + dressing + personal work Critical dimensions of the workstation are combined with those of sleep	H: 215 [84″] L: 105 [41″] W: 105 [41″]	2.37 m^3 [83.6 ft^3]
Crew quarter Planetary surface habitat	Sleep position should be perpendicular to the vertical (or, horizontal)	H: 215 [84″] W: 215 [84″] D: 105 [41″]	4.85 m^3 [171.2 ft^3]
Changing clothes	Volume provided should allow free movement of the entire body	H: 215 [84″] L: 101 [39″] W: 101 [39″]	2.19 m^3 [77.3 ft^3]
Personal Hygiene Micro-G	Good habitability may be defined by the space required to perform the activities of cleaning the whole body in privacy	H: 215 [84″] L: 101 [39″] W: 101 [39″]	2.19 m^3 [77.3 ft^3]
Personal Hygiene Partial G surface habitat		H: 215 [84″] L: 101 [39″] W: 202 [80″]	4.38 m^3 [154.6 ft^3]
Waste management Toilet partial G		H: 201 [79″] W: 90 [35″] D: 105 [41″]	1.9 m^3 [67.0 ft^3]
Waste management Toilet Micro-G	Requirements for personal hygiene station might be added to waste management		4.09 m^3 [144.4 ft^3]
Food Preparation Micro-G	Galley equipment placed close together for ease of restraint Envelope in each direction ∼101 cm [40″]	H: 215 [84″] L: 101 [39″] W: 101 [39″]	2.17 m^3 [76.6 ft^3]
Food Preparation Partial G and full G	Double-loaded if optimized Min. preparation galley L: 2 m	H: 215 [84″] W: 100 [39″] L: 240 [94″]	5 m^3 [176.5 ft^3]

(continued)

Table A.3 (continued)

Function	Notes	Dimensions in cm (in.)	Minimum volume
Exercise	For a crew of 4–6 Treadmill H: 245 cm [96″] L: 150 cm [60″] Cycle ergometer W: 101–150 cm [40–60″] L: 150 cm [60″]	W: 251 [99″] L: 150 [59″] H: 245 [96″]	9.22 m^3 [325.6 ft^3]
Personal workstation	Dimensions for a personal workstation should be taken around the user up to the face of the computer monitor	H: 205 [80″] W: 101 [40″] At elbows D: 90 [35″]	1.86 m^3 [65.5 ft^3]
Inventory management	A double-loaded stowage area will have a depth of 60 cm + 85 cm + 60 cm For proper inventory management and access to all stowed items, a basic translation path of 85 cm [32″] must be kept clear between every two stowage banks Each bank of stowage, if optimized for accessibility, has a maximum depth of 60 cm [24″]	H: 215 [84″] L: 300 [118″] D: 205 [80″]	13.2 m^3 [466.1 ft^3]
Trash management	Trash center H: 215 cm [84″] L: 120cm [47″] D: 90 cm [36″] Minimum initial allocation of volume for a crew of 6+ accessible space added	H: 215 [84″] L: 120 [47″] W: 172 [67″]	4.44 m^3 [156.7 ft^3]

Sources Adams 1999

equipment fails to meet requirements. In those cases, it may be necessary to return to the selection of alternatives to modify or select another preferred option."[3]

Deployable structures (or modules)—structures/modules that can change or alter their shapes and as a result, change dimensions and volumes. Included are: inflatable and telescopic structures and modules, foldable elements and structures, etc. See also: **Module** and **Module Types.**

GCR—"*Galactic Cosmic Rays (GCR) are the slowly varying, highly energetic background source of energetic particles that constantly bombard Earth. GCRs originate outside the solar system. These highly energetic particles consist of essentially every element ranging from hydrogen, accounting for approximately*

[3]Technology Readiness Assessment Guide, p. 11: http://www2.lbl.gov/dir/assets/docs/TRL%20guide.pdf.

