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AN ARCHITECTURAL APPROACH TO THE DESIGN OF A LONG DURATION HUMAN SPACE MISSION

Case Study: Human Mission To Mars

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Doktors der technischen Wissenschaften

unter der Leitung von

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Abstract

The present thesis discusses an architectural approach to the design of a long duration human space mission taking the case study of ESA's Human Mission to Mars Study.

Configuration options, habitability and architectural aspects of a first human spacecraft to Mars have been developed within the larger context of the European Space Agency's (ESA) AURORA program for future human space exploration. The author was part of a committee that consulted with the scientists and engineers of the European Space and Technology Center (ESTEC) and other European industrial communities on developing the first human mission to Mars, which is scheduled for 2030. The author's task within the Human Mission to Mars study was to develop an interior configuration for a Transfer Vehicle (TV) to Mars, especially a Transfer Habitation Module (THM) and a Surface Habitat (SHM) on Mars. The thesis focuses on the architectural issues of crewed habitats.

The total travel time from Earth to Mars and back for a crew of six amounts to approximately 900 days. After a 200-day flight three crewmembers will land on Mars using the Mars Excursion Vehicle (MEV) and will live and work in the SHM for 30 days. For 500 days the spacecraft continues to circle the Martian orbit for further exploration before making the 200-day journey back to Earth. The entire mission program is based on our present knowledge of technology. The topics of the thesis were exposed to a constant feedback design process and a trans-disciplinary cooperation with the experts of ESTEC's Concurrent Design Facility.

Long-term human space flight sets new spatial conditions and requirements for the design concept. The guidelines are based on relevant numbers and facts of recognized standards, interviews with astronauts/cosmonauts, and analyses regarding habitability, sociology, psychology and configuration concepts of earlier space stations, in combination with the topics of individual perception and relation to space. The study result consists of the development of a prototype concept for the THM and SHM of detailed information and complete plans of the interior configuration. The thesis also contains a detailed explanation of the design process development, including all suggested design and configuration options.

The thesis starts with a preface and ends with an outlook into the future. The preface introduces the term [space]architecture, describes the operational field of [space]architects and addresses possible conceptual ideas that influence the design implications. „The Socio-Psychological Component" stresses the need to consider this component when designing a habitat. Further topics also have implications for outer space design: „Buildings without Foundations" deals with recognizing forces other than the gravitational force, while „Technology" is based on the current architectural discourse on technologized space. „Expanding Real Space" addresses ways to expand real space into virtual but perceivable dimensions. The chapter „Outlook" is an attempt to formulate a more comprehensive design philosophy than the one currently applied, mostly by engineers, in planning for outer space. It also points towards future trends for design approaches by interpreting the footprints of long-duration missions.

The chapter „Overview of the AURORA Human Mission to Mars" provides information on the mission case summary and its characteristic values. This part also refers to the architectural design methodology applied during the HMM design process, integrating the comprehensive investigation with previous research results as well as offering an overview of the general functional aspects and their spatial implications. Moreover, the chapter contains a concise reference to a major issue: human factors.

An „Architectural Analysis of Historic and Current Crewed Space Stations" forms the introduction to the main part of the thesis. It also offers an unprecedented overview of vernacular [space]architecture because the same diagrammatic analysis is applied to each space station presented, thus paving the way towards better comparability among all crewed stations designed so far. The chapter discusses interior configuration issues in the Salyut space stations (1971-1991), Skylab (1973-1974), MIR space station (1986 - 2001), ISS (1998 -), and the inflatable crewed space module Transhab, with schematic diagrams and quantitative data allowing for direct comparison of all cases. The appendix to this chapter provides information on the composition of materials for inflatable and deployable technologies.

The main part of the thesis concentrates on the architectural design study of the THM and the SHM with their respective configurations. The development of the two baseline designs follows a similar structure: first of all, figures for the ‚Habitable Volume per Function' were collected and investigated; scientific research findings were accumulated, and relevant issues and findings were listed according to specific topics important for long-duration habitability. All figures and findings are combined into a single „Architectural and Habitability Recommendation". This part tries to pull together scientific reference information on habitability from different recognized sources other than ESA, NASA or RSA standards. The information is presented in tables and structured according to topics, e.g. adjacency/separation, communication, flexibility of use, exercise, windows etc., and supplemented with various recommendations found in books or papers. A rationale explains the necessity to incorporate the issues into the design development. Examples illustrate the case for implication and are followed by literature references. Apart from standardized requirements, there is no such compliation as yet on the soft factors involved in designing future space habitats. The set of recommendations was drawn up for this specific European Human Mission to Mars Study, and does not cover all issues relevant in long duration human missions. Nevertheless it is intended as an example for more sophisticated data banks to be compiled in the future.

Deriving mostly from the engineering environment, the chapter „Design Drivers" covers issues such as safety, radiation, redundancy and main configuration requirements. The chapter on the „Concept and Development" of the THM and the SHM deals with aspects of configuration. On this basis, numerous design options were investigated and developed up to the final stages of the „Baseline Designs".

The two baseline designs of the THM and SHM today form the basis for the European approach to a human mission to Mars.

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Firstly I would like to thank Prof. Helmut Richter for his far sight that space architecture may become an integral part of the architectural field of operation and for the support of diverse space architecture projects which I could initiate in the last years at the institute. Additionally I would like to thank Wolfgang Winter for his support with this thesis.

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Context and Objectives

The five objectives of this thesis were to demonstrate

1) An alternative approach and methodology in the design for long duration human missions including novel compilations of data and analysis adding a different set of recommendations to the existing technical requirements (Section 1 Overview of the AURORA Human Mission to Mars Study, Section 2, 3.2.1 and 4.1.2)

2) That architects can substantially contribute to the planning and design of a long duration human mission including the early phases of systems configuration, systems engineering and interior configuration (Section 2-5 of the thesis)

3) That a multi-disciplinary approach is required for long duration human missions (see acknowledgements)

4) That there is a new field of operation for architects where they can draw spin-offs from Earth to space and take spin-ins from space to Earth (In the preface examples are given)

5) That this new field of [space]architecture is about to be established (the preface introduces the term [space]architecture, the outlook continues with this term and the CV and biography of the author supplies further information and sets the context for the reader)

GENERAL COMMENTS

The aim of this thesis was to design for a human mission within a real mission scenario. The opportunity for this came up when ESA conducted the Human Mission to Mars Study in the Concurrent Design Facility (CDF) in 2003/04 and invited the author for consulting the engineers' team. Never before has an architect participated in a human mission study developed in the CDF at ESA. This was also a good possibility to demonstrate how engineers, scientists and architects can work together in a field, which is dominated by engineers and where the architectural profession has not been accepted as valid for substantial contribution so far. Human spaceflight, the field of exploration and future visions, implies a new operational territory for architects because wherever humans will go to live they will need architects if they want to stay longer on a particular location.

DESIGN OF THE SPACE SYSTEM

The role of the author of this present thesis at the beginning was „to make some nice sketches" for the engineers and scientists to providebetter better three-dimensional schemes of how the configuration would look like. After the first couple of CDF-sessions it became apparent that the author could contribute far more: the whole configuration and layout was developed. The author supported the engineers and scientists with expertise in configuration options (setting up complex systems and modules) for the whole spaceship, quickly visualized through sketches, and accelerating the process of integration of all subsystems; this is one of the work tasks of an architect in preparation for on-site building phases. The integration of an architect into the design team and the implications this had on the study was firstly novel to ESA as an organisation and secondly novel to the other experts involved in it.

OPERATIONAL FIELDS FOR ARCHITECTS

Whether a cellular phone, a laptop computer or a spacecraft there are always two sides to an interface, a system side and a human side, and thus two sets of goals must be expressed. (1)

In human spaceflight these two set of goals are the technical system and the human system within its full scope. The human dimension is vital for a crewed mission if the mission should be successful. As the technical system is, compared with the human system less complex, and the focus up to now has been on the technical system more understanding has been created and more knowledge has been developed. For long duration human missions to which we are looking ahead when planning for outposts on the Moon and Mars the human system has to play an equal role. The environment for which space architects are planning demands an extremely economical use of time, material and resources for the astronauts on mission, as well as attempts a maximum integration of environmental conditions and user requirements in design decisions, but also the mutual influence between humans and their environment, between active and passive systems.

Human needs are always the same regardless of whether we are on the planet or in outer space. (2)

And human needs are a very architectural topic. Architecture is the three-dimensional creation of a shelter for humans supporting their needs and expanding their culture. Factors such as habitability (which include colour, smell, surface material tactility, food and the human – machine interface), socio-psychological factors (which include crew selection and training, heterogeneity versus homogeneity of the crew, coping with stress, group dynamics, cognitive strategies, cultural background of the crew and its implications), culture and thus the resulting proportion of inhabitable space and it's functionality are a few topics of the complex operational fields of [space]architects. Also the wider organizational and political contexts, which allow the participation of architects in space projects, belong to this broad field. The work in these fields requires a multi-disciplinary team of creative experts.

CURRENT CHANGES

At the beginning it is mostly pioneering work to establish new operational fields within one professional area and it requires some stamina because it is as if someone would inscribe a blank blackboard. To be able to work towards establishing a new operational territory one needs support from people with a similar vision or from people with a belief in progress and change and one needs trust from all of the supporters. This is one part of the discourse.

The other part lies in the fact that architecture nowadays is not a sharply drawn professional field any more. More than ever one can realize that either "everything is architecture", as we can see with the terms Information Architecture, Systems Architecture etc.; Or one could argue that architecture hardly exists anymore because it has become subject of pure economy and profit-oriented investing companies. Additionally, planning phases which were earlier part of the architect's work have been taken over by large building companies or structural engineering offices. In both cases the cultural surplus value which architecture in its built form always has incorporated decreases. [Space]architecture is the physical manifestation of a designed space which also has been derived from the relationship of the socio-psychological factors and the architectural space in extreme environments (if it is a physical or a psychological environment). In this way, amongst others the addtional value of architecture can be proved.

All of the above mentioned implies that the professional field of an architect is subject to change; therefore new areas can be entered and developed if others release. [Space]architecture, therefore, is only the logical and "natural" development for the professional field of architecture.

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(1) Colletti, M.; Humanware versus Hardware, in „Transcripts Of An Architectural Journey – Musings Towards A New Genre In Space Architecture" , Vienna 2004, LIQUIFER –www.liquifer.at, p.265

(2) Eichinger, G.; Conceptual Overlaps in Space and Terrestrial Architecture, in „Transcripts Of An Architectural Journey – Musings Towards A New Genre In Space Architecture" , Vienna 2004, LIQUIFER –www.liquifer.at, p.266

Preface

An Introduction To *[space]architecture*

The term *[space]architecture* refers to architecture designed for extraterrestrial conditions. In essence, this means that gravitation, instead of 1 G ($g=9{,}81\ m/s^2$) as on Earth, equals 0 G in orbit, 1/6 G on Moon and 1/3 G on Mars. Apart from gravity, of course, many other environmental conditions differ strongly from terrestrial standards. The first word of the term is put in brackets to indicate that there is no clear dividing line between the concepts of (terrestrial) space and outer space, between architecture at O G and architecture at 1 G. Instead of separating concepts and disciplines, the entire spectrum of possible contexts should be taken as a common basis.

The visionary roots of *[space]architecture* can be found in 19th century fantasy novels e.g. by Jules Vernes and Herbert G. Wells, who tried to draw more or less realistic images of functioning spacecrafts, and in the early history of filmmaking by Georges Méliès, Fritz Lang and their contemporaries. By the 1940's and 1950's a new genre rich in visionary designs had emerged, which eventually led to the development of modern science fiction literature and the famous films of the 1960's and 70's (e.g. Kubrick's "2001 – A Space Odyssey"). During this process of development, space-defining objects followed a very original sense of aesthetics geared to the cultural climate of the respective times, far from the prosaic reality of engineers' designs in the early days of space travel.

The 1940's and 50's saw the first real attempts at exploration beyond the terrestrial environment. The shaping of spaceships was primarily inspired by ballistic objects – in a direct line that lead from Wernher von Braun's V2 rocket designed for the National Socialists in 1943 through to the first US projects in space travel, in which von Braun again played a significant role. In all cases, however, formal design concepts for the space objects were mainly based on the approach of development engineers, and this has not changed do date. Specialists in space design, such as architects, have not been given a say in developing any of the spaceships currently in use. Though *[space]architecture* based on architectural design concepts would, quite arguably, also have turned out as an advantage for astronauts and cosmonauts in manned spaceflight of the past and present; and even though there have been several ambitious attempts at developing contemporary *[space]architecture*, implementation will depend on extraterrestrial space being privatized – at least to some part. Space Ship One, first tested in 2004, constitutes a first step in this direction. After all, only pressure from highly demanding customers can trigger the development of high-quality space design.

Fig. p - 1: Susan Helms on the ISS, courtesy of NASA

Fig. p - 1 shows astronaut Susan Helms in 2001 inside the International Space Station (ISS), looking at Earth from above. Astronauts spend about 80 per cent of their free time watching their home planet, which makes this pastime immensely important. Nevertheless it was virtually ignored in the design process, as can be seen from the photo: there are neither handles nor other effective grips around the window, so the astronauts usually held on to the fittings above the window and the hose outlet at the bottom right, which broke off as a result. On the photo, Susan Helms delicately holds on to one of the window screws with her thumb and index finger because the practice of using the outlet as a grip was obviously not permitted and should not have been documented on a photo. This is a clear example for the current type of space design that is dominated by the engineering paradigm and fails to take account of the users' "soft" needs and requirements, focusing exclusively on "hard" factors. In longer-term manned-missions, however, i.e. missions that take six months or longer, it is indispensable to give "human factors" a more central role.

Crew autonomy will become increasingly important, especially with a view to a human mission to Mars during which the time lag in communication can be up to twenty minutes. In this case, Mission Control could no longer have an eye on every single moment in the crew's life, and daily life in a habitat will be a sort of "everyday life under extreme conditions" rather than a set of pre-programmed actions following a pre-defined plan. As a result, everyone involved will have to adapt their ways of thinking and training methods. In a next step, the astronauts' future habitats will develop into a highly complex designed space geared to the new requirements of "daily life in the extreme".

This implies: the more time humans spend in the hostile conditions of outer space, the more decisive the design of the architecture surrounding them will become. Given NASA's and ESA's ambitious plans to establish moon bases in the near future and send the first human missions to Mars, experts are already looking into innovative design solutions for future Moon and Mars habitats.

Sending human astronauts to Mars is the central aim of ESA's Aurora program. The current project is based on studies for a transfer ship and a Mars surface habitat. A human mission to Mars is bound to count among the greatest and most challenging expeditions ever. The crew will take 200 days to reach Mars, spend 500 days in the planet's orbit or on the Mars surface (depending on the mission scenario), and then another 200 days traveling back to Earth. All in all, the mission itself will take almost two and a half years. Six crewmembers are meant to spend this long period of time together in good physical and psychological health, i.e. keeping up a reasonably good mood, while maintaining a high level of productivity.

The crewmembers sent to Mars after years of preparatory training will be highly skilled individuals perfectly trained in a very wide range of fields. Apart from the necessary technical aspects, however, an ideal spaceship should also meet architectural requirements so as to support the relevant socio-psychological and physiological aspects. Flexible spaces that can be adapted to conditions in extreme situations, multi-functional inflatable space, but also shape, expression, materiality and functionality will be of decisive importance for the crew's wellbeing.

"We are fed up with this tiny, crammed station" (1), Russian cosmonaut Valentin Lebedev complained after several months on the MIR station. Statements like this should be a thing of the past. An undersized station that fails to provide enough living space for the crew during a prolonged stay on the Moon or a mission to Mars may prove life-threatening; after all, the entire mission could be doomed if one or several crewmembers can no longer fulfill their tasks.

Just imagine a fire breaking out on board during a human mission to Mars. The four crewmembers stay calm and try to put out the fire. They fail to succeed, the flames keep spreading through the ship. Would a given individual keep trying to save the mission until the very last minute? How would astronauts or cosmonauts from highly different cultural backgrounds react to this situation? While some of them tend to take the initiative themselves, others are more used to following orders. How would a Japanese crew member handle the situation? Would they panic? The usual reaction to panic is escape, which would be plainly impossible in this case. As a result, an individual could instinctively resort to the very opposite. Some people retreat into themselves, others might turn against their crew partners when they are running short of oxygen and it seems as if not all crewmembers can survive the situation. Would there be enough time for Mission Control on Earth to find a solution – as was the case for Apollo 13 – and transmit orders to the crew in space?

The Socio-Psychological Component

As a manned Moon or Mars base is developed to meet the high requirements of the hostile environment in space, it may be assumed that it is brought to the highest possible degree of technological perfection. As a consequence, unpredictable crew behavior constitutes the essential remaining risk. Crew composition and the subjective well-being of the crewmembers, their physical and mental health, and their ability to perform their tasks for a prolonged period in time without friction and problems – all these factors assume key importance for mission success. Crises and conflicts among the crewmembers can cause the entire mission to fail. Adequate habitat planning, in conjunction with other factors like adequate training, plays a key role in minimizing the danger of "human failure". Cosmonaut Valeri Polyakov, who spent almost two years on MIR and still holds the record in long-duration stays in outer space, found that psychological survival is the most difficult part during a prolonged space mission. Making life outside our "spaceship Earth" both pleasant and productive is therefore not a task for engineers alone, but should also involve psychologists, physicians, sociologists and designers.

In trying to meet this new challenge, we can benefit from the knowledge of astronauts and cosmonauts who have served on MIR, as well as from experience gathered during Arctic and Antarctic expeditions. For experts, surviving and living on unknown territory is a vast and unexplored field of work. Human social behavior is conditioned for life in a diverse macro-society rather than in small groups, such as the expedition teams that will be sent to distant places before human settlements are established in outer space.

In the micro-society of such a team, the astronauts and cosmonauts are bound to develop group ties, and the pressure of being dependent on each other whilst being so far away from Earth may trigger many conflicts. Solving these conflicts is of vital importance for successful human missions to Mars and beyond.

Architecture can be a manifestation of inter-personal behavior given that the users' individual behavioral patterns leave behind certain traces or imprints. High-quality design must combine different gravity zones, e.g. on the Moon or on Mars; after all, they imply different forms of life, different cultures, different perceptions of time, and a different speed of action in every-day life. The major difference between Earth and space lies in the physical laws of mass and space. In this context, architecture can make a major contribution by providing adequate design concepts to prevent inter-personal conflicts. For this purpose, the design should be true to the human (real-life) scale, and should interactively communicate with its inhabitants and with those people on Earth who are part of the mission. For example, it would be conceivable for the rooms of a habitat to be soft, flexible, and transparent to different media, allowing the crew to modify and adapt the habitat. The sleeping quarters, though separated most of the time to provide maximum privacy, could be joined together if crewmembers choose to spend time together. As for communication with Earth, an astronaut could, for example, enjoy a game of table tennis with his daughter: the astronaut plays against an interior wall of the ship that is equipped with active sensors, the information is transmitted to a similar wall on Earth, and the daughter returns the virtual ball to her father in space, etc...

Entire space segments could be modified by messages projected from Earth. The developments of modern computer technology allow us to connect real spaces and virtual spaces. In addition to seeing Earth from space and keeping in touch "by phone", a Moon base crew could thus receive information from their home planet in a variety of forms, right up to the simulation of physical exchange with people on Earth in special games. This would help to ease the feeling of loneliness distant from Earth, and the monotony prevailing on a planetary surface base or in a spaceship.