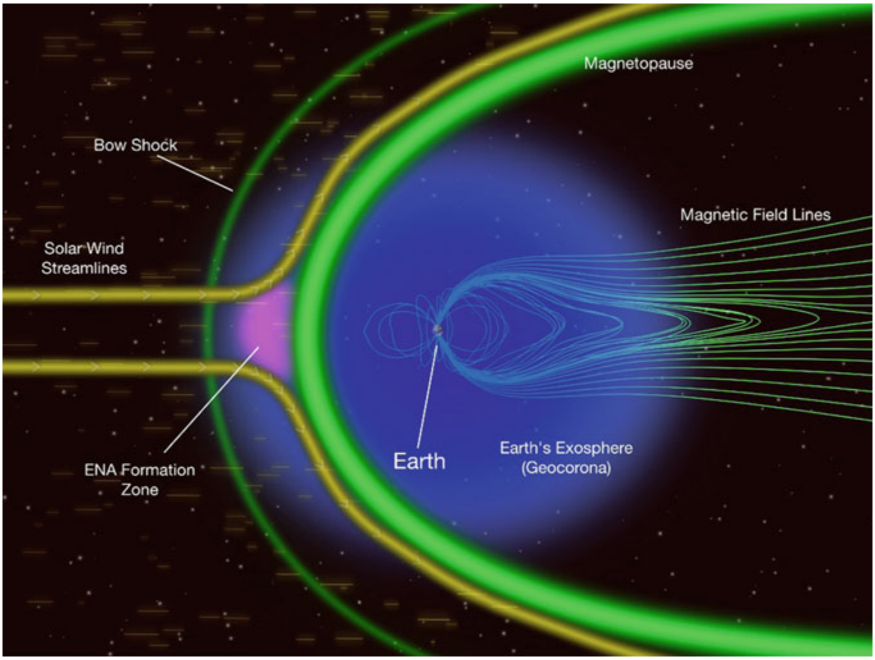

Fig. A.1 Our space environment (NASA/Goddard Space Flight Center)

89 % of the GCR spectrum, to uranium, which is found in trace amounts only. These nuclei are fully ionized, meaning all electrons have been stripped from these atoms. Because of this, these particles interact with and are influenced by magnetic fields.[4] (See Fig. A.1)

GEO—A Geostationary Earth Orbit is a geosynchronous orbit directly above the Earth's equator, with a period equal to the Earth's rotational period and an orbital eccentricity of approximately zero.[5]

GTO—A Geostationary Transfer Orbit is an elliptical transfer orbit with an apogee of 42,164 or 35,786 km and a perigee above the Earth's atmosphere (a few hundred kilometers), its inclination approximately equal to the latitude of the launching site and the launch azimuth/direction.[6]

Habitability—scope of conditions, human factors, and functions and activities that are necessary for human living (that includes: breathing, sleeping, eating, self-cleaning, and hygiene), and also: working, socializing, resting, playing (see Sect. 4.2).

[4]Space Weather Conditions: http://www.swpc.noaa.gov/phenomena/galactic-cosmic-rays.
[5]http://celestrak.com/columns/v04n07.
[6]*The Complete Book of Spaceflight: from Apollo 1 to zero gravity, by D. Darling. 2003, p. 159.*

Mary Connors from NASA Ames states in her book Living Aloft—Human Requirements for Extended Spaceflight, that "*Habitability is a general term that connotes a level of environmental acceptability*" (Connors et al. 1999, p. 59). In Architecture for Astronauts the term 'habitability' is used as "*a general term to describe the suitability and value of a built habitat (house or spacecraft) for its inhabitants in a specific environment (Earth or Space) and over a certain period of time*." (Häuplik-Meusburger, Architecture for Astronauts, 2011, p. 14)

Habitation—a place to live; a house or home or the state or process of living in a particular place (Oxford Dictionaries). In terms of space architecture, a habitat is always designed as a pressure vessel.

HRLs—Habitation Readiness Levels address habitability requirements and design aspects in correlation to Technology Readiness Levels (TRLs) (see Chap. 3, Table 3.12).

Human Factors—comprehensive scope of considerations and features that focus on physical conditions of human body as well as its psychological status and health.

ISS—International Space Station operates in Low Earth Orbit. Perigee: 419 km (260 miles) AMSL, Apogee: 422 km (262 miles) AMSL, Orbital inclination 51.65°.

IVA—Intra Vehicular Activity (inside of a spacecraft or module).