A space habitat is a space permeated by technology. Thanks to the advancement of technical infrastructure, it may well become "intelligent space" in just a few years. Given the rapid progress in computer technology and other fields of research, e.g. biotechnology, genetic engineering or experimental physics (- just think of wormholes and other "miraculous spaces" , the concept of a "thinking" spaceship that interacts with its inhabitants and Mission Control on Earth is becoming increasingly feasible. Our perception of the world around us is bound to change accordingly. The same is true for the difference between real and virtual, which is being blurred by media like television, telephone or internet, already allowing us to cross the limits between real and virtual spaces.

Building without Foundations

In zero gravity, buildings have no more foundations. Their structure no longer reflects the human sense of equilibrium - which, due to its function, could also be referred to as our sense of gravitation. „Vertical" is no longer a valid concept given the basic equivalence of all directions. During a research expedition to Mars, zero gravity and partial gravity would alternate, i.e. the habitat would not be oriented along vertical lines only. In his book "Animate Form", Greg Lynn outlines a way of integrating movement - time of space - into architectural design. Zones, limits and paths are defined by the inhabitants' behavior. At the same time these "user-defined" imprints are subjected to a hierarchy that, in turn, depends on a variety of factors, including environmental conditions. There is a mutual influence between the users' behavioral patterns and environmental framework conditions: changes on one side trigger changes on the other side. Any change in the social structure, i.e. in society, affects spatial concepts and the buildings based on these concepts. Humans have an instinctive capacity of orientation in both known and unknown spaces, even though they may take some time to adapt. In our heads we sketch cognitive plans containing the smells, sounds or feel of a given place, even though this implies abandoning our geometric reality and objective truth. The self-developed plans in our heads change with our spectrum of experience. This, in turn, leads to modifications in our spatial behavior. In this context, dancer Kitsou Dubois (2) refers to a kind of confusion humans experience due to the lack of vertical orientation in zero gravity environments. It feels as if you are exposed to a second, superimposed level of experience, a state of perception that "slows down" time due to our own reduced speed of action. An increase in gravitational forces, e.g. upon entering a planet's atmosphere, invariably reminds us of the great significance of our origins. The relation to our original home environment - the planet Earth - is an indelible fact and is thus always manifest in our bodies.

Fig. p - 2: Dance experiments conducted by French dancer-choreographer Kitsou Dubois and troupe on a parabolic flight. © The Arts Catalyst

Technology

In terms of technological progress in space travel, we have reached a phase of desperately trying to gain height. In a way, this might be compared to the situation of Archaeopteryx, a bird-like creature of the late Jurassic period, i.e. 150 million years ago. One of the few flying creatures of its time, it had neither feathers nor fur, only a pair of skin-covered wings similar to those of today's bats. It must have been extremely strenuous for Archaeopteryx to follow its desire to fly, yet the effort was surprisingly effective. „There is something tragically absurd in the obvious discrepancy between mechanical imperfection and the desperate effort to overcome gravity in spite of it all; the very same absurdity inherent in the everlasting human dream of flying."(3, trad.)

The few hundred thousand kilometers we have ventured into space are not enough to assert that "we can survive in space", or to take a view like "we've already been to the Moon, why should we go there again". Given our fragile world with its very limited resources, as well as human curiosity and the development potential of the human species, making further expeditions is a virtually inevitable challenge.

Expanding Real Space

Though *[space]architecture* has hardly ever been used in the actual practice of space design apart from the engineering paradigm (- a rare exception being designer Raymond Loewy, who was integrated in the design of Skylab), it is interesting to apply some characteristic features of this fundamental planning approach to non-space architecture, i.e. architecture in 1-G-environments, or to promote exchange between the different environments. This includes all aspects involving extremely economical use of time, material and resources, as well as attempts at maximum integration of environmental conditions and user requirements in design decisions, but also the mutual influence between humans and their environment, between active and passive, that is generated in responsive, adaptive systems. All of these concepts are a matter of course in *[space]architecture*.

Consequently, concepts for intelligent or sustainable houses can be seen as a practical application of basic features inherent in *[space]architecture*. The same is true the idea of Biosphere 2 in Arizona. Using the technologies developed in *[space]architecture* for disaster relief, i.e. in life-support systems after earthquakes, floods ore similar crises, would mean going one step further. What is more, this is not just about responsive systems, but also about complementing "real" space with virtual expansion. And about a "technologized" space, which expands the real space with a virtual component, thus increasing its complexity - a highly important effect in employing simulation to counter the negative effects of long-term isolation.

The way we perceive our environment today has changed radically compared to our parents' generation. We find that computer technology enables us to redefine our notion of space. In long-duration human space missions, the human factor and their in-space environment will become crucial to mission viability. We will need to incorporate an architectural space into our habitable environment, which critically reflects our state of knowledge and technology and is designed to serve and stimulate human beings of the 21st century.

The increasingly important role socio-psychological factors play in long-duration human missions, and their implications for *[space]architecture* challenge the current typology of space habitats and vehicles. Interaction between humans and their closest environment - the habitat - are crucial factors for mission success. The quality of interaction depends on the user's awareness and notion of the architectural space.

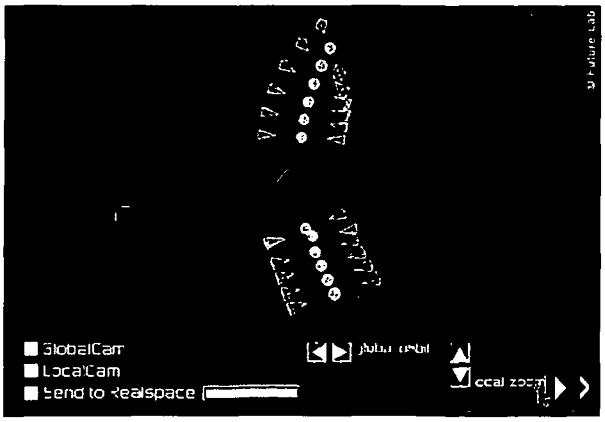


Fig. p - 3: Internet - virtual dimension, „Rückprojektion", ESCAPE*spHERE (Imhof, von Klot, Trenkwalder), Ars Electronica Festival, Linz, 2001

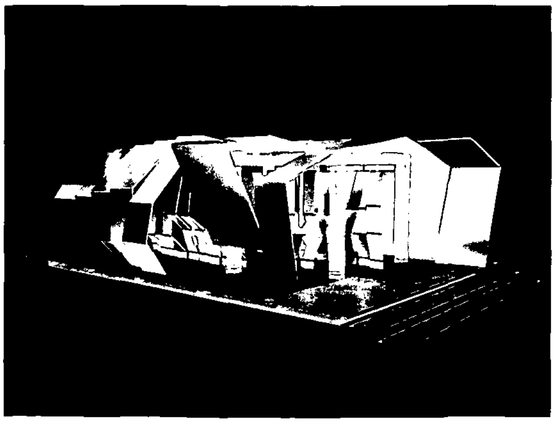


Fig. p - 4: Installative architecture, „Rückprojektion", ESCAPE*spHERE (Imhof, von Klot, Trenkwalder), Ars Electronica Festival, Linz, 2001

Fig. p - 5: Protoype, „Rückprojektion", ESCAPE*spHERE (Imhof, von Klot, Trenkwalder), Ars Electronica Festival, Linz, 2001

References - Preface

(1) Lebedev, V.; Diary of a Cosmonaut: 211 Days in Space, (p. 300)
Texas: Phytoresource Research, 1988.

(2) Dubois, K.; Der sinnliche Flug - Choreographie und Schwerelosigkeit, (p. 143)
Alldesign, Lars Müller 2001

(3) Trummer, T.; Panamarenko, Multiples, (p. 11), ed. by Thomas Trummer, Atelier im Augarten, Wien

Additional references

Clarke, A.C.; 3001 : The Final Odyssey, Ballantine Books (Mm) March 1998

Wachhorst, W.; The Dream of Spaceflight: Essays on the Near Edge of Infinity, Da Capo Press, Perseus Book Group, 2000.

1 Overview of the AURORA Human Mission to Mars Study

In November 2001, the European Space Agency (ESA) Council at Ministerial level approved the Aurora Programme dedicated to the human and robotic exploration of the Moon, Mars and asteroids. The ultimate goal of the Aurora Programme is the human exploration of Mars foreseen in the 2025-2030 time frame. Within the time frame of September 2003 to February 2004, in two phases, for a total of 23 sessions, the European Space and Technology Center's (ESTEC) Concurrent Design Facility (CDF) performed an assessment study of a Human Mission to Mars, known as the HMM study. (1)

The main objective of the study was not to define an ESA "reference human mission to Mars" but rather to start an iteration cycle which should lead to the definition of the exploration strategy, the associated missions, and the requirements for further mission design and feedback to the exploration plan. (1)

The author was invited to take part in this study as an expert in architecture, space architecture, configuration and systems. She gained this expertise in several space architecture projects throughout the last seven years, starting in 1997 when she worked at NASA's Johnson Space Center (JSC) in Houston on a test-bed facility project (BIOPLEX) for the upcoming human mission to Mars.

For the mission elements of the HMM study, for the Earth-Mars Transfer Module – Transfer Habitation Module (THM) – and the Surface Habitation Module (SHM) on Mars an interior configuration was developed. The first study phase terminated in February 2004 including feed-back by experts of the scientific and engineering fields coming from the Russian and European industries. The engineering quantification was developed within ESA and was taken as a reference for the architectural study for this mission, which is the subject of this thesis.

This thesis therefore focuses on the architectural aspects of the HMM study, on pointing out the potentials inherent in the research, conceptualization, and general approach to a task as specific as this one, and on presenting the corresponding design proposals. This approach also provides a more detailed analysis of the architect's role in the design of space habitats, and the scope of operation architects have in this field. The thesis shows how this field can be opened up to issues of system engineering, system architecture, configuration and human factors, all of which can be tackled by joint teams of engineers and architects.

The author of the present dissertation primarily concentrates on the architectural concept and segments of other disciplines that she has been able to define in this study. Detailed technical data of peripheral significance for the project are not included. The data are available on the ESA website and are merely quoted as secondary parameters here at the beginning, in order to provide a technical context for the present project.

1.1 Human Mission to Mars

A human mission to Mars may well be the most ambitious space mission to undertake - even more so when linked to an overall planet exploration program that can involve several expeditions and long permanence on the surface.

A consistent long-term plan needs to be elaborated considering all the technological, programmatic and cost aspects. Preparation of such a long-term plan and associated missions requires a deep understanding of the technical and programmatic issues relevant to human missions to Mars. (2)

A design case for a Human Mission to Mars has been analyzed by ESA. It contains several design elements of general applicability.

The issues of life support, radiation protection, long permanence in space, internal habitats and overall vehicle configurations, entry, descent and landing, Mars surface operations, assembly in Earth orbit, etc. have been tackled in the HMM study, and design solutions have been proposed.

1.2 Mars Mission Statement

- Land a crew of humans on Mars around 2030 and return them safely, ensuring planetary protection for both Earth and Mars. (3)

- Demonstrate human capabilities needed to support human presence on Mars. (3)

- Assess suitability of Mars for long-term human presence (habitability, resources availability, engineering constraints).(3)

These objectives imply specific requirements that help define the mission (3):

- Landing on the Martian surface is required. Missions limited to Mars orbit or fly-bys are not acceptable. (3)

- Duration of the stay on the Martian surface shall allow for excursions (surface Extra Vehicular Activity (EVA) and sample collection. (3)

- Mission case shall take into account all the constraints associated with human requirements (physiology, psychology, radiation, architecture, habitability, etc.). (3)

The ultimate goal is the establishment of a permanent outpost on the surface of Mars. This will require a number of missions for the setup and several more missions for the routine exploitation of the outpost. The design is to be used to identify and recommend further investigation in potentially promising mission options and scenarios. (3)

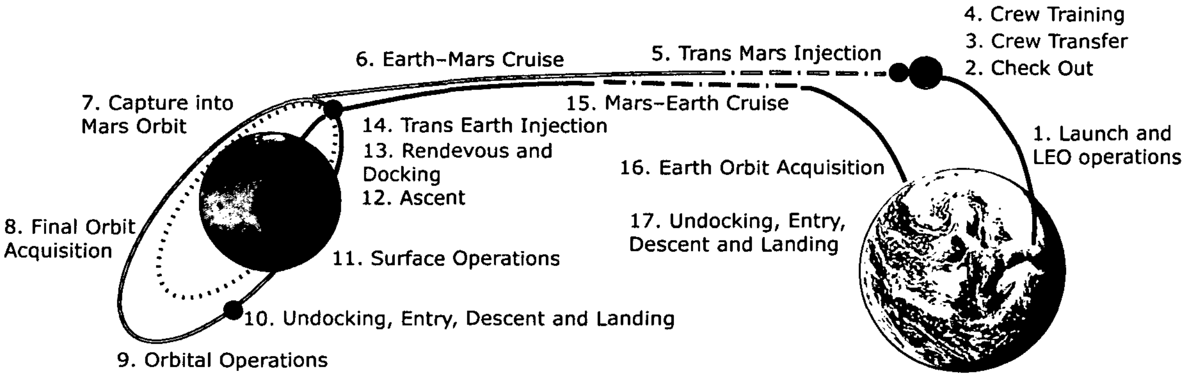


Fig. 1.2 - 1: Mission Phases

The primary mission elements investigated are:

- The Transfer Habitation Module (THM), defined as the vehicle that hosts the crew in its trip from Earth orbit to Mars orbit and back towards Earth and during the orbital phase around Mars. Though several configurations are possible depending on the type of technology used for the transfers and orbit insertion, many subsystems are common to all cases. Mastering the design and technology challenges for such a vehicle will be fundamental to perform any human mission to Mars, or long duration missions within the solar system. (4)

- The Mars Excursion Vehicle (MEV), defined as the vehicle that performs the entry descent and landing onto the Martian surface, hosts the crew during the Mars stay, lift-offs to Mars orbit at the end of the surface mission and performs the rendezvous with the THM before departing back to Earth. This vehicle is part of all the mission scenarios and it is most critical. Entry, descent and landing are the most crucial challenges. (5)

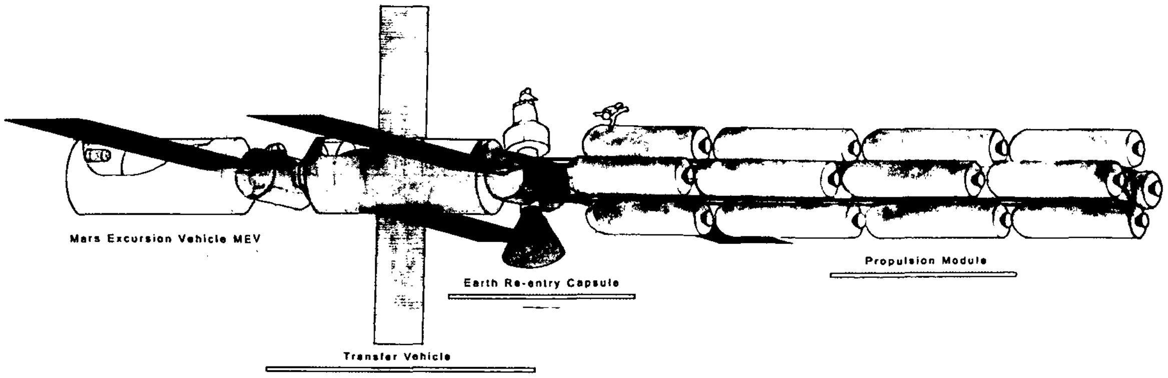


Fig. 1.2 - 2 Overall configuration of the Mars transfer spaceship showing the main parts

1.3 Mission Scenario

Overall Characteristics	**Value**
Number of total crew during transfer	6
Crewmembers landing on Mars	3
Mars sample mass to be collected	20 kg
Extravehicular activity (EVA) required	every second day for approx. 6 hrs.
Launch dates	from 2025 and 2040
Maximum assembly time in Low Earth Orbit (LEO)	6 years
Total Mission Duration (days)	963
Surface Duration (days)	30
THM in Martian Orbit	533
Consumables (tons)	10.2
Mass to LEO (tons)	1541
Launch Characteristics	**Value**
Overall mass (tons)	1541
Launcher	Energia (currently out of production)
Payload mass of ENERGIA (tons)	80
Fairing length of ENERGIA (m)	35
Fairing diameter of ENERGIA (m)	6

Fig. 1.3 - 1 CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004

1.4 Overall Configuration

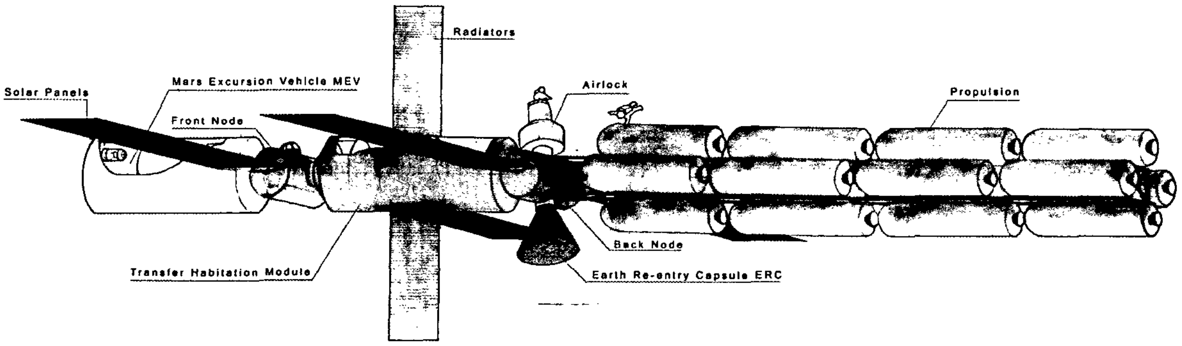


Fig. 1.4 - 1 Overall configuration of the Mars transfer spaceship; description of the single elements

1.5 Transfer Habitation Module (THM)

This mission element is the core of the mission. It will provide the basic functions during cruise, e.g. life support, communications, data handling, etc. and the habitable volume for the astronauts during most of the duration of the mission. It is composed of a central cylinder, which houses most of the facilities and equipment, and two nodes that act as connection points with the rest of the mission elements and provide extra volume for the crew. Each of these units can be sealed in case of emergency. A storm shelter is also included to protect the crew during possible solar particle events. (6)

The THM also provides docking interfaces with the MEV and ERC as well as an airlock to allow EVAs and a spare docking port. Mechanical interfaces with the propulsion modules are also provided. (7)

Overall Characteristics THM	**Value**
Overall mass (tons)	67
Consumables mass (tons)	10.2
Total pressurized volume (m^3)	480
Overall length (m) about	20
Main cylinder diameter (m)	6
Nodes diameter (m)	3.5
Nodes length (m)	5.2
Solar arrays (m x m)	5.1 x 15

Fig. 1.5 - 1 CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004

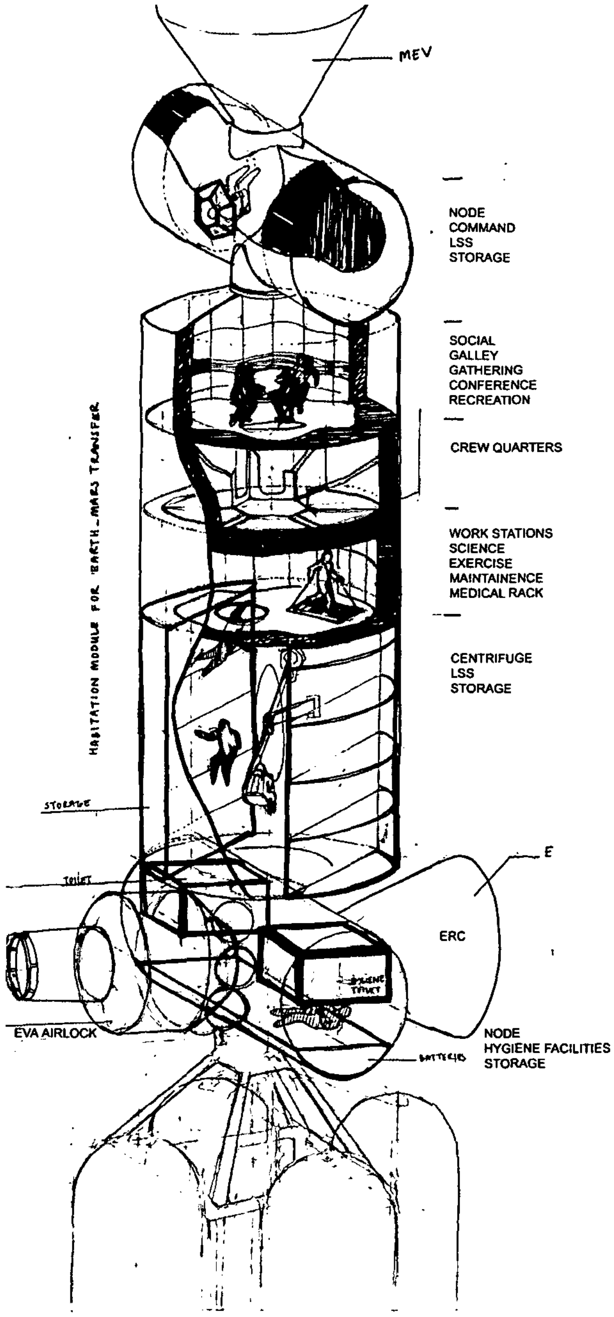


Fig. 1.5 - 2

The interior volume is split into:

Command module, in the front node, including a window cupola.