Lagrangian point—"*One of five equilibrium points at which a spacecraft or some other small object can remain in the same relative position in the orbital plane of two massive bodies, such as the Earth and the Sun, or the Earth and the Moon. Lagrangian points are named after the Italian-born French mathematician Joseph Louis de Lagrange (1736–1813).*"[7] (Fig. A.2)

LEO—A low Earth Orbit is an orbit that extends from the Earth's surface at sea level to an altitude of 2000 km.[8] Most of it lies within the Earth's atmosphere. Most telecommunication satellites operate on low earth orbits between 400 and 1000 km above sea level. All inhabited space stations have been operated in LEO, the ISS operates at about 400 km.

Mission Goals (sometimes can be referred to as Mission Objectives)—A set of scientific, technological, humanistic milestones that need to be achieved (Chap. 3).

Mission—The core function(s) and primary job(s) of the Agency (Sect. 3.3).

Module (or space module)—a self-contained segment of a spacecraft or a surface settlement that can serve different purposes and carry various functions: command control, living, servicing, etc. Modules can be pressurized or not, depending on their purpose and function. For example, the International Space Station (ISS) consists of multiple pressurized modules (Zarya, Unity, Zvezda, Destiny,

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[7]*The Complete Book of Spaceflight: from Apollo 1 to zero gravity, by D. Darling. 2003, p. 230.*
[8]http://www.universetoday.com/85322/low-earth-orbit/.

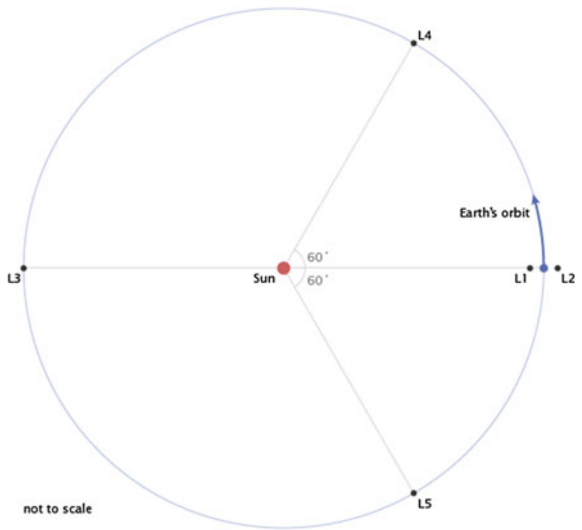

Fig. A.2 Lagrangian points (NASA, illustration by Robert Simmon)

Quest, Pirs and Poisk, Harmony, Tranquility, Cupola, Kibo and other) and non-pressurized elements (robotic arm, solar arrays, trusses and cranes).

Module Types—in addition to pressurized and non-pressurized categories modules can be (Sect. 5.3):

Conventional—ISS (International Space Station) type of a hard shell (envelop) module;
Deployable—whole modules or modules with parts that are launched in a packed configuration and can be expanded when needed. *Inflatable, Telescopic or Hybrid* modules are deployable types.
Hybrid—usually a combination of hard and soft modules but other types can be combined as well. *Inflatable*—soft shell modules that are packable and stowable during launch operations. Example: SpaceHab or Bigelow Aerospace's Genesis I and II, and Bigelow Expandable Activity Module (BEAM).
Telescopic—hard shell module, which consists of two or more parts stowed within another during launch operations that "telescope" out of the outer shell when deployed.

Requirements (including mission requirements)—technical, performance and human factors prerequisites and constraints defined by mission's goals and objectives.
Shirt-Sleeve Environment—"A space station module or spacecraft cabin in which the atmosphere is similar to that found on the surface of Earth, that is, it does not require a pressure suit."[9]

[9]From the Encyclopedia of Space and Astronomy, Joseph A. Angelo, 2006, p. 542.

Standards—norms and regulations accepted by space agencies and industries.

Space Architect—Rarely 'space architect' can be found as a job title. Space architects can be system architects, system engineers … "Practicing space architects currently contribute to mission planning, vehicle integration, habitat design, and human factors, but are particularly attracted to the areas of design integration and concept development." (Griffin, Chap. 2.5)

Space Architecture—Space Architecture is the theory and practice of designing and building the human environment in outer space. It is a unique discipline by combining attention to technical systems, human needs for working and living, and human reactions to the natural and built environments. It is simultaneously technical, pragmatic, humanistic, and artistic. (First Space Architecture Forum, IAC 2002, Houston, USA) "The work of space architecture can be grouped into three major areas: requirements, functional integration, and design integration." (Griffin, Chap. 4.6)

Spacecraft or spaceship—is a vehicle, vessel, or machine designed to fly in outer space. Spacecraft can be manned or unmanned depending on mission objectives and used for a variety of purposes, including communications, Earth observation, meteorology, navigation, planetary exploration, and transportation of humans and cargo.