Social area, providing a space for crew gathering, dining, galley and infrastructure for conference and a virtual expansion of the interior space. Exterior windows are provided.

Crew quarters, noise isolated from the rest of the vehicle, act also as storm shelter. Extra water is used in this area to increase the radiation protection.

Work stations, a small laboratory and a maintenance area, providing the working area for the astronauts.

Exercise area, largest volume in the THM. It houses the centrifuge, life support equipment and storage units.

Back node, extra storage volume, hygiene facilities, airlock and Earth Return Vehicle (ERC) docking port.

1.6 Mars Excursion Vehicle

This mission element allows a crew of three astronauts to land on the surface of Mars and take off after 30 days to rendezvous and dock with the TV. (8) It is composed of three main elements:

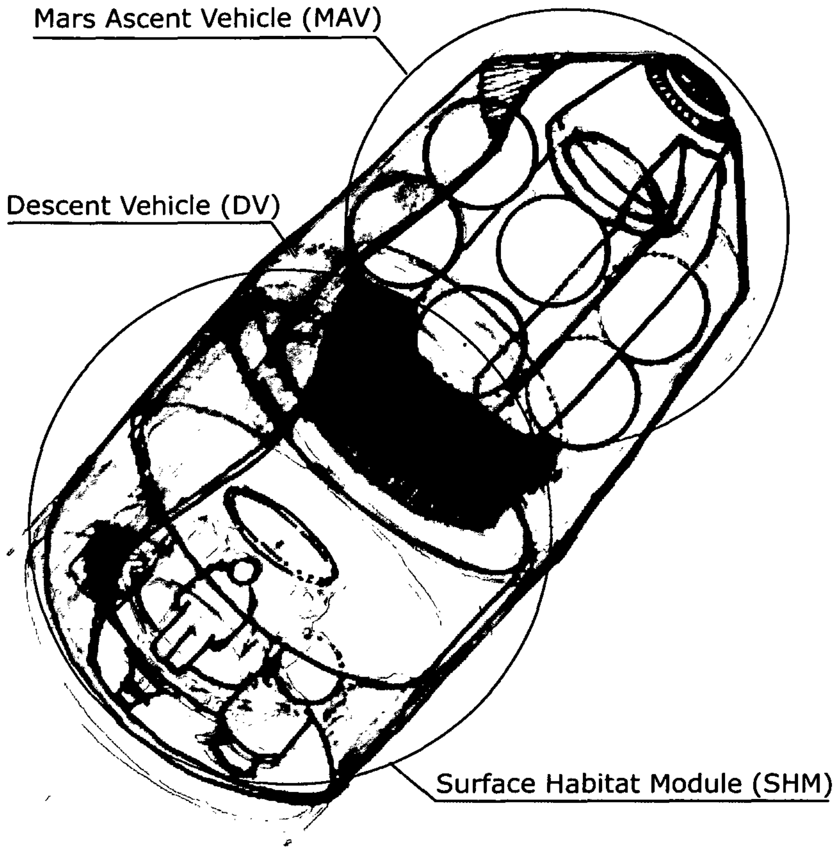


Fig. 1.6 - 1 Mars Excursion Vehicle - Overall Configuration

- Mars Ascent Vehicle (MAV), the ascent vehicle in which the astronauts return to orbit, mainly composed of a capsule (in which the astronauts are also during descent) and a propulsion module split into two stages. It provides life support for 5 days. (8)

- Surface Habitation Module (SHM), a cylindrical module that houses the astronauts during their permanence on the surface providing life-support systems and EVA equipment. The landing systems (retrorockets and landing legs) are located in this module. It also provides the interfaces with the MAV. (8)

- Descent Module (DM), mainly composed of the de-orbiting propulsion system, inflatable heat shield, back cover and parachutes for the entry and descent. (8)

The MEV is attached to one of the extremities of the Transfer Vehicle (TV), in a docking port on the longitudinal axis of the TV.

Characteristics MEV	**Value**
Overall mass (tons)	46.5
Consumables mass (tons)	0.3
Propellant mass (tons)	20.5
Total pressurized volume (m^3)	80
Overall length (m)	12.1
Overall diameter (m)	6

Fig. 1.6 - 2 CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004

1.7 Surface Habitation Module (SHM)

The SHM hosts the astronauts during their stay on the surface (30 days plus 7 for contingency). It provides interfaces with the MAV capsule and an airlock for the surface EVAs. (9)

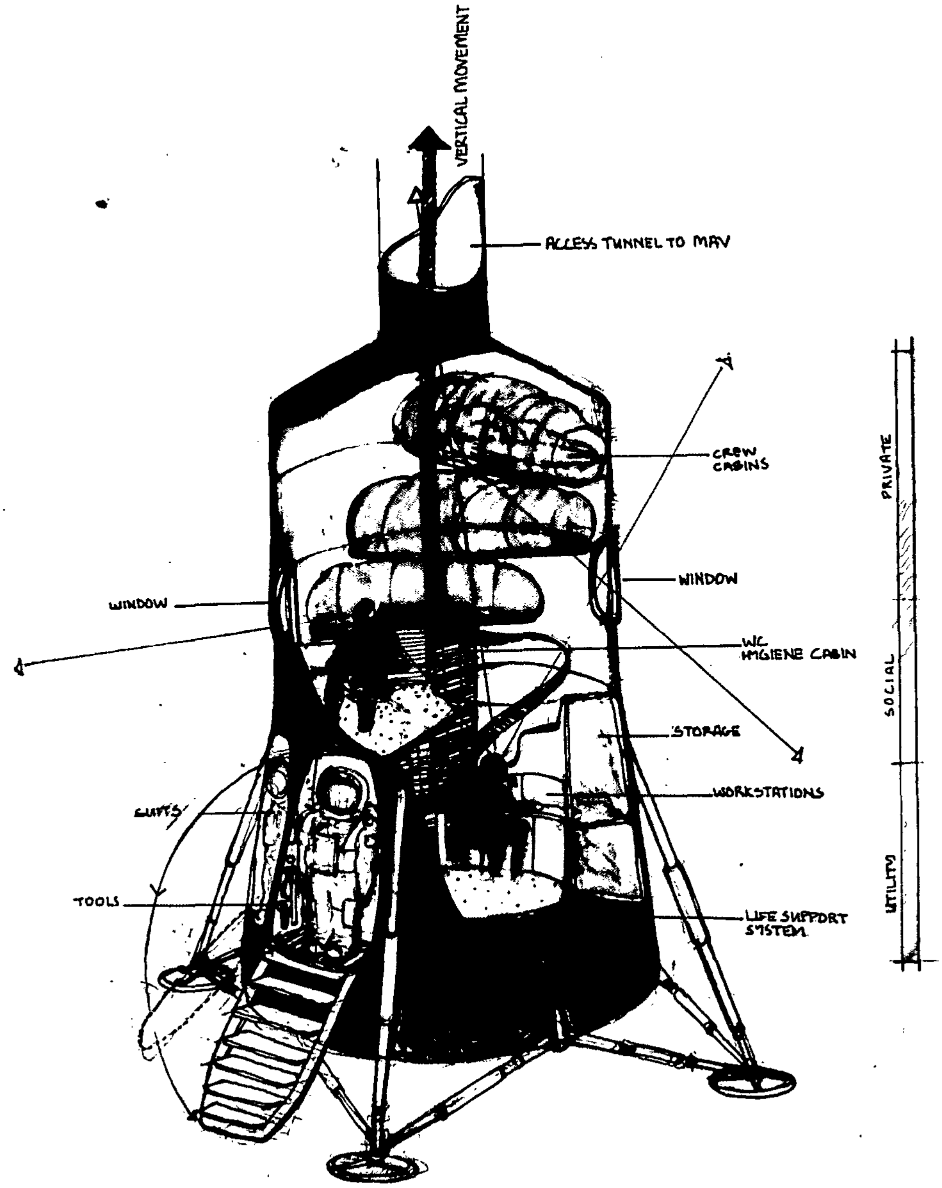


Fig. 1.7 - 1 Final baseline design of the SHM

- The top level is used for the crew cabins, close to the MAV tunnel. (9)

- The middle level provides the main social area. It has two windows. The stowage system, galley and necessary infrastructure are located here. (9)

- The lower level is used as the working area. It also includes the decompression chamber and the EVA infrastructure. The hygiene facilities are located between the lower level and the middle level. Most of the heavy equipment (power and life support) has been placed down to lower the vehicle's overall centre of gravity. (9)

Three suits are provided for EVAs. They are located on the outer surface of the SHM due to planetary protection issues (no contaminated surface should see the habitable volume). Bio locks are also provided for sample handling.

1.8 Mission Case Summary - Characteristics Value

Crew	**Value**
Total number of crew	6
Number of crew landed on Mars	3
Masses	
THM mass (tons)	66.7 (wet) 56.5 (dry)
MEV mass (tons)	46.5
ERC mass (tons)	11.2
Consumables (tons)	10.2
Propellant (tons)	1083
Propulsion systems (tons)	130
Supporting structures (tons)	19.7
Total mass at Earth departure (tons)	1367.3
Sampled collected (kg)	20
Trajectories	
Earth departure	8 April 2033
Mars arrival	11 November 2033
Mars departure	28 April 2035
Earth arrival	27 November 2035
Duration of stay on the surface (days)	30
TMI ΔV (m/s)	3639
MOI ΔV (m/s)	2484
TEI (m/s)	2245
Earth atmospheric entry velocity(m/s)	11505
Launches	
Total number of launches	28
Total mass launched (tons)	1541
Assembly time (years)	4.6

Fig. 1.8 - 1 CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004

1.9 General Conclusions with a Focus on Overall or Technical Issues

The most important technical issues and major conclusions are listed below (see reference 10 for whole section 1.9):

- A design point exists for an entirely "chemical" mission (e.g. all based on chemical propulsion). However, this gives a rather high mass in LEO (above 1000 tons) and as a consequence, high time of assembly in LEO.

- Even the simplest mission based on very limited functions and capability leads to extremely large and massive vehicles and requires assembly in Earth orbit before departure.

- The most critical technical showstopper for such a mission is the overall vehicle assembly time in LEO that could result in unacceptable phasing of subsequent missions and lead to unacceptable ageing before

- Launcher availability is critical in any case. The study assumed that a launcher with the performance of Energia would be available for most of the launches. If this hypothesis cannot be confirmed a very high penalty on the mission is expected.

- The reason for the high overall mass of the mission stems from the very large dry mass of the Transfer Habitation Module and the relative inefficiency of the chemical propulsion system.

- Among the possible alternatives not requiring technology leaps, aerobraking and aerocapture have been briefly investigated. It has been found out that the implementation of these techniques will require large changes in the vehicle designs as compared to the chemical case. The detailed analysis of these options was considered out of scope of this first study and will be performed in later phases.

- Verification of safety requirements has proven impossible without an overall risk model. However, mission abort cases have been investigated and the design has taken into account failure cases to a certain extent. Failures in the propulsion system cannot be recovered without unacceptable penalty on the mission; therefore very high reliability is a key requirement for the systems implemented.

- High closure of the life support system (e.g. recycling) is a must. The penalty associated with an open system would be too big for such a mission.

The design case analyzed represents a simplified mission. Among the limitations of this approach, the following should be stressed:

- Permanence on the surface has been limited to about 30 days to simplify the design task and associated models. Though this short duration is unlikely to be selected within the frame of a planet human exploration program, it represents a good starting point when setting the mission architecture.

- No previously installed surface infrastructure has been assumed for this design case. Therefore neither precision landing nor separate cargo mission is required.

- Implementation of micro-gravity countermeasures

- Techniques for reduction of boil-off in cryogenic propulsion system (for the chemical option)

- Ground and Space System infrastructures for very high data rate telecommunications and mission support

- Entry descent and landing systems for very large arrival masses

- Automatic assembly techniques in LEO

- Fuel cells

- Advanced avionic systems and architectures

1.10 Architectural Conclusions

The integration of architectural concepts with their technical implications and their implementation into human space missions is necessary for long duration human spaceflight so as not to jeopardize the whole mission. The human system needs to be reflected with respect to implications of living in extreme environments, which includes habitat design. Major factors to be considered when planning a habitat are the socio-psychological factors, notably interaction among the crew.

Relationships form the basis of human existence. Compared to 'normal' life on Earth, the relevance of social interaction increases considerably when individuals live under extreme conditions in a harsh environment. And architecture embodies human relationships; after all, it focuses on the manifestation of space and how relationships between inhabitants influence their environment.

In fact, 'living in extreme conditions' is a somewhat ambiguous concept. It refers to the relationship humans have to an environment they can only experience with technical aids and instruments, an environment that is physically tangible to begin with but leaves traces in the realm of psychology. In this sense, 'living in extreme conditions' also refers to an extreme psychological situation, a 'psychological environment' that may also have physical impact on the individual. On long-duration human missions, the Astronauts/Cosmonauts usually glide from one of these extremes to the other and back again.

Every habitat is expected to reflect a holistic understanding of processes in space. As a space machine, the space habitat implies a flexible rather than a rigid structure. The point is to develop an outlook on architecture that focuses on processes rather than just on rigid walls.

Therefore buildings, as we see them, are intermediary results rather than statements. Accordingly, architecture needs to be understood as the product of a process - an adaptable expression of a living society or an adaptable appropriation to a future society.

The architectural approach, methodology and design results of this project are to be seen in the context of these general architectural themes and the task of creating a spaceship within the possibilities of status quo technology.

1.10.1 Approach

As regards the architectural approach chosen, it is best described as the process-oriented development of two baseline designs for the THM and the SHM. The design was developed from an initial idea, and the design options were modified with feed-back from the engineering and scientific expert community. From an architectural point of view, constant reassessment also proved appropriate since it allowed for the designs to be altered to obtain a space perceivable in qualitative terms, where specific shapes, materials, light and surfaces made the gave the inhabited space a more emotional feel. After every step, especially with the different design options, some parameters were changed and the most crucial ones were identified.

Communication and interaction with all relevant people from engineering and science was vital to the development of the two baseline designs. Most important to this were the fields of systems and configuration engineers, the expertise of the human factors and safety engineers, as well as expert knowledge on life support systems. Through that the design was informed and the author could gain important knowledge, which could subsequently influence the decisions of the engineers and scientists by integrating their designs into comprehensive solutions.

1.10.2 Methodology

The key issues for the methodology applied were the following:

- Comprehensive investigation into previous research - this field of research is not very common in space engineering or space management:
    - All space stations are put together for overview and comparison
    - Take space station or Mir or Skylab designs and Transhab and review the volumes, functionality and use
    - Based on the previous investigation, draw up recommendations for the two baseline designs of the THM and the SHM

- Integration of all necessary functional aspects

- Human centered approach - integration of human needs

- Perception of space in a small limited space

- Taking into account the socio-psychological factors

- Flexibility of use of spaces although the technical infrastructure is complex

1.10.3 Baseline Design for the THM

The development of the baseline design was a longer iterative process with constant feedback from the ESA experts. Many options regarding the overall configuration of the Transfer Habitation Module were discussed and developed. Redundancy and backup systems became a major issue. The standards developed by NASA for volume requirements were taken as a reference. The individual steps are briefly listed in the following paragraphs:

1. Integration of all functional aspects such as

- Exercise (centrifuge, ergometer, treadmill etc.)
- Command module
- Laboratory including workstations

- Medical facility
- Galley and food storage
- Hygiene facilities
- 6 private crew quarters
- Communal area (dining, recreation, communication including communications with mission control and family, friends etc.)
- Virtual extension of the communal area through advanced communications technologies

2. Developing the functional aspects and their spatial implications in more detail

3. Integration of

- Windows
- Life support systems
- Ducts
- Redundancy
- Storm shelter
- Safety

This process was followed by the development of up to 10 options with different configuration and layout until the final baseline design was established, focusing on the issues of the 'private', the 'personal', and the 'social' areas as described by Constance Adams in "Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One - Habitability" (paper no.: 1999-01-2137, AIAA)

1.10.4 Baseline Design for the SHM

For the design development of the SHM the lessons learnt from the THM were taken further for the various options of the SHM, though the partial gravity environment implied different layouts and designs. The main structure derives from the integration into the overall configuration of the MEV.

- Integration of the SHM into the MEV

To assure a safe and practicable connection from the MAV to the SHM, a tunnel between the two hardware parts is proposed. It allows the transfer of the three person crew from the landing in the MAV to the SHM where surface operations will be conducted and back to the MAV for transfer to the main orbiting spaceship.

- Inflatable Options

Various options for inflatable surface habitats were developed but all discarded in the end due to the lack of proven data for successful deployment. The only prototype built so far with current technology is NASA's Transhab, which is not sufficient to draw any conclusions for implementing crewed Martian surface structures.

Just as the THM, the SHM underwent a longer iterative process with different steps in which the final baseline design was altered.

All aspects described for the development of the THM, such as the integration of all functional aspects, their more detailed spatial implications and the integration of windows, life support systems, ducts, redundancy, radiation shelter and general safety aspects were equally taken into consideration for the SHM.

1.10.5 Human Factors

The following section briefly describes an important area with high influence on the architectural design, given the fact that this area of research is extremely large and cannot be covered in this project in full depth. Additional reference literature is given in the reference section.

Main issues in the highly comprehensive research area of human factors are psychological, social and physiological stressors. The 'man-machine-interface' is also part of this research. It is important to investigate all topics when planning a long duration human mission. The research findings need to be integrated into the architectural layout as well as the final implementation of the mission.

Physiological stressors include environmental factors such as long exposure to radiation, weightlessness and hypogravity. Psychological stressors will arise from different areas related to the technical constraints of a space habitat, its life support system, the mission-specific operational and experimental workload of astronauts, but also the psychological situation in a space habitat, which is again closely interconnected with the layout, the design and the architectural expression of the habitat.

The stressors include:

- Remoteness from Earth
- Confinement
- Potential interpersonal conflicts
- Medical risks including trauma

„Generally, future long-duration exploratory missions to Moon and Mars can be expected to involve the same range of psychological issues and risks which have been reported from long-duration orbital flights, simulation studies and expeditions into analogue environments.(12)

Socio-psychological factors relevant for these missions:

- Mission duration
- Architectural layout
- Crew size and composition (selection)
- Degree of isolation and social monotony
- Crew autonomy
- Evacuation in case of emergency
- Availability of support measures - e.g. communications
- Entertainment
- Amount of meaningful work

All long-term habitability aspects such as crew composition, interpersonal dynamics, motivation, communication, crisis management and privacy have architectural implications such as the extension of the confined space through soft and malleable, non-defined spaces which are permeated by technology and represent virtual dimensions, so-called augmented realities. Other programmatic aspects for investigation include spaces for gathering and for privacy with a distinct and changeable atmosphere, designed objects for everyday use incorporating the human-machine/object interface, and the creation of flexible deployable multifunctional spaces.

The design parameters for space habitats, which were originally determined by engineering aspects and safety precautions, will have to change due to the increased duration of space missions, and will equally need to incorporate psychological, sociological and architectural factors. Thus spaceflight for long-duration missions is presently entering a new stage in its development and the technical orientation of past designs will have to be complemented with a greater focus on architectural and habitability aspects.

Originally, the criteria mentioned above were considered irrelevant since astro/cosmonauts (pilots) were usually recruited from the military. Space missions, even lunar landings, used to be of short duration, originally taking a maximum of six to eight days. From the 1970's to the 1990's, missions to Skylab (USA), to the Salyut station (USSR) and to the MIR station (USSR/Russia) were extended to a duration of many months. A mission to Mars, however, would take thirty months - six months in zero gravity to reach Mars, over one year in partial gravity on the planet's surface (depending on the mission scenario), and another six months to return to Earth. This is a very long period of time, during which each member of the crew would have to take on considerable responsibility, and which would require substantial autonomy and decision-making power, given that radio communication with ground support would involve a time lag of twenty to thirty minutes at this distance. After all, most of the design parameters for space architecture are based on terrestrial architecture. In spite of this, design strategies and methods that have developed out of experience and tradition over thousands of years cannot be applied directly to an environment in space or on another planet, where we have no such experiences. To provide functioning designs for space missions, we have to adapt our concept of design and possibly change the design paradigm over the coming years.

When discussing psychosocial factors it is interesting to note that, for quite a long time already, many projects and space designs on Earth - particularly commercially successful projects such as in the entertainment industry - also focus on psychological aspects and the customers' subjective perception, and that the entire architecture of these projects revolves around these factors.

A space habitat is a space that is permeated and dominated by technology. In addition to life-support systems, it has to provide technologies for food preparation, personal hygiene (showers), communication (e.g. Internet access) and other „everyday" needs in life on extra-terrestrial missions. However, technology is also a destabilizing force; in an architectural context, it creates a dynamic space characterized by different media. Consequently, architecture needs to introduce new (virtual) dimensions which go beyond the real, material quality we are accustomed to, allowing for a new perception of space, which undergoes a process of psychological, social, political and eventually formal redefinition.

„One of the environmental limitations of spaceflight is that the individuals are confined to a small area. It has long been understood that when individuals are so restricted, both physical and psychological symptomatologies result." (Mary Connors, Mary Albert Harrison, Living Aloft", „Human Requirements for Extended Spaceflight, Government Printing Office, 1985, http://www.hq.nasa.gov/office/pao/History/SP-483/contents.htm)

For architecture this means that the individual rooms of an isolated habitat allowing an international crew of several members to live and work in space or on a planetary surface must not have the effect of restricting the crewmembers in their perceptions; instead, they must provide an open environment for the crew, and allow the inhabitants to live in and experience their habitat. This implies both a specific material shell and an infrastructure that is designed to allow subjective perception, like an instrument that inhabitants can use individually. Perception turns into an object of design, and individual psychology acts as a mediator between the habitat's shell and perception.

In this thesis only a few of the many new habitability aspects will be exemplarily discussed.

But in the long run there will inevitably be some fundamental changes to the way we perceive our environment. Firstly, habitats on Earth are subject to considerable changes due to the progress and increasing importance of technology; by now, technical services in large office buildings are nearly as sophisticated as the life support systems of the International Space Station.

The planning of space missions is bound to become even more complex due to various engineering aspects, especially safety issues, which must be considered on top of the other factors. We will be able to develop the necessary tools for this complex task with the aid of modern computer technology and other fast-progressing technologies, and based on modern scientific findings.

1.11 References - Part 1

(1) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.9
(2) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.11
(3) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.13
(4) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.11
(5) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.12
(6) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.27
(7) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.29
(8) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.34
(9) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.36
(10) CDF Study Executive Summary, Human Mission to Mars, ESA, CDF-20(c), 2004, p.43
(12) DLR, Medes, Astrium, Dera, HUMEX: a Study On Survivability And Adaptation Of Humans To Long-Duration Exploratory Missions, ESTEC, Co.No. 14056/99/NL/PA

Additional general references

Adams, C. M.; McCurdy, Matthew R. (1999 July). Habitability as a Tier One Criterion in Advanced Space Vehicle Design, Part One: Habitability (SAE 1999-01-2137). 29th International Conference on Environmental Systems (ICES), Denver, Colorado, USA, 12-15 July 1999. Warrendale, Pennsylvania, USA: Society of Automotive Engineers

Adams, C. M.; Design Concepts for the ISS TransHab Module (NASA TSP MSC-23090). Houston, Texas, USA: Johnson Space Center, National Aeronautics and Space Administration, 2000

Cohen, M.M.; Habitat Distinctions: Planetary versus Interplanetary Architecture (AIAA 96-4467). Space Programs and Technologies Conference, Huntsville, Alabama, USA, 24-26 September 1996. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics

Cohen, M. M.; Space Habitat Design Integration Issues (SAE 981800). 28th International Conference on Environmental Systems (ICES), Danvers, Massachusetts, USA, 13-16 July 1998. Warrendale, Pennsylvania, USA: Society of Automotive Engineers

Cohen, M. M.; Analysis of Designs of Space Laboratories (NASA TSP ARC-14965). Moffett Field, California, USA: Ames Research Center, National Aeronautics and Space Administration, 2003

Connors, M.; Harrison, A.; Akins, F. R.; Living Aloft: Human Requirements for Extended Spaceflight (NASASP-483). Washington, DC, USA: National Aeronautics and Space Administration, 1985

Imhof, B.; In the Simulator (Architecture, Technology and Innovation), Interview with Fred Smith, Simulation Astronaut, NASA, 26.08. 2003, Radio Orange

Imhof, B.; Schartner, H.; Mars Surface Habitats: Architectural Designs and Concepts for Planetary Outposts (SAE 2001-012174). 31st International Conference on Environmental Systems (ICES), Orlando, Florida, USA, 9-12 July 2001. Warrendale, Pennsylvania, USA: Society of Automotive Engineers

Kennedy, K. J.; Lessons from TransHab: An Architect's Experience (AIAA 2002-6105). 1st Space Architecture Symposium (SAS 2002), Houston, Texas, USA, 10-11 October 2002. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics

Larson, W. J.; Pranke, L. K.; Human Spaceflight: Mission Analysis and Design. New York, New York, USA: McGraw-Hill, 1999

NASA; Man-Systems Integration Standards, Revision B. Washington, DC, USA: National Aeronautics and Space Administration, 1995

Hoffman, S. J.; Kaplan, D. L. (Eds.); Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team (NASA SP-6107). Houston, Texas, USA: Johnson Space Center, National Aeronautics and Space Administration, 1997

Toussaint, M.; Russian Manned Space Program & Russian Space Stations Evolution, From Salyut 1 to MIR, ESA-HQ, Paris

2 An Architectural Analysis of Historic and Current Crewed Space Stations

Analyzing historic space stations is essential in developing a baseline design for a transfer spaceship to Mars and a surface habitat on Mars. It provides important factors for the configuration but also with regard to habitability aspects, thus forming a base for recommendations for the design study at hand.

The following is an investigation into the spatial layout and use of space stations. Each space station included represents a separate concept. The following fundamental issues have been selected to compare the different designs:

- Main characteristics
- Advantages and disadvantages
- Special characteristics - highlighted

2.1 Interior Configuration Issues in Salyut 7, MIR (core), Skylab, ISS (Zarya)

2.1.1 Concepts of Space Stations – a General Overview

Salyut I (1971) and Skylab (1973) were single-element configurations with all subsystems integrated in one pressurized module.

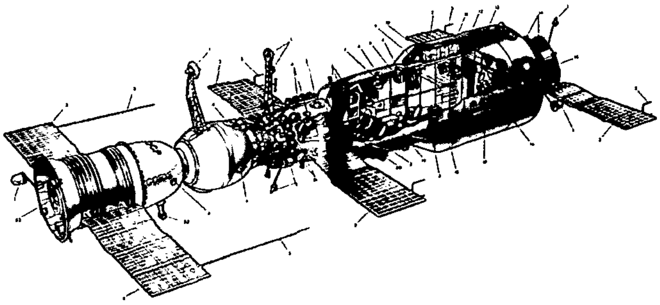


Fig. 2.1.1 - 1: Salyut Station, image courtesy of NASA

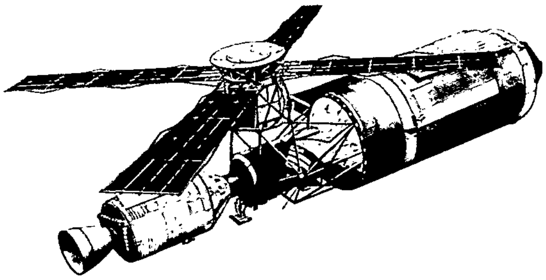


Fig. 2.1.1 - 2: Skylab, image courtesy of NASA

Characteristics:

One self-contained element

- One launch required to deploy and operate
- Low cost and risk (The single element can be fully tested on the ground before launch)

- No growth potential
    - limited to launch mass and volume
    - limited redundancy

Especially suited for:

- One to three crewmembers
- Small power and heat rejection
- Several years of lifetime
- Specialized mission profile
- National programs

The MIR space station was a multi-element pressurized module backbone.

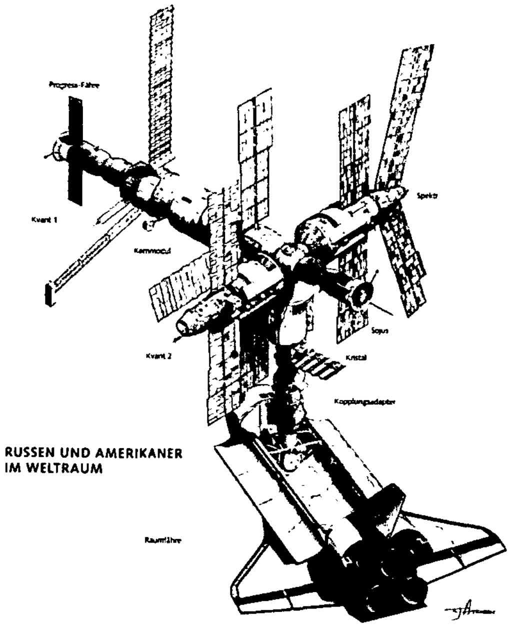


Fig. 2.1.1 - 3: Space Station MIR with docked Space Shuttle, courtesy of NASA

Characteristics:
Subsystems integrated in each pressurized module with a lot of autonomy between elements

- Structure is very stiff
- More redundancy
- Continuous and flexible growth potential
- G-jitter at higher frequencies
- Good flexibility for reconfiguration on module level

- Several launches required to deploy and operate
- Limited power density to support collectors and radiators
  (it shadows the arrays and doesn't dissipate as much heat)
- Limited external payload accommodation
- Reconfigurations inside modules more difficult

Especially suited for:

- Medium-sized configurations
- < 10 years lifetime
- Sharp mission profile
- Highly flexible configuration
- Moderate power and heat rejection
- High microgravity requirements
- International programs

The Space station Freedom and the International Space station (ISS) uses a multi-element truss backbone concept.

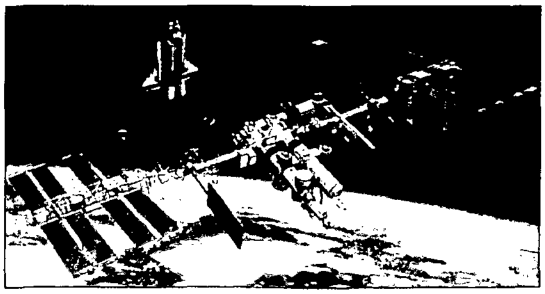


Fig. 2.1.1 - 4: Space Station Freedom, courtesy of NASA

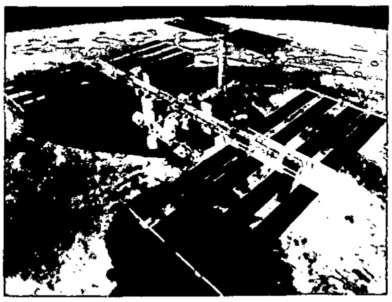


Fig. 2.1.1 - 5: International Space Station, courtesy of NASA

Characteristics:
Centralized subsystems with ample interaction

- Good external payload accommodations for multi-mission scenario
- Design favors building separate functional areas (power generation, habitat, laboratory, thermal control, etc.) and orbit replaceable units (ORUs)
- Higher power densities attainable
- Centralized subsystems can save mass
- Higher usable volume in a given payload module's volume

- Many launches required to deploy and operate (flight elements depend on each other)
- Limited growth (size and power)
- G-jitter at lower frequencies
- More efforts to distribute resources (power, thermal, data)

Especially suited for:

- Diversified mission profile
- High power and heat rejection
- Up to 7 crewmembers
- Lifespan of 10 years
- Multinational programs

General Aspects and Numbers

The dimensions of the modules were restricted by the capabilities of launch vehicles

System	Used for	LEO	Fairing Diam.	Fairing Length
Proton	Salyut stations	20.9t	4.1m	10.8m con + 3.0m tap
Space Shuttle	ISS-Modules	24.4t	4.7m	18.6m + flight deck
Saturn V	Skylab		6.61m	34.81m

Fig. 2.1.1 - 6

Volume and Mass comparisons of Space Stations

Space Station	Module	Volume	Mass	Diameter	Length
	Soyuz	6.3 + 3 m^3	6.8t	~3m	7.8m
Salyut		100 m^3	18.5t	max. 4.1m	13-15m
MIR	Base Block	95 m^3	20.9t	< 4.15m	13.13m
	KVANT 1	40m^3	20.6t	< 4.15m	5.8m
Skylab			89t	6.6m	36m
	Orbital WS	275m^3	25.4t	6.6m	14.7m
ISS	FGB	60m^3	19.3t		12.63m
	SM/Zvezda	82m^3	22.25t		12.63m
	UDM/Node 1		19.34		8.4m
	Transhab	595m3		3.4/8.3m	10.52

Fig. 2.1.1 - 7

The following section provides a more detailed description of the major space stations. As an overview it serves as a good basis for subsequent decisions and discussions.

2.1.2 Concepts of Space Stations - Overview Regarding Configuration and Habitability

2.1.2.1 Salyut - Space Stations (1971 - 1991)

Volume:	~ 90 - 100 m³
Mass:	18.5t
Diameter:	max. 4,1 m
Length:	13 - 15 m
Crewmembers:	3-6
Flights:	several, see below
Duration:	various, see below

Salyut refers to a series of space stations launched by the Soviet Union. The Salyuts were all relatively simple structures consisting of single main modules placed into orbit in a single launch.

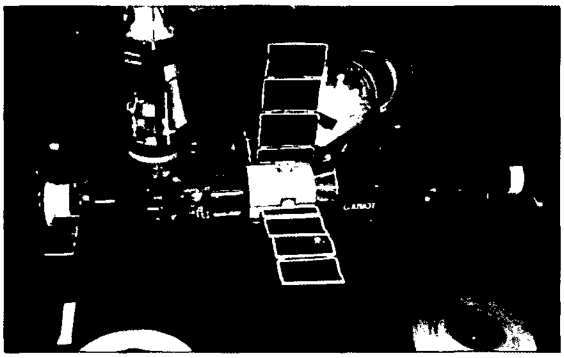


Fig. 2.1.2.1 - 1: Model of Salyut 6, with docked Soyuz, docked Progress and Kosmos, courtesy of NASA

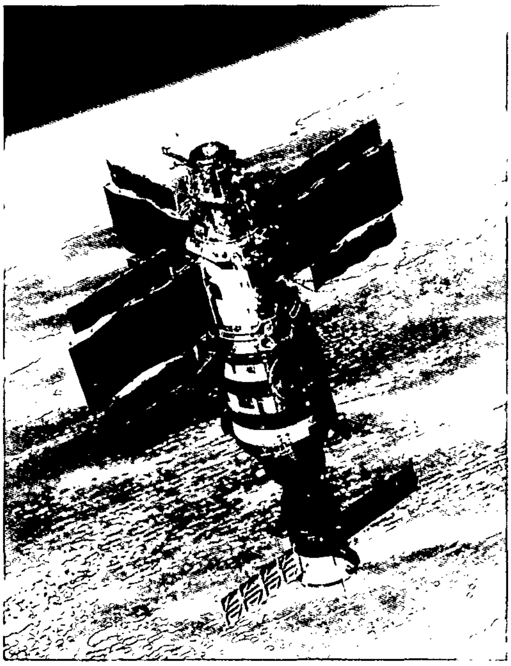


Fig. 2.1.2.1 - 2: Salyut with docked Progress Freighter, courtesy of NASA

Salyut 1 (1971) 23 days successfully occupied

Salyut 2 (Almaz) (2) (1973), unsuccessful
The Almaz project, though officially named Salyut station, was internally meant for espionage purposes only. It was a high-secret project of the Soviet military. The Almaz stations can not be compared with the Salyut stations. The Almaz stations were stationed in substantially lower orbits. They possessed photo equipment with an extremely fast lens to take espionage photos. Besides they were equipped with a telescope and possessed highly precise measuring instruments to place the station optimally over a target.

Salyut 3 (Almaz) (1974), only one crew successfully boarded

Salyut 4 (1974 - 1977)
was the first civil space station, 91 days successfully occupied (longest one 63 days)
It possessed a solar telescope and other measuring instruments.

Salyut 5 (Almaz) (1976 - 1977) was the last military space station.

Out of ten dockings so far, only five had been successful. The Station was redesigned.

Salyut 6 (1977-1982), (15 Progress missions + 17 human missions - 2 unsuccessful), 676 days successfully occupied
Featured several revolutionary advances including a second docking port where an unmanned Progress cargo spacecraft could dock and refuel the station - includes many expeditions and a long term stay of 185 days.

Salyut 7 (1982-1991) (13 Progress missions + 12 human missions - 1 unsuccessful)
The station was also redesigned to test long-term occupancies (the first crew spent 211 days in orbit) as well as the docking and use of large modules with an orbiting space station. Better lighting for the work area, a refrigerator, and a system for cold and hot water for better food preparation was installed.