ΔV—change in velocity or a measure of the amount of "effort" that is needed to change from one trajectory to another by making an orbital maneuver.

Siting—construction site, an area where a structure is landed, deployed and/or built.

SPE (SEP)—Solar Particle Events caused by Solar Energetic Particles, are high-energy particles coming from the Sun which had been first observed in the early 1940s. They consist of protons, electrons, helium ions, and HZE ions with energy ranging from a few tens of keV to GeV (the fastest particles can reach speed up to 80 % of the speed of light). They are of particular interest and importance because they can endanger life in outer space (especially particles above 40 MeV). Solar energetic particles can originate from two processes: energizing at a solar-flare site or by shock waves associated with coronal mass ejections (CMEs). However, only about 1 % of the CMEs produce strong SEP events (Fig. A.1).

TLI (TLI Orbit)—Trans-Lunar Injection is a propulsive maneuver at TLI orbit used to set a spacecraft on a trajectory to the Moon orbit.

TRLs—Technology Readiness Level(s), TRLs describe the maturity of a technology with respect to its development stage. More explanations in Chap. 3, Table 3.11.

According to NASA and ESA (Chapter 3: Table 3.11): "*Technology Readiness Levels (TRLs) are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology.*" (Mankins, John C., 6 April 1995 and Strategic Readiness Level, ESA, 13 February 2012)

A.7 Guest Statement: The Role of the Space Architect—Part 3 Aptitude (Brand N. Griffin)

A.7.1 Aptitude[10]

"*The ideal architect should be a man of letters, a skillful draftsman, a mathematician, familiar with historical studies, a diligent student of philosophy, acquainted with music; not ignorant of medicine, learned in the responses of juris consults, familiar with astronomy and astronomical calculations.*"[11] This is a rather expansive description of an architect and what is even more remarkable is that it was written by Vitruvius 25 years before the birth of Christ.

More than technical depth, the absolutely essential attribute of a space architect is the ability to conceptualize. Space architects must possess technical breadth and must know how to get the depth from experts on the team. In this there is a positive mutual dependency building on individual inclination, training, and experience. To get the most out of this relationship, the space architect must also be a good manager, with the people skills necessary to lead a team. This skill involves knowing how to ask good questions and when to curtail non-productive discussion. Management consultant, W. Edward Deming says, "*If you don't know how to ask the right question, you discover nothing.*"[12]

What are some of the personality traits of successful, creative system (space) architects? Professor M. Chignell in an interview with Jonathan Losk derived the following list from questioning practitioners in the field:

1. Communication skills
2. A high tolerance for ambiguity
3. The ability to make good associations of ideas
4. The ability to work consistently at an abstract level
5. A level of technical expertise (level not specified)
6. A tempered ego; the opposite of arrogance
7. Leadership; gets the most out of others
8. The willingness to backtrack, to seek multiple solutions
9. The ability to build teams
10. Charisma
11. The ability to read people well
12. Self-discipline, self-confidence, a locus of control
13. A purpose orientation
14. A sense of faith or vision

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[10]This section relies on the work of Professor Mark Chignell who describes the personality traits of successful, creative system architects.
[11]Vitruvius: Ten books on architecture, edited by I.D. Rowland and T.N. Howe.
[12]Dr. W. Edwards Deming, The system of profound knowledge. https://deming.org/theman/theories/profoundknowledge.

15. Drive, a strong will to succeed
16. Curiosity, a generalist's perspective

Like the architect's description by Vitruvius, this is another expansive list of attributes. In a subset of these, being a creative space architect requires a strong combination, but not necessarily in equal measure of the following:

2. A high tolerance for ambiguity
4. The ability to work consistently at an abstract level
8. The willingness to backtrack, to seek multiple solutions
12. Self-discipline, self-confidence, a locus of control
13. A purpose orientation
14. A sense of faith or vision
15. Drive, a strong will to succeed
17. Curiosity, a generalist's perspective

As is seen from the list of personality traits, space architects should have a high tolerance for ambiguity. In many ways this attribute is self-selecting because those who are comfortable with linear, analytic thinking become frustrated with the creative exploration in the synthetic approach.