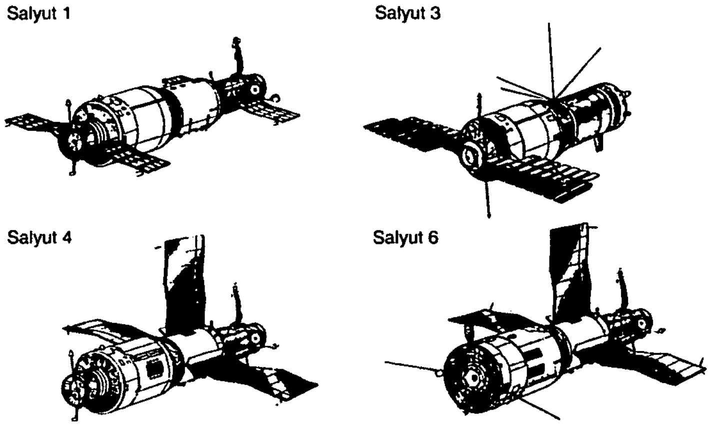


Fig. 2.1.2.1 - 3: Evolution of Salyut Space Stations, courtesy of NASA

In terms of overall configuration, this concept of a singular module to be launched into space in a single launch seems to be a good approach for the present Human Mission to Mars study.

Configuration

This section focuses on the three different zones (private, personal and social). Salyut 7, the largest of all space stations, was selected as an example and reference for the THM.

Salyut Stations had a large volume for subsystems, mixed habitability and laboratory functions, and limited living and working volumes.

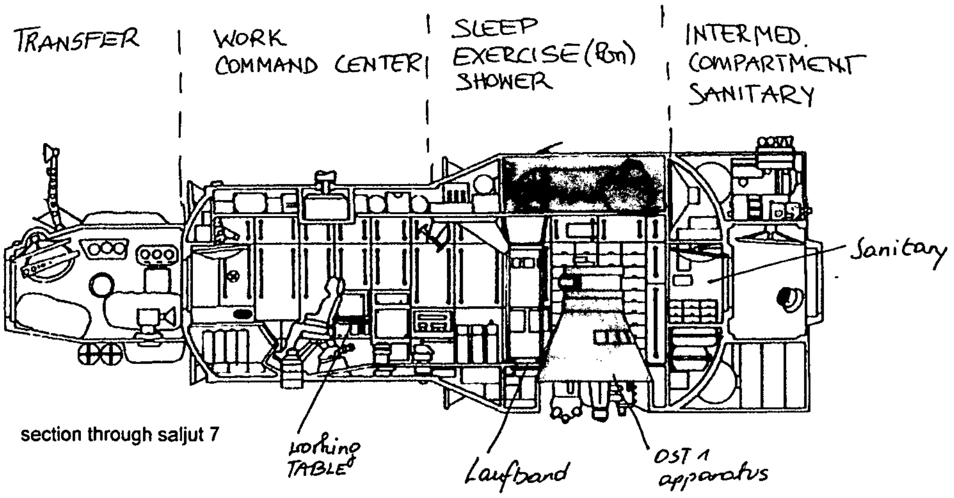


Fig. 2.1.2.1 - 4: Section of Salyut 7

"The multiple diameters of the Salyut station (2,0 m, 2.9 m and 4.15 m) derived from mounting the Salyut on top of the launcher. The different diameters made equipment and payload accommodation more complex and difficult." (Cohen, Marc M., 2001-01-2142, Analysis of Designs of Space Laboratories, NASA Tech Briefs)

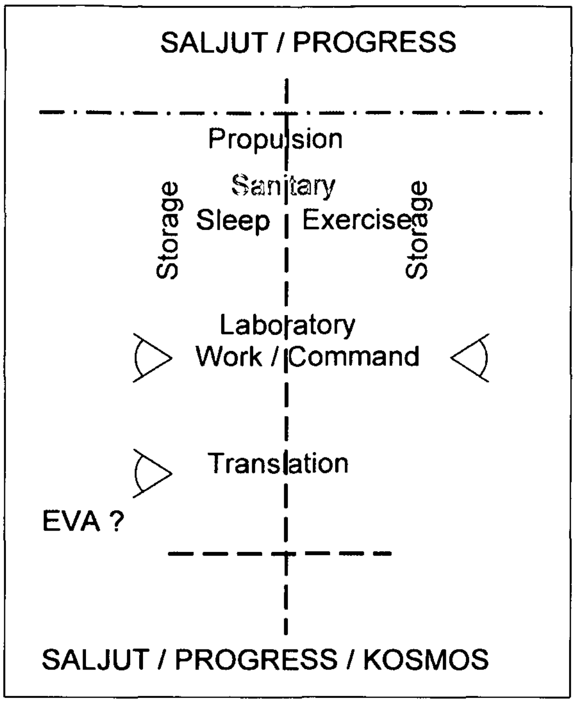


Fig. 2.1.2.1 - 5: Schematic structure of Saljut 7

The **Transfer** module serves as a docking adapter and EVA port at the same time. The manned spaceships and unmanned cargo ships dock here. On the side of the 3m long cylindrical module is an opening for EVA, as well as the EVA suits and little openings for earth observation and astronomical experiments.

The **Work** module has a length of 3.5 m with a diameter of 2.9 m. It is hermetically sealed off from the docking adapter. The command centre with two permanent installed seats is situated in this module.

The **Experiment** module is next to the work module and has a length of 5.5 m with a diameter of 4.15 m. The conical part is 1.2 m long. All scientific and medical experiments are carried out here. Moreover, the sleeping compartments, kitchen, toilet and shower are located in this module.

Stowage
Along the walls of the work and experiment module there are standardized instruments and stowage areas. Since Salyut 6 a second docking adapter was added to the intermediate compartment with a little opening for EVAs.

In this minimal habitat the private and personal zones are not spatially set off from each other, and the community and recreation zone is missing altogether, although there were quite a number of windows. The exact number could not be found out.

Exercise
"The Russians used a combination of a treadmill and gravity suits on early Salyut flights, adding a bicycle ergometer on later flights. The cosmonauts followed a compulsory program of daily exercise, for instance, 2.5 hr/day on Salyut 4." (1)

Average Timetable for the Cosmonauts (2):

Sleep + Body hygiene	9h
Eating	2h
Exercise	2h
Contact to Mission Control	1h
Leisure	2h
Work + Experiments	8h

(Salyut 4 & 5: 6 d work, 1d rest / Salyut 6 & 7: 5 d work, 2 d rest >same on MIR)

Fig. 2.1.2.1 - 6: View from command centre to the airlock module, courtesy of NASA

Fig. 2.1.2.1 - 7: In the transfer module of Salyut 6, courtesy of NASA

2.1.2.2 Skylab (1973 - 1974)

The next important space station especially concerning design criteria was the American Skylab Station.

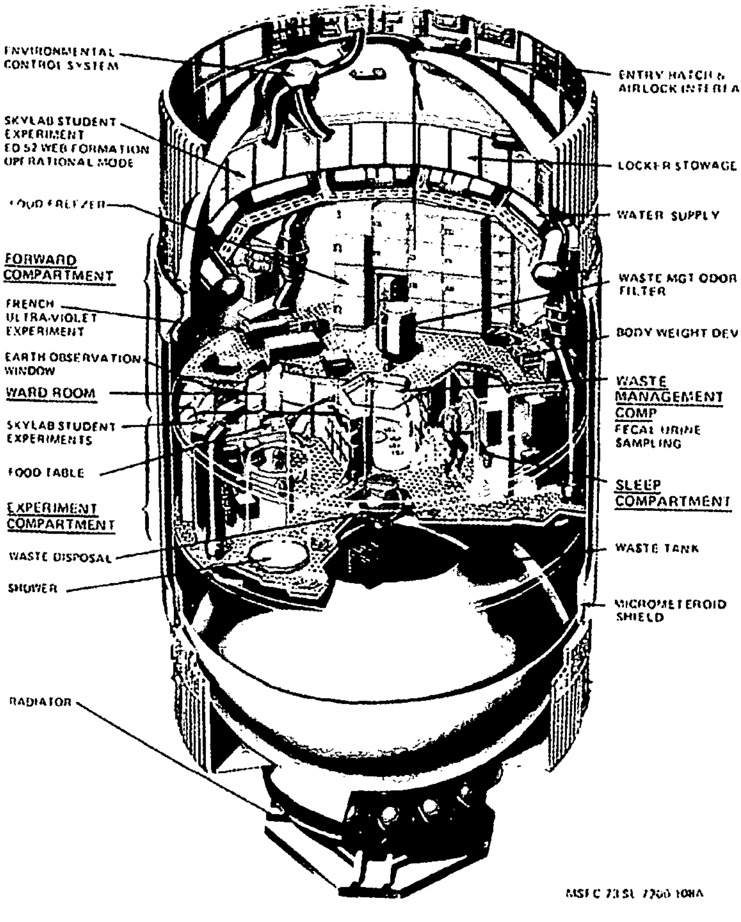


Fig. 2.1.2.2 - 1: Cut-away view of Skylab Orbital Workshop, courtesy of NASA

The following figures give an overview:

Volume:	275 m³
Mass:	85 t/ 25,4 t
Diameter:	6.6 m
Length:	14.7 m
Crewmembers:	3
Flights:	3
Duration:	28, 56 and 84 days

Skylab essentially consisted of a converted third Saturn V-rocket stage. The converted rocket tank formed the backbone of the station - the Workshop.

Habitability
Selection of issues:

"Astronauts on Skylab were enthusiastic about the possibilities of tumbling and acrobatics in space, and suggested that all future space stations include a facility for acrobatics." (3)

The Orbital Workshop was partitioned by a grid plane into a living and a work area.
"Below" the living area there was a stowage compartment for firm and liquid waste.

The space station had 13 "talking stations" allowing the crewmembers to communicate with each other and with mission control.
"Without this communication system it would have been difficult to communicate, because the station was so large and because low air pressure hampered acoustic transmission within the station." (72% N, 28% O, 0.3 bar) (4)

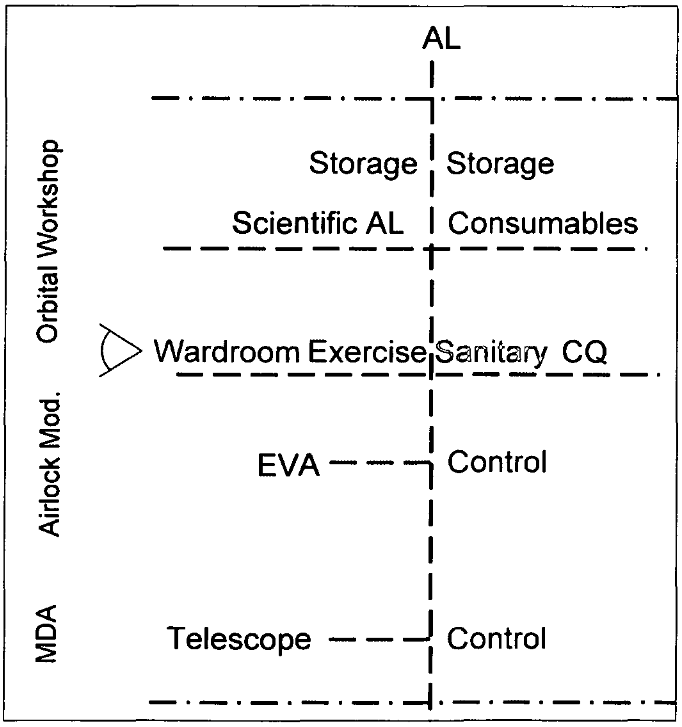


Fig. 2.1.2.2 - 2: Diagram of Interior Configuration

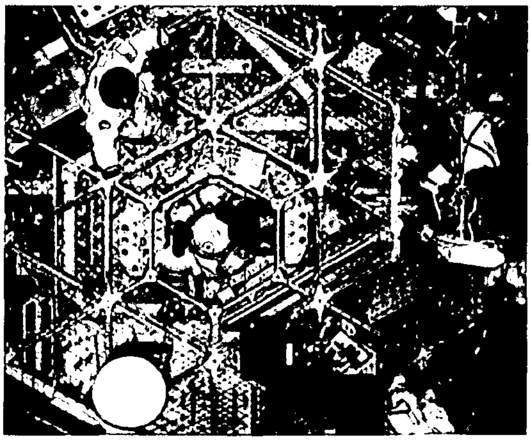


Fig.2.1.2.2-3:Triangulargridfloorsystem,courtesyofNASA

Orbital Workshop - 1st Floor

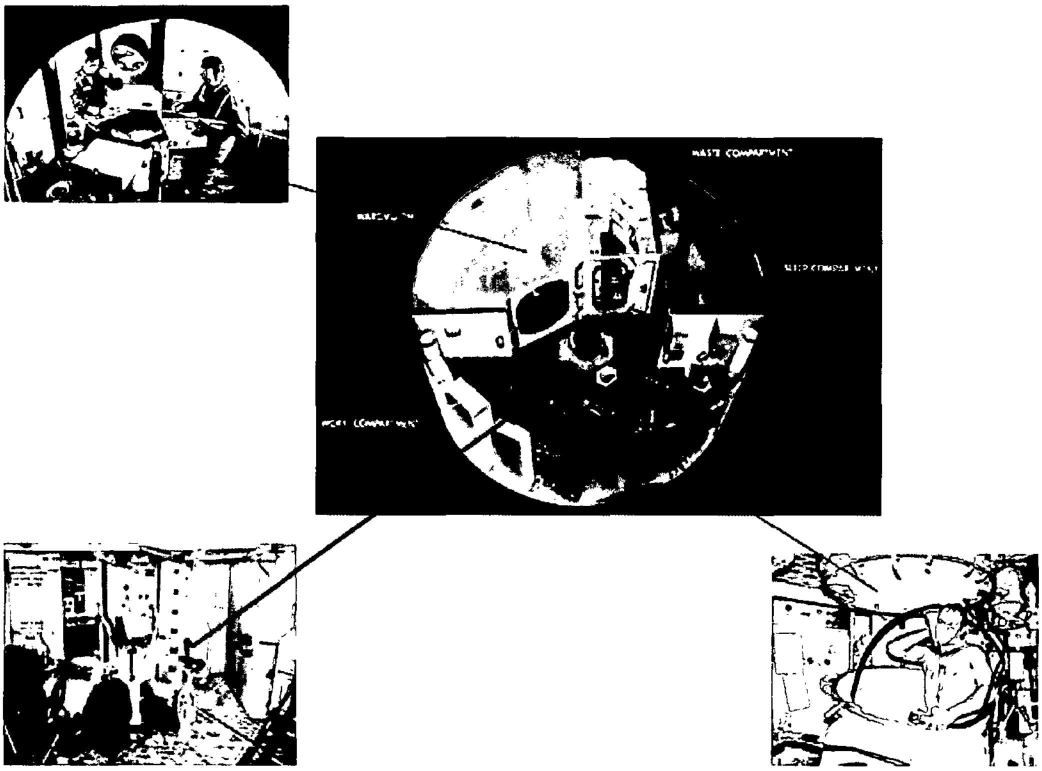


Fig. 2.1.2.2 - 4: Diagram of Orbital Workshop – 1st Floor, courtesy of NASA

List of Functions
In the primary Living and Working Area the following hardware and functions were arranged:

- Wardroom
- Earth observation window
- Table for whole crew

- Waste compartment
- Sleep compartment
- Work compartment
- Hygiene and exercise equipment
- Toilet
- Shower
- Ergometer
- Body mass device

The living area comprised hygienic systems as well as sleeping, eating and resting facilities for the crew.

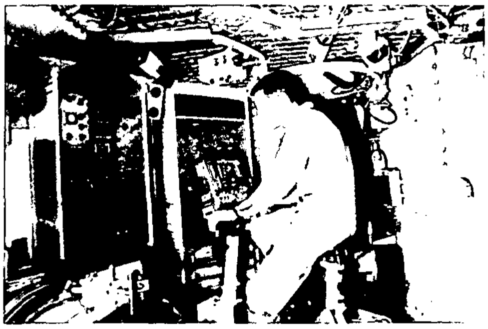


Fig. 2.1.2.2 - 5: Typically, astronauts used the treadmill 10 min/day, courtesy of NASA

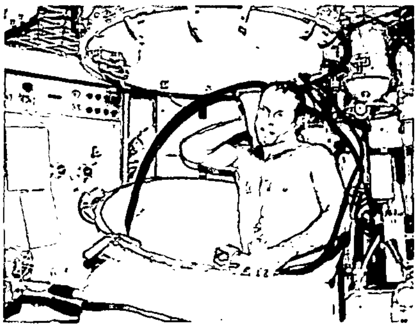


Fig. 2.1.2.2 - 6: Shower on Skylab, courtesy of NASA

Hygienic Facility

Following the example of Apollo, considerable attention was given to a new design of the hygiene facility. Although vastly improved over earlier systems, bathing and waste management facilities on Skylab still did not allow the kind of ease and comfort that long duration space travelers would require.

"The **Wardroom** had a table to accommodate all crewmembers with a window for Earth observation. During the missions the crew spent much of their free time watching Earth." (5)
The Skylab flights were the first to demonstrate that food could be eaten from open dishes; Skylab also provided the first opportunity for astronauts to "share a meal". However, even here, astronauts did not always eat together, since it was difficult to access the pantry area when all three astronauts occupied the dining area simultaneously.

On long duration missions, a common space for sharing meals is bound to be essential for crew health and productivity. The value of this "table-gathering-space" was also reported by Fred Smith, a simulation astronaut, who participated in a 90-day isolation test in the Bioplex project in 1997. (6)

Apparently passing over an eating area in Skylab was perceived as inappropriate behavior and the astronauts chose rather to squeeze past each other or to take turns in the eating area. (7)

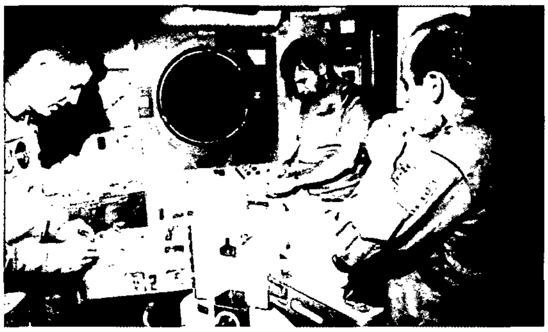


Fig. 2.1.2.2 - 7: Astronauts around the table, courtesy of NASA

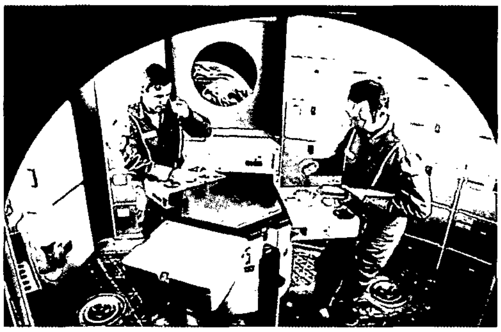
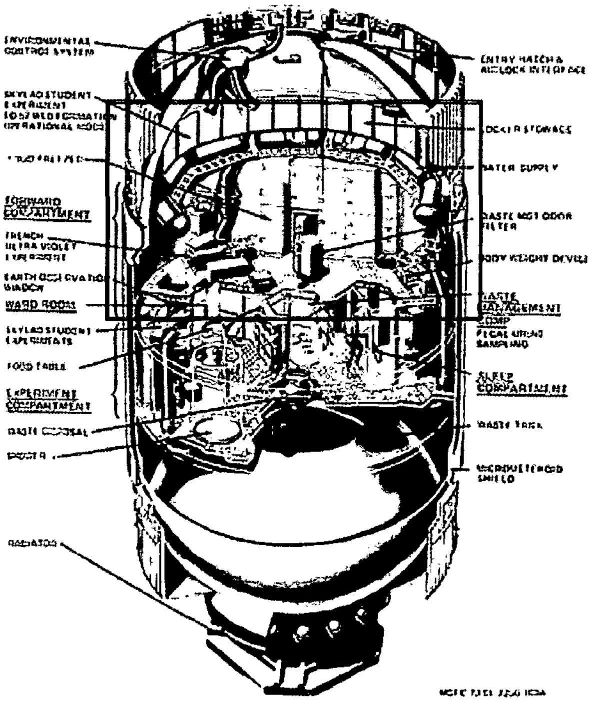


Fig. 2.1.2.2 - 8: Mock-up of wardroom, courtesy of NASA

Crew Quarters

For each crewmember a private compartment was provided. Skylab Orbital Workshop Crew Quarters had fixed stowage lockers and sleep restraints, with unsatisfactory habitability ratings. Skylab crews suggested that individual sleeping areas be separated further. Skylab astronauts reported that the sameness of colors within their vehicle was disturbing. This suggests a rich color palette for long duration missions.

Orbital Workshop - 2nd Floor



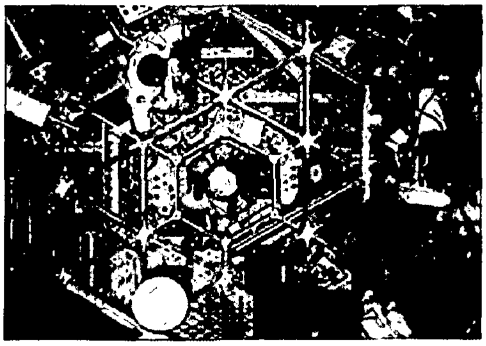


Fig. 2.1.2.2 - 9: Diagram Orbital Workshop – 2nd Floor, courtesy of NASA

List of Functions

Experiment / Laboratory / Stowage

- Food Freezers
- Scientific Airlock
- Stowage
- Food
- Water
- Containers

The „upper“ work area consisted of water tanks, refrigerators, storage containers for films as well as scientific experimentation equipment. Two solar panels and nozzles for small control maneuvers were attached to the outside of the workshops.

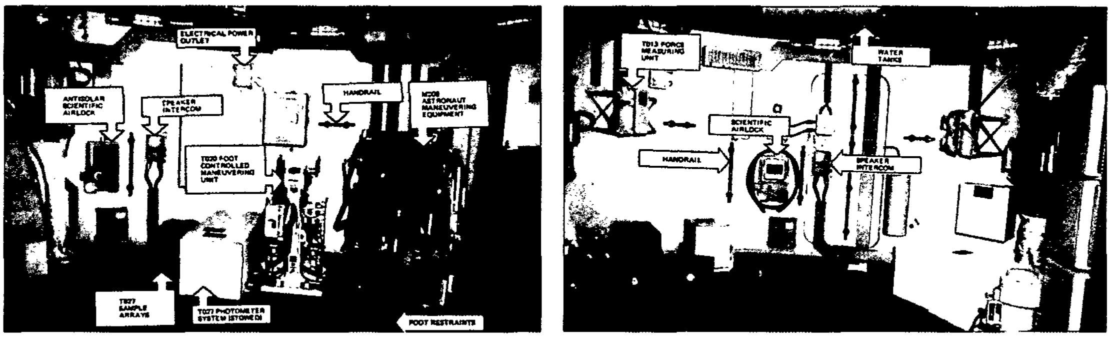


Fig. 2.1.2.2 - 10: Skylab interior views, courtesy of NASA

Orientation

Astronauts of Skylab preferred areas with a local vertical, i.e., a defined „floor“ and „ceiling.“ Astronauts felt least comfortable in the large upper deck of Skylab where orientation was difficult due to the large size and lack of architectural orientation cues. (Connors Mary M., Living Aloft, Human Requirements for Extended Spaceflight, NASA Ames Research Center, 1985)

Therefore it is assumed that in future spaceships different kind of layouts (Skylab, ISS) can be used if there are enough specific cues to support the inhabitant when navigating through the space, similarly to walking through a European city where the changing rhythm and structure of spaces, buildings, and squares aids visual and spatial orientation. Russian cosmonauts reported that they had no problem changing orientation when floating through different modules on MIR. Apparently they had enough cues to find their way through the station easily.

Airlock

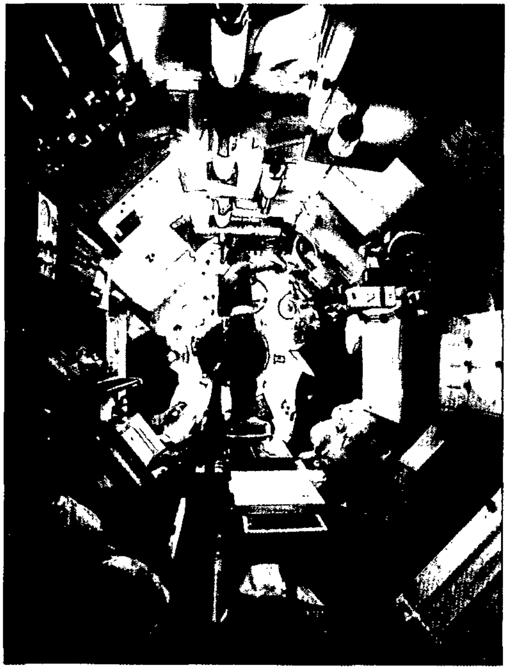


Fig. 2.1.2.2 - 11: inside the airlock of Skylab / mockup, courtesy of NASA

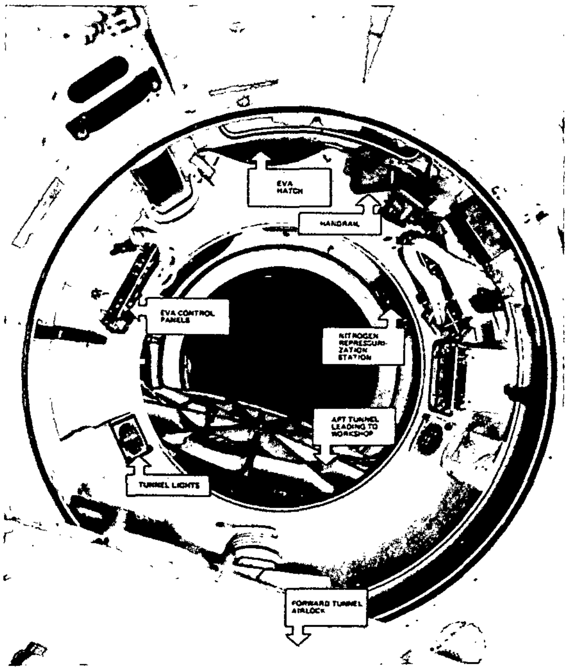


Fig. 2.1.2.2 - 12: a view of the airlock / graphic with descriptions of single hardware parts, courtesy of NASA

Airlock

Length: 5.1 m
Diameter: 3.1 m, tunnel only 1.8 m
Volume: 17.7 m^3
Mass: 19.1 t

- Power control & distribution
- Environmental systems control
- Utility Centre
- Data System
- EVA Port

The Airlock was situated directly next to the Workshop. It was used by the Skylab crews for EVAs and accommodated the central life support and communication system.

Docking Module
The adjacent Docking Module served as a connection to the Apollo capsules. It accommodated two docking ports, of which one was intended for emergencies. Here were also the controlling devices for Sun and Earth observation (ATM) as well as for material experiments.

The sun observatory of Skylab was installed at the docking module, which was equipped with four solar panels for power supply. The photographs taken from of the observatory were saved on diskettes, which were exchanged regularly by Skylab crews during EVA.

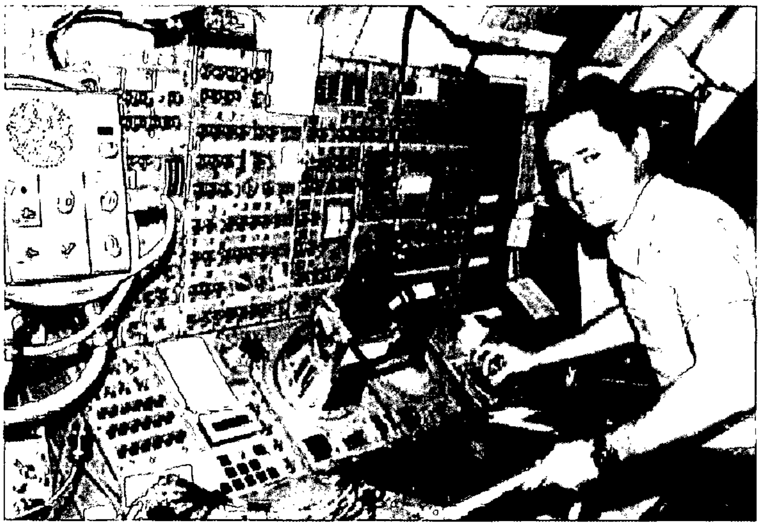


Fig. 2.1.2.2 - 13: Skylab 4 Astronaut in the Multiple Docking Adapter at the Telescope Mound control, courtesy of NASA

2.1.2.3 MIR Space Station (1986 - 2001) - Core Module

With the launch of the core module in 1986 the Soviet Union had two space stations in orbit, Mir and Salyut 7. MIR was the first modular space station.

Volume: 170 m^3 / MIR total 400 m^3
Mass: 20.9t / MIR total 140 t
Diameter: 4.15 m
Length: 13.13 m
Crewmembers: 3 - 6
Flights / Duration: Avdeyev, 3 missions, 748 d
Polyakov , 2 missions, 678 d
(longest manned spaceflight: 438 d)
Solovyov, 5 missions 651 d
7 US astronauts spent more than 940 d in MIR
Longest woman flight duration: 188 d

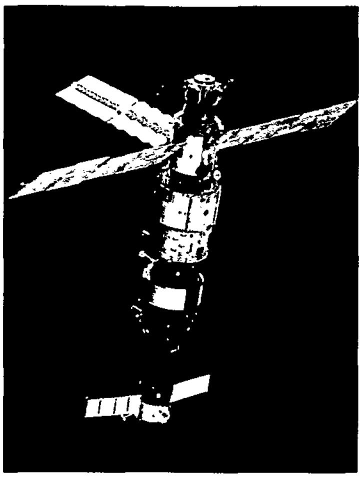


Fig. 2.1.2.3 - 1: Early configuration of the MIR station, courtesy of NASA

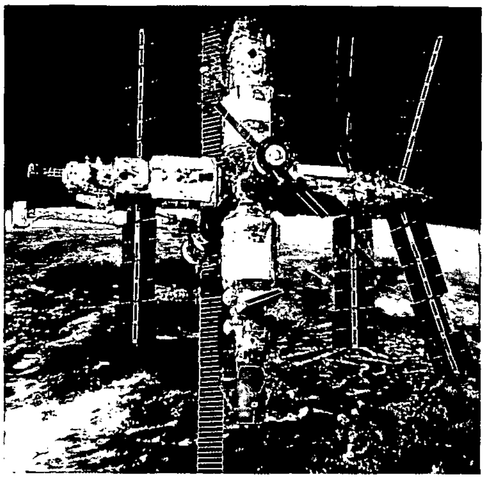
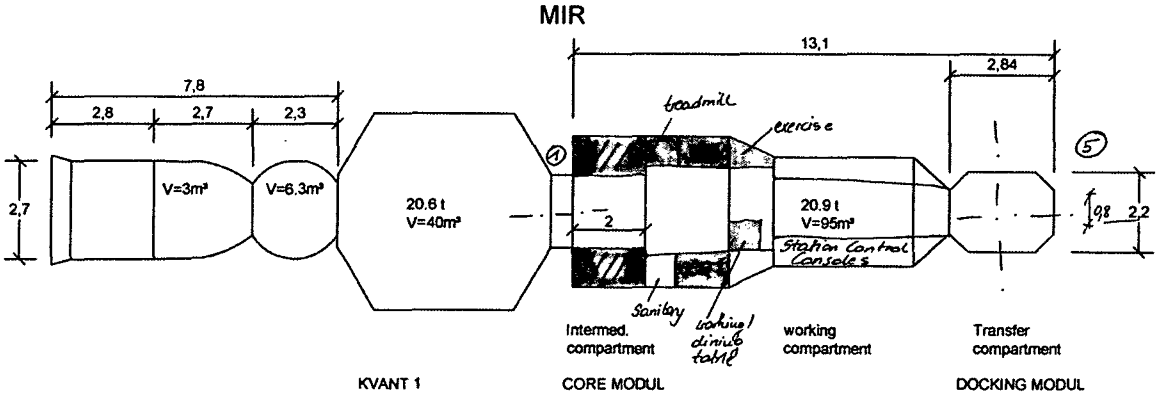


Fig. 2.1.2.3 - 2: Final configuration of the MIR station, courtesy of NASA

The Space Station MIR stayed in orbit for 15 years and was permanently occupied for 10 years (- in total: 29 occupancies, three visiting crews and 9 US shuttle missions). Guest cosmonauts of 11 nationalities visited the station. This entitles MIR to be called the first International Space Station.

Configuration

The Core module was launched in 1986. At the long sides and ends additional modules such as supply ships or Kvant / scientific module could dock. Kvant 1 was launched in 1987, Kvant 2 in 1989, Kristall in 1990, Spektrum in 1995 and Piroda in 1996. There were six docking units, five of them located on the transfer compartment and one at the rear. The diameter of all docking hatches is 0.8 m.



13 windows for earth observation

Fig. 2.1.2.3 - 3: Section through MIR

Infrastructure was basically similar to the Salyut program, but due to the station's size the zones for privacy, personal and social activities were given more space and were more differentiated than in previous Soviet space stations.

- Functions were split and optimized in different modules
- (> Skylab approach)
- Different architecture for Habitability and Laboratory functions

The Mir base block was divided into four parts:

- Transfer compartment
- Working compartment
- Intermediate compartment
- Engine compartment

In the Transfer compartment there were five further docking ports for supply ships and further modules.

The working / living compartment comprised the command station and central computer, a body training device, as well as the living and eating space.

A total of 13 portholes for Earth observation were installed. The rear engine area of the Mir basis block housed the drive system as well as the rendezvous and radio antennas.

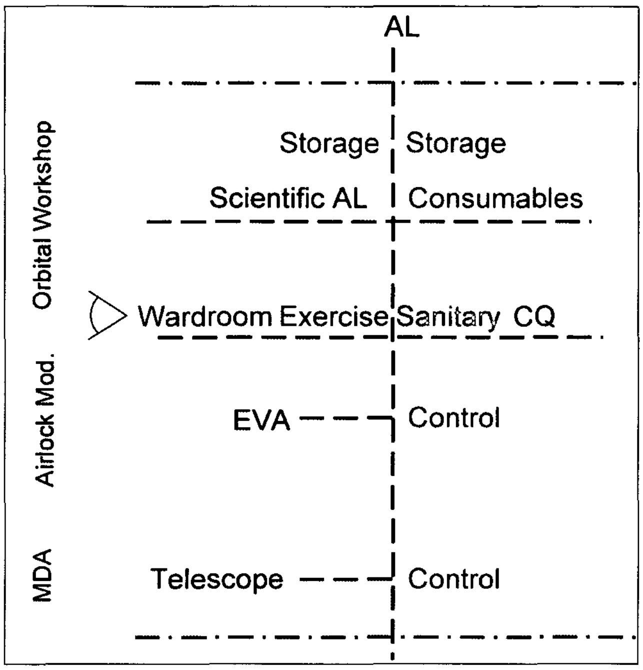


Fig. 2.1.2.3 - 4: Diagram of Interior Configuration

Stowage

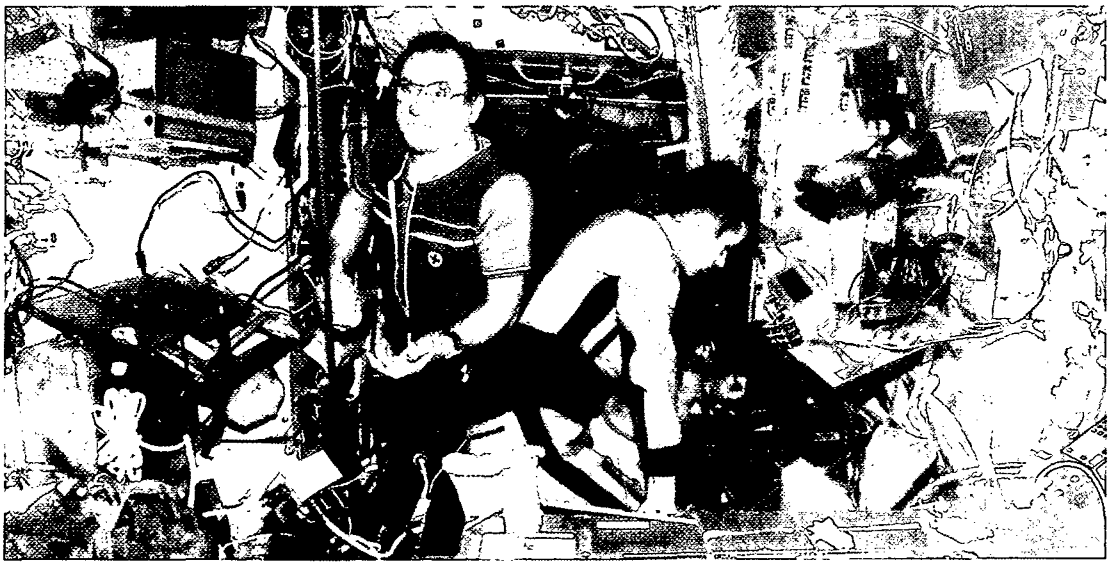


Fig. 2.1.2.3 - 5: Stowage problems on MIR, courtesy of NASA

Fig. 2.1.2.3 - 6: inside MIR, courtesy of NASA

The "bolt it down anywhere" configuration was used, i.e. the system of equipment accommodation was highly subjective. It was very difficult to track and inventory the pieces, especially for a new crew. (8)

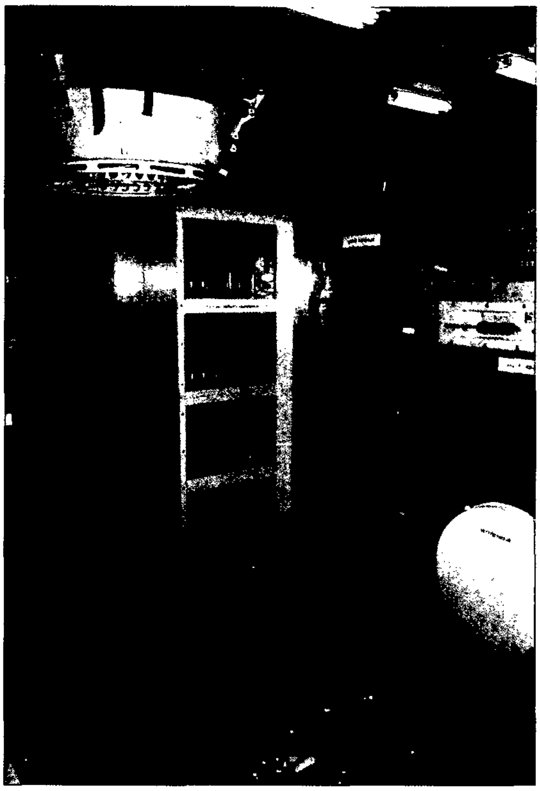


Fig. 2.1.2.3 - 7: Mock-up of working/living area, courtesy of NASA

Fig. 2.1.2.3 - 8: Mock-up of MIR crew quarter, courtesy of NASA

The MIR crew quarters provided a place to sleep, work, and had private communication.

2.1.2.4 ISS (since 1998)

The current configuration of the ISS will be investigated within its limits because major modules such as the US - Hab, the Japanese module, the European Columbus module and the relevant nodes valuable for an investigation into habitability aspects are missing.