A.7.2 Self-starters

Surviving successful space architects are self-starters. That is to say, they take the initiative by proposing and advancing ideas. In some cases this attribute is welcomed if not encouraged, while in others (in particular with large organizations) it is seen as self-serving and worse, bucking the chain of command. Being a self-starter does not imply avoiding or ignoring direction from managers (very career limiting), but is appropriate when the project is stalled or there is little or no direction.

A.7.3 Pride of Ownership

Concept originality is a very sensitive area. Most designers take pride in their ideas; it is connected with their image of self-worth. They want to be recognized for contributing innovative, well-reasoned concepts. From Vitruvius, to Bernini, to Le Corbusier and Gehry, ideas are associated with individuals. This is the history of architecture. However, space design is different (with the notable exception of Apollo era Max Faget). The attitude is, "*Thank you ma'am for the baby, we'll take it from here.*" If the project is successful, it will have many fathers, if not, it is an orphan. At the risk of stretching the metaphor, many ideas are conceived but few develop to full maturity. If so, the path from concept to hardware is so convoluted its true genealogy is untraceable. To avoid being discouraged, this realization should be an early career lesson for space architects.

A.7.4 Fork in the Road

Space architects do not start out wanting to be space architects. Usually, they spend long hours in schools of architecture (or engineering) with aspirations for a more traditional career. Somewhere along the way, there is the revelation of applying their trade to space. For architects, a large number assume they are the first to make this connection, charging off with grand visions of zero-g hotels and lunar condominiums. That is, until they discover there is a loose community of employed space architects actually designing space stations, deep space habitats, and planetary bases. Now, they are faced with the major career choice of practicing traditional architecture or chasing the dream. It is possible to carry the initial love of architecture into a space career, but to truly contribute; it will no longer be the "day job." Because there are few full time opportunities for space architects, this is a risky decision. Some have chased the dream, but for the lack of government or contractor openings were forced to pursue other ambitions. Others have had the fortune of good timing, a broad skill set, or a position in the organization to make a career of space architecture. If only it could be like Yogi Berra[13] says, "*When you come to the fork in the road, take it.*"

A.7.5 Takes Time to Develop

The commitment to space architecture, even more than to engineering as a whole, is long term—decades. As with other professions, it takes about 10 years after graduation from college to acquire the knowledge and judgment necessary to head an architectural team. And those 10 years need to be well spent.

A.7.6 Maintaining the Vision

The ideal situation is for the architect to maintain the integrity of the system from concept to operation. This is possible on some projects, but very unlikely with the multi-phase, competitive, government programs. The long ride down the waterfall creates opportunities to diverge from the original purposes, functions, and form. The space architect, more than anyone else, must maintain and strengthen that integrity, must intervene when it is threatened, must retain many options and "hang on to the agony of decision as long as possible" (Spinrad 1988 at USC, as quoted in Rechtin 1991, p. 93), and must imbue the rest of the project with the values that were built into the customer's judgment.

[13]Lawrence Peter "Yogi" Berra is a retired American Major League Baseball player.

A.7.7 Conclusion

If it is possible to make a noun a verb, this paper is architected. It integrates developed, well-presented ideas into a different product for the purpose of providing an overview of the role, work, and aptitude of the space architect. The identified contributors have each done a masterful job articulating particular parts of the narrative, but liberties were taken. For the sake of compression, descriptions were truncated, amplified, reordered, or eliminated. Ideally, the reader is able to extract a summary message, but is drawn to the original writings for a deeper understanding of space architecture.

The answer to the opening question, "*Is space architecture a vocation?*" if yes… for a handful. They have had to be flexible and engaged; sometimes taking on assignments only distantly related to the field. In closing, there is no perfect time, position, or team, so, don't wait for the job posting, "Wanted: Space Architect." Theodore Roosevelt summarized it well, "*Do what you can, with what you have, where you are.*"[14]

[14]Theodore Roosevelt (1858–1919). An Autobiography (1913) Chapter IX: Outdoors and Indoors.

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Index

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