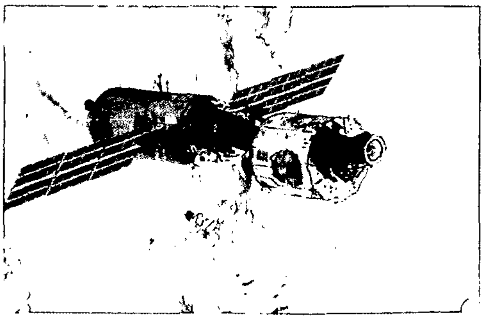


Fig. 2.1.2.4 - 1: Early configuration of the ISS, courtesy of NASA

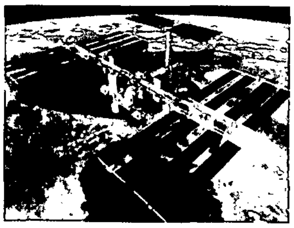


Fig. 2.1.2.4 - 2: Final configuration of the ISS, courtesy of NASA

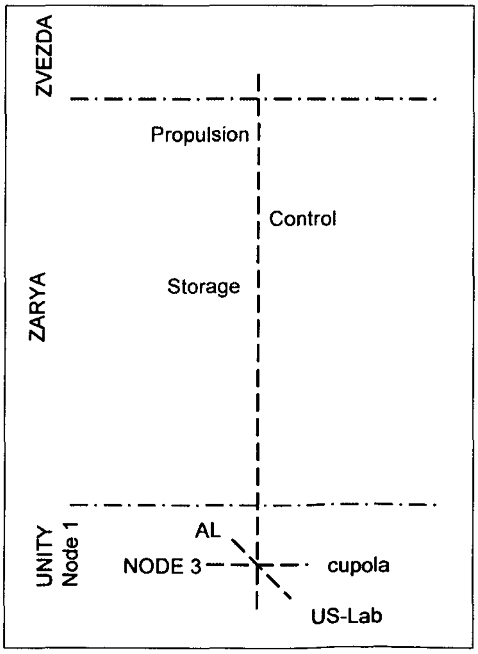


Fig. 2.1.2.4 - 3: Diagram of first configuration

Stowage Rack System

Due to the changeability of the racks according to the different experiments to be coordinated on an international level, it seemed appropriate for NASA to base the interior configuration concept of uniform tall modules on a simple rack system. All Modules were the same, regardless of which function they were to house. The inner structure features rack-based accommodation of stowage and is divided into

- racks (for equipment, stowage, laboratory, crew quarters)
- stand offs (for infrastructure elements)
- habitable space

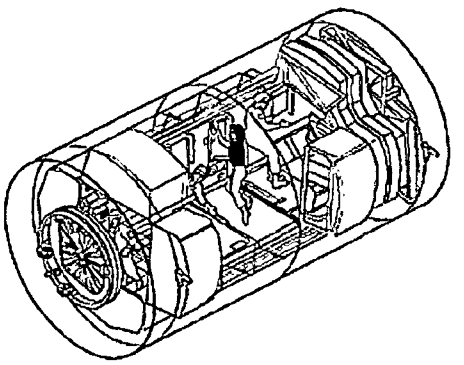


Fig. 2.1.2.4 - 4: 4-Standoff-system in US Destiny Lab Module, courtesy of NASA

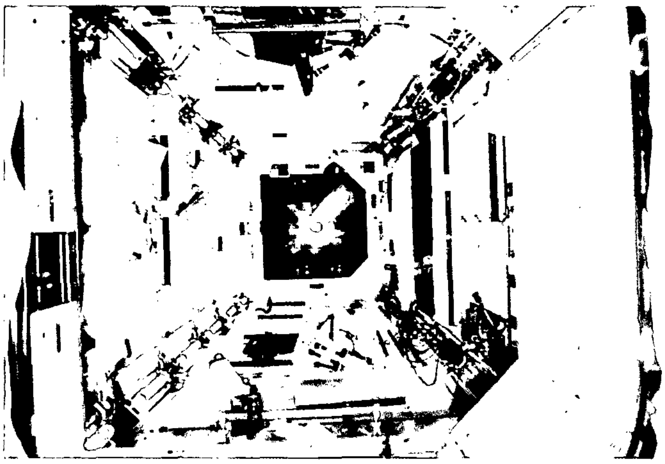


Fig. 2.1.2.4 - 5: Interior Configuration in the ISS Columbus Module, courtesy of NASA

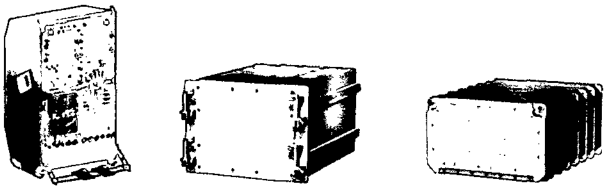


Fig. 2.1.2.4 - 6: Standard ISS rack, drawer and locker, courtesy of NASA

Fig. 2.1.2.4 - 7:
Zarya - Passageway,
courtesy of NASA

Disadvantages of the ISS-type HAB include: (Adams, Constance, Design Concepts for the ISS Trans Hab Module, NASA Tech Briefs, MSC-23090)

- Inability to separate functions by activity
- Need to stow/deploy activity-related equipment for rack translation
- Insufficient height for the crewmembers above the 89th percentile in racks
- Difficulty of meeting acoustic requirements
- Co-location of exercise with wardroom, hygiene and sleep stations
- Impossible to locate group activities outside of the main translation

Zarya 1988

Volume:	60 m^3
Mass:	19.3 t
Diameter:	~ 3 m
Length:	12.63 m

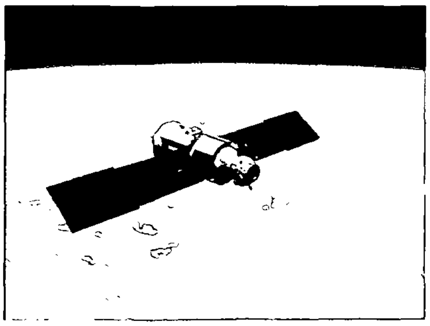


Fig. 2.1.2.4 - 8: Zarya - first module of the ISS, courtesy of NASA

- Initial propulsion
- Power, steering
- Communication

Used as:
- Passageway
- Stowage facility
- Docking port
- Fuel tank

"Zarya" is equipped with a spherical coupling adapter featuring three coupling connecting pieces at the front end. The connecting piece at the front end connects to Node 1, "Unity". The zenith and nadir connecting piece have the Russian coupling mechanisms according to standard for spaceships of the type Soyuz and Progress. The coupling connecting piece at the rear end connects with the Russian service of modules „Zvezda".

It has a mass of 19.3 tons, is 12.5 meters long and has a maximum diameter of 4.1 meters. Each of the two solar cell wings measures a length of 10.6 meters and is 3.3 meters wide. The solar cell wings align themselves independently to the sun, whereas „Zarya" maintains its stable position, while it circles the earth.

Although its life span is 15 years, it was replaced in its function during the development of the station. During the early assembly phase, assembling it played a key role. „Zarya" provided for position control, communication and power supply of „Unity" before the start of „Zvezda". Afterwards „Zarya" was shut down and many of its functions were taken over to a large extent by „Zvezda".

Unity 1989

Volume: 116.4 m^3
Mass: 19.3 t
Diameter: ~ 4.2 m
Length: 8.4 m

Used as:
Connection module - Node 1
- berthing ports

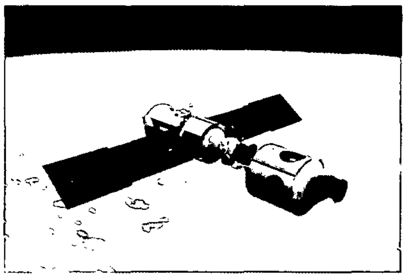


Fig. 2.1.2.4 - 9: Unity and Zarya, courtesy of NASA

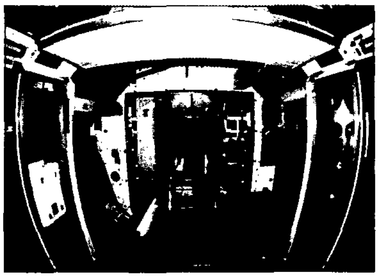


Fig. 2.1.2.4 - 10: Inside Unity, courtesy of NASA

Zvezda

Volume: 82 m^3
Mass: 22.25 t
Diameter: ~3m
Length: 12.63 m

Used as:
Service module
- Living area
- LS, navigation, propulsion
- Communication

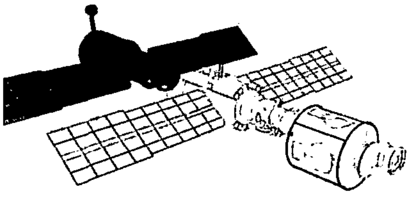


Fig. 2.1.2.4 - 11: Zarya, Unity and Zvezda

The space for crew quarters has been reduced to sleeping bags with little privacy.

2.2 Interior Configuration Issues in the Inflatable Crewed Space Module Transhab - an Advanced Habitat (Adams, Constance, Design Concepts for the ISS Trans Hab Module, NASA Tech Briefs, MSC-23090)

Volume:	~ 95 m^3 deflated 569 m^3 inflated
Mass:	
Diameter:	8.3 m
Length:	10.52 m
Crewmembers:	<12

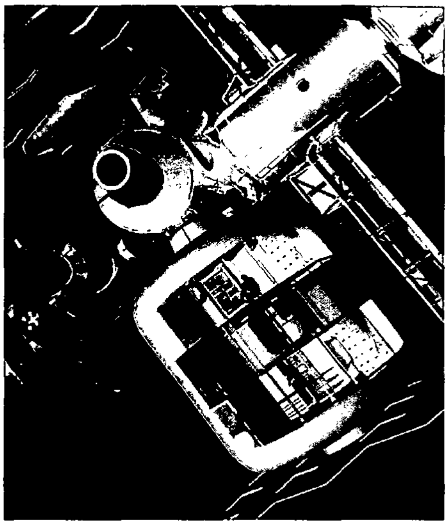


Fig. 2.2 - 1: Computer model, showing the Transhab installed on ISS, courtesy of NASA

TransHab is the first space inflatable module specifically designed for human habitation in a microgravity environment. It is vertically orientated with a three-level plan and single orientation.

2.2.1 Structural System

„Transhab uses a structural system that allows for reconfiguration by the crew, systems exchange and modifications. It separates individual volumes (or "rooms") for different types of activity on board. All outfitting was designed to a base module of 90 cm to permit flexibility in interior organization. Provisions for an appropriate acoustic environment include the separation of group activity centers from areas dedicated to private and personal activities, with acoustic separation from functional units by means of absorbent material panels.

All activity centers are situated outside the main path of translation and are appropriated to specific tasks. Stowage and redeployment of equipment is not necessary for its use. Stowage is accommodated in an array of fully visible, fully accessible standard stowage units on levels 1 and 3.

The overall layout is consistent with terrestrial architectural analogies and thus helps reduce SAS-related confusion while maintaining a high level of productivity." (9)

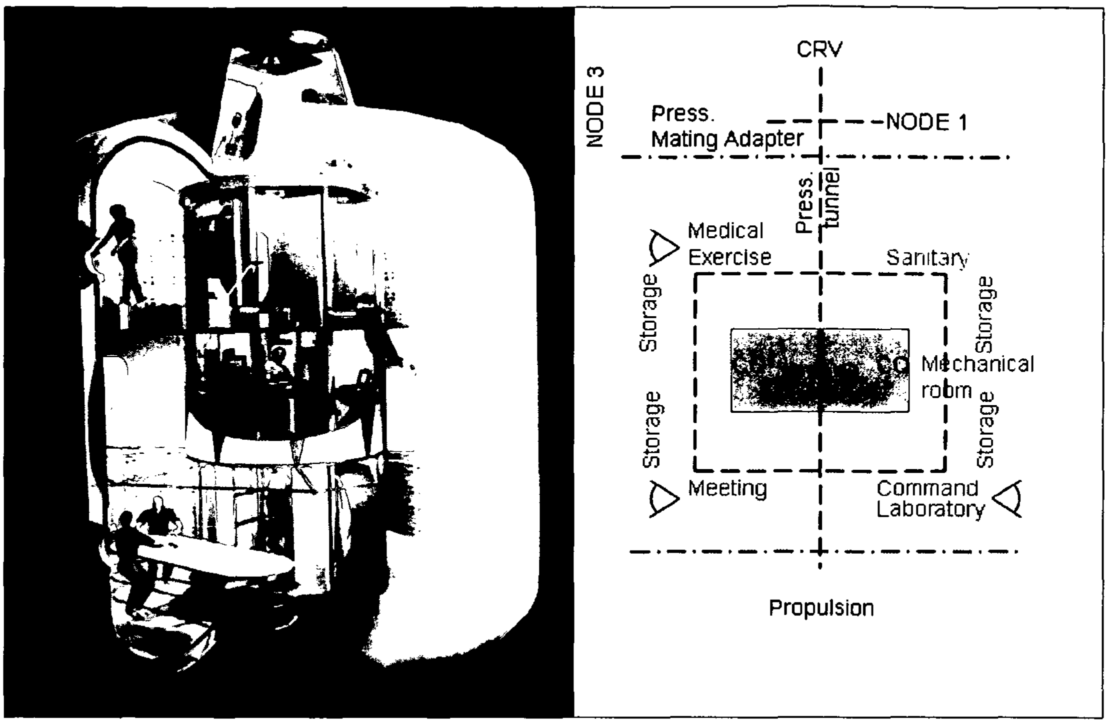


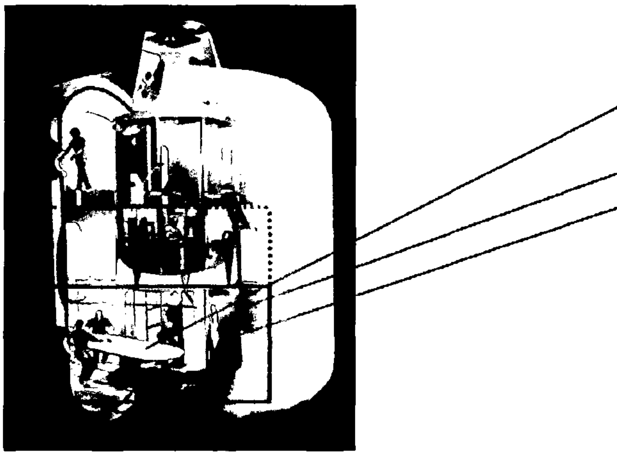
Fig. 2.2.1 - 1: Cut-away view of Transhab and Diagram of interior configuration, courtesy of NASA

2.2.2 Features

Transhab is launched in a minimized cylindrical package and is inflated and reconfigured on-orbit into a complex, three-level habitat, which supports a wide array of functions.
It is the first human rated vehicle to provide:

- Full-height crew quarters
- Radiation shielding on crew quarters, which can also serve as a safety area during solar-particle events
- Special areas for all private, personal and social/group activities
- Centralized area for critical machinery, separate from living/working quarters

2.2.3 Level One - Plan of Transhab



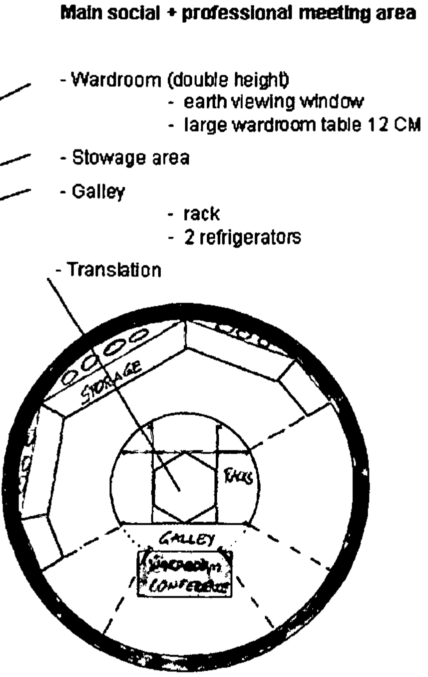


Fig. 2.2.3 - 1: Cut-away-view and plan of level one, courtesy of NASA

The **Wardroom** and Galley area is located on level one, designed to accommodate ISS galley hardware and seat up to 12 crewmembers (full ISS and Shuttle Crew) at a permanent table. It is situated in its own volume of double-story height and also has an Earth-viewing window. The table is used for conferencing and other team activities, thus supporting group cohesion.

2.2.4 Level Two - Plan of Transhab

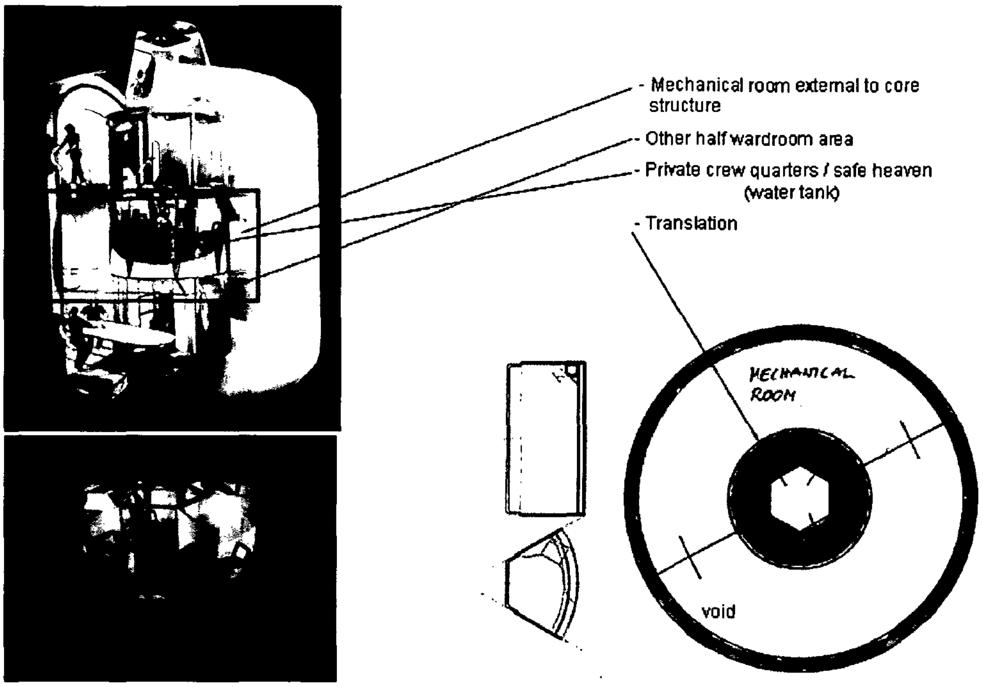


Fig. 2.2.4 - 1: Cut-away-view and plan of Level Two, courtesy of NASA

Mechanical Equipment is launched with the vehicle, mounted on shelves that are relocated to the second level in orbit and become "walls" within an enclosed, sound-insulated area of fully accessible dimensions. This ensures easy access to maintenance areas.

Crew Quarters
The crew's sleep and private quarters are located inside the core within a radiation shielding water tank, outside the main path of equipment translation, able to accommodate the 95th percentile male. (Adams, Constance, Design Concepts for the ISS Trans Hab Module, NASA Tech Briefs, MSC-23090)

2.2.5 Level Three - Plan of Transhab

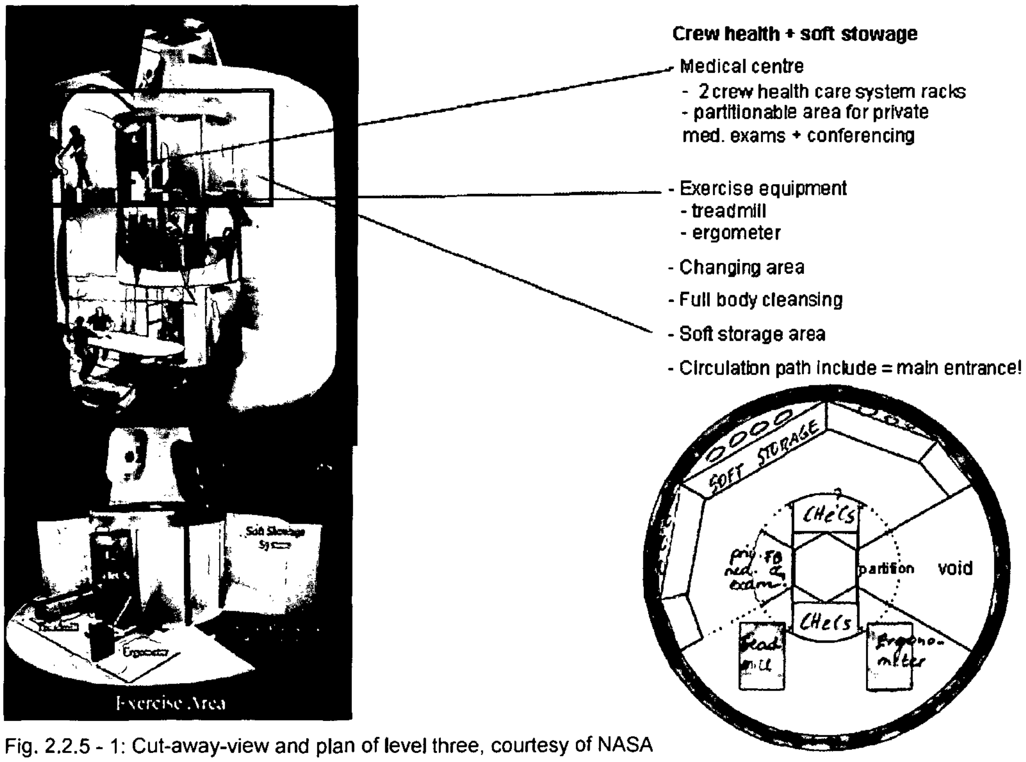


Fig. 2.2.5 - 1: Cut-away-view and plan of level three, courtesy of NASA

The **Exercise Compartment** is located in discrete and dedicated area adjacent to the personal hygiene station but acoustically and physically separated from other functions. Its height is sufficient to ensure comfortable use of the exercise equipment (two items), as well as and an Earth-Viewing window.

In this inflatable habitat, the materials protecting the crew from the space environment are important and partially inspired by the skin design for space suits, though a more rigid design needed to be developed.

2.2.6 Composition of Materials for Outer Skin

The **Beta Cloth Shield** was tested as a possible shielding design for the ISS Common Berthing Module (CBM) shield. It consists of multiple layers of beta cloth placed in front of a rear wall.

Beta cloth is widely used in multi-layer insulation which thermally protects spacecraft components. Beta cloth is also used because it offers protection against atomic oxygen degradation in space. For this reason, beta cloth is sometimes tested for its shielding characteristics as well.

Nextel is a woven ceramic fabric manufactured by 3M Corporation. It is one of the most widely used shielding materials. Its aluminum-boride-silica fibers shock incoming projectiles and turn them into small, less threatening, debris fragments. Nextel comes in many different styles and weights.

Kevlar is another popular spacecraft shielding material. Manufactured by Dupont Co., it is also widely used in bullet-proof vests. Many spacecraft shields use a combination of Nextel and Kevlar for protection against a whole range of incoming debris.

Fig. 2.2.6 - 1: Layers of Transhab, courtesy of NASA

Aluminum is a widely used aerospace material. It is also used as the rear wall and bumper material in many shielding solutions. Though it is heavy, in comparison to Nextel and Kevlar, it does offer some beneficial shielding characteristics

Aluminum Mesh is sometimes used on top of the front bumper of a shield. It helps initially shock and break up the incoming projectile just before striking the bumper plate.

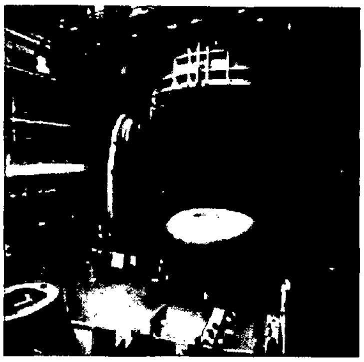


Fig. 2.2.6 - 2: Transhab prototype, © NASA

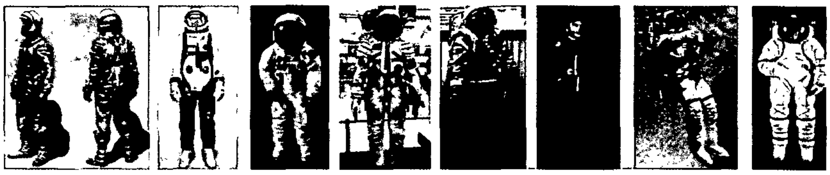


Fig. 2.3 - 1: Skins - Space Suit Evolution, courtesy of NASA

2.3 References - Part 2

(1) Connors M.; Living Aloft, Human Requirements for Extended Spaceflight, NASA Ames Research Center, 1985, http://history.nasa.gov/SP-483/contents.htm

(2) Engelhardt, W.; Enzyklopädie Raumfahrt, Verlag Hari Deutsch, Frankfurt, 2001

(3) Connors M.; Living Aloft, Human Requirements for Extended Spaceflight, NASA Ames Research Center, 1985, http://history.nasa.gov/SP-483/contents.htm

(4) Engelhardt, W.; Enzyklopädie Raumfahrt, Verlag Hari Deutsch, Frankfurt, 2001

(5) Connors M.; Living Aloft, Human Requirements for Extended Spaceflight, NASA Ames Research Center, 1985, http://history.nasa.gov/SP-483/contents.htm

(6) Imhof, Barbara; In the Simulator (Architecture, Technology and Innovation), Interview with Fred Smith, Simulation Astronaut, NASA, 26.08. 2003, Radio Orange

(7) Connors M.; Living Aloft, Human Requirements for Extended Spaceflight, NASA Ames Research Center, 1985, http://history.nasa.gov/SP-483/contents.htm

(8) Cohen, M.; 2001-01-2142, Analysis of Designs of Space Laboratories, NASA Tech Briefs

(9) Adams, C.; Design Concepts for the ISS Trans Hab Module, NASA Tech Briefs, MSC-23090

2.3.1 Additional general References on Inflatable and Deployable Technologies

- Fraser, A.L., B.M. Pitts, P.B. Schmitt, J.A. Hoffman, and D.J. Newman, (2002), "Astronaut Performance: Implications for Future Spacesuit Design", International Astronautical Congress IAC-02-G-5.3.
- Kennedy, K. J.; AIAA 2002-6105, Lessons from TransHab, An Architect's Experience, NASA Johnson Space Center
- Lupton, E. J. T.;Imperiale A.; Jeffers G.; Mates R.; Skin: Surface, Substance, and Design, Princeton Architectural Press, New York, p 29., 2002
- Mohanty, S.; Fairburn, S.; Skins by Design: Humans to Habitats, SAE 2003-01-2655
- Portree, D. S.F.; Trevino R. C.; Walking to Olympus: An EVA Chronology, Monographs in Aerospace History Series 7, NASA History Office, Washington, D.C., 1997
- SICSA; Inflatable Space Structures. SICSA Outreach, Vol. 1, No. 7., 1988
- Toussaint, M.; Russian Manned Space Program & Russian Space Stations Evolution, From Salyut 1 to MIR, ESA-HQ, Paris
- Vogler, A.; Modular Inflatable Space Habitats, First European Workshop on Inflatable Space Structures, ESA/ESTEC, 2002

2.3.2 Airbags

- http://www.firehouse.com/extrication/archives/2001/october01.html
- http://www.space.com/scienceastronomy/solarsystem/mars_airbags_000707.html
- http://www.kfztech.de/kfztechnik/sicherheit/airbag/airbag.htm
- Architecture-structures
- http://www.airairarchives.com/search2/index.php
- http://www.calatrava.com/
- http://www.arch.columbia.edu/DDL/cad/A4534/Alias/F98/assignments/assign2temp/
- http://www.fibersource.com/Textile_Arch/Winners.htm#index
- Siegal, Jennifer (2002). Mobile: The Art of Portable Architecture, Princeton Architectural Press, New York
- Oosterhuis, K, O. Bouman, I. Lénárd (2002),"Programmable Architecture", L'Arcaedizioni, pp. 20-21.
- air-texture
- http://www.festo.com/INetDomino/coorp_sites/de/d948c8ea6f89ec2ac1256b3b004f8f18.htm
- pneumatic balloon
- http://www.festo.com/INetDomino/coorp_sites/de/54e4e4d1b7d37649c1256db1004d4b10.htm
- deployable structures
- http://www.deployables.net/ddf/academic/deployable.html
- http://www2.eng.cam.ac.uk/~sdg/dstruct/
- movies
- http://www-g.eng.cam.ac.uk/125/media/video/sp_pantographic_reflector.mpg
- http://www-g.eng.cam.ac.uk/125/media/video/sp_tube_inflation.mpg

2.3.3 Inflatable Space Structures

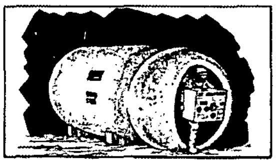


Fig. 2.3.3 - 1:
Inflatable Lunar Shelter, 1965

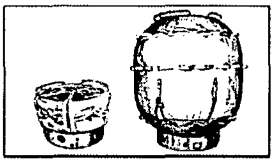


Fig. 2.3.3 - 2:
Skylab Airlock, Inflatable, 1967

- inflatable space & planetary habitats

http://www.sicsa.uh.edu/Documents/publication/pdf_files/past/inflatable_space_structures.pdf
http://www.ilcdover.com/SpaceInf/habitats.htm)

- deployable lunar habitat

http://www.ilcdover.com/SpaceInf/Habitats/lunar.htm

- marstranshab

http://www.ilcdover.com/SpaceInf/Habitats/transhab.htm

- Lawrence Livermore .

http://www.ilcdover.com/SpaceInf/Habitats/livermore.htm

- Sasakawa International Center for Space Architecture (SICSA), "Inflatable Space Structures", May-June 1998, SICSA Outreach Publication, Vol. 1, No. 7, p. 2.
- ESA, Technical Dossier, Inflatable Technology, 2003
- ILC Dover Inc., IAA-98-IAA.13.2.04, Inflatable Composite Habitat Structures for Lunar and Mars Exploration

- Inflatable rovers (solar array)

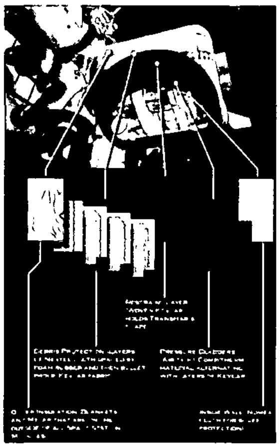
http://www.jpl.nasa.gov/adv_tech/rovers/summary.htm
http://www2.jpl.nasa.gov/adv_tech//rovers/tmblweed.htm

- Solar sails

http://www.planetary.org/solarsail/animation.html

- http://www.kp.dlr.de/SolarSail/
- Airlocks: http://www.nasatech.com/Briefs/July01/MSC23076.html

2.3.4 Materials



- Transhab

http://www.metropolismag.com/html/content_0799/jy99pspa.htm
http://www.frassanito.com/Station.html
http://hitf.jsc.nasa/hitfpub/shieldev/index.html
Transhab, Kamenetzky, R. R.; Finckenor, M. M. (1999). Comparison of Observed Beta Cloth Interactions With Simulated and Actual Space Environment (NASA TM-1999-209575). NASA Marshall Space Flight Center. Downloaded from http://trs.nis.nasa.gov/ archive/00000496/01/tm209575.pdf

- Industries

http://www.dupont.com/kevlar/whatiskevlar.htm
aerospacescholars.jsc.nasa.gov/HAS/Cirr/EM/glossary.htm
http://www.lgarde.com
The world leader in inflatable space structures
Lots of technical papers for download
http://www.ilcdover.com
Technical papers
http://www.ilcdover.com/SpaceInf/technicalpapers.htm
http://www.festo.com

- Aero gel: www.aerogel.com
- Memory metals: http://www.memory-metalle.de
- Spektrum der Wissenschaft Digest Moderne Werkstoffe Spektrum der Wissenschaft Vangerowstr Heidelberg ISSN 0945-9537

2.4 Other internet References

- Hard Suits – NASA AX Series: http://www.astronautix.com/craft/axseries.htm
- Hybrid Suits: NASA Mark III: http://www.astronautix.com/craft/nasrkiii.htm
- Transhab : http://trs.nis.nasa.gov/archive/00000496/01/tm209575.pdf

3 The Development of the Transfer Habitat Module (THM)

The development of the THM is basically a long process that produced many different design options and focused on the issues deriving from these different options. Safety, for example, was prioritized and therefore discussed separately. Basic topics, requirements and volumetric figures are provided first so as to set the pre-conditions for the further development of the design study.

3.1 Habitable Volume per Function for a Zero-G Spacecraft

In the following all the important functions of a zero-g spacecraft are listed and described.

The requirements and design drivers consist of several parts, which include the relevant numbers and factors of recognized standards (mass and volume calculations and recommendations) and some very specific research conducted by the author for the design development of the THM, including an analysis of habitability and overall configuration issues of built space stations and modules.

The requirements are based on volumetric and mass standards established by NASA, ESA and RSA over the years of their experience. This forms the basis for architecture and interior configuration in the HMM study. (For further details on the overall mission scenario - see the general AURORA HMM study report.)

When designing a human mission basic required volumes have to be integrated to fulfill one of the many human factor requirements. Based on the Man System Integration Standards, the NASA Standards 3000 (STD) and the paper „Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One Habitability" by Constance Adams, the following minimal functional and volume requirements for a transfer habitat module to Mars were defined.

In accordance with Constance Adams' analysis, three different zones are important in terms of habitability in a spaceship or space station:

- The private zone (crew quarters, personal stowage - this place should stay calm and quiet and away from noisy equipment shifts.) - red in the sketch below
- The personal zone (command, the laboratory, medical and hygiene facilities or typically the exercise facilities where the crew trains/works mostly on their own) - blue in the sketch below
- The social or communal zone (galley, recreation, gathering, dining, communications together) - yellow in the sketch below

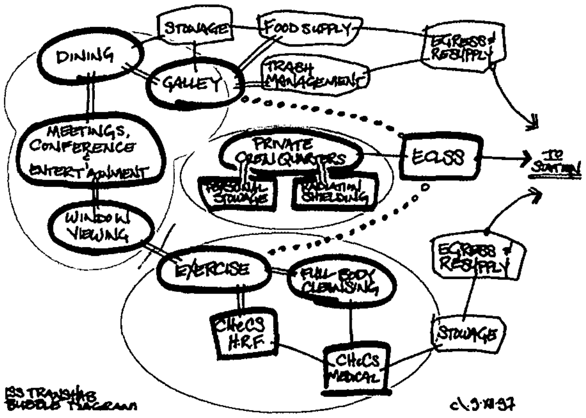


Fig. 3.1 - 1: Different zones (private, personal, social) exemplified with Transhab
© Constance Adams

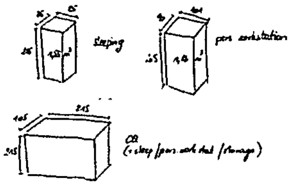


Fig. 3.1 - 2: Crew Quarters

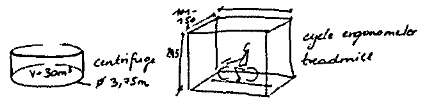


Fig. 3.1 - 3: Exercise

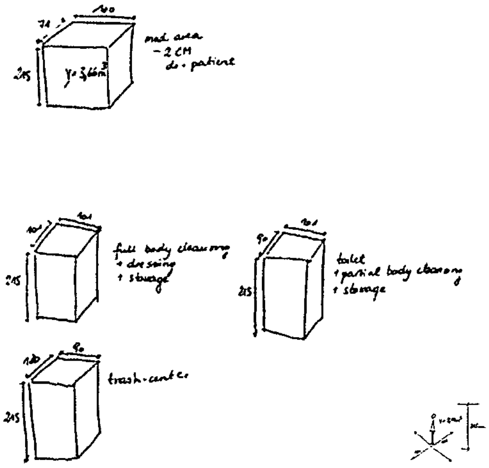


Fig. 3.1 - 4: Hygiene Facilities, Waste, Medical Equipment

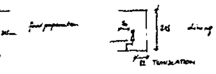


Fig. 3.1 - 5: Translation

A summary of the zoning and the implied volume requirements are shown in Fig. 3.1 - 2 to 3.1 - 5

Crew Quarters

Function	Height (cm)	Length (cm)	Width (cm)	Volume (m³)
Sleep	215	85	85	1.55
Personal Workstation	205	101	90	1.86
Personal Stowage				0.63

Fig. 3.1 - 6: Volume recommendations for different areas in the private zone

Command, Laboratory and Exercise Area

Function	Height (cm)	Length (cm)	Width (cm)	Volume (m³)
Centrifuge	215	187.5	187.5	23.77
Ergometer	101-150	150	245	3.71-5.51

Fig. 3.1 - 7: Volume recommendations for different areas in the personal zone

Medical

Function	Height (cm)	Length (cm)	Width (cm)	Volume (m³)
Private exams	71	100	215	1.53

Hygiene

Function	Height (cm)	Length (cm)	Width (cm)	Volume (m³)
Toilet	215	90	101	1.95
Full body cleansing	215	101	101	2.19

Waste

Function	Height (cm)	Length (cm)	Width (cm)	Volume (m³)
Trashcenter	215	90	120	2.32

Fig. 3.1 - 8: Volume recommendations for different areas in the personal zone

Social Area
For the social area the following recommendations were given:

Function	Height (cm)	Length (cm)	Width (cm)	Volume (m^3)
Food preparation	215	101	101	2.19
Dinner	215	82 for translation	70	
Conference Screen		80	70	
Galley	215		85	

Fig. 3.1 - 9: Recommendations for volumes for different areas of the social zone

3.2 Architectural and Habitability Recommendation For a Zero-G Spacecraft

A set of recommendations were accumulated, some through interviews of ESA astronaut Frank de Winne, RSA cosmonauts and NASA simulation/isolation experts. In addition references were taken from "Human Spaceflight - Mission Analysis and Design", scientific papers or from interviews. As this information was analyzed the important issues were collected and now serve as recommendations. Personal work experience with the architecture and interior configuration part of human space missions is also reflected in the tables below. As long duration human spaceflight implies a new set of spatial conditions, new approaches and methodologies different from the current architecture or aerospace architecture concepts are absolutely required. Due to the critical success factor of human survival, the following guidelines address issues of psychology, interior space perception, and the relationship between humans and the inhabited space.

Additionally design drivers and orientation options are discussed in this chapter.

3.2.1 Recommendations

In addition to the NASA Standards 3000 (STD), the following recommendations with their sources are listed here:

Recommendation	Rationale	Examples	Reference
GENERAL			
Anthropometric design and layout	• Neutral body posture changes the geometry of the eye's reference point • Different muscular effort in 0g and Xg	Different design requirements for workstations, clothing and equipment in zero-g and partial-g	"Human Factors of Crewed Spaceflight", Barbara Woolford, Robert Bond, Human Spaceflight, Mission Analysis and Design p147
Socialization	• Support social cohesion • Reduction of interpersonal tension • Groups vs. Privacy of small groups	• Areas designed for group interaction (dining, wardroom, entertainment area, group work sites) • Translation nodes such as corridor intersections (for spontaneous or intended meeting)	1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One--Habitability Constance M. Adams, AIAA
Privacy	Individual crew activities such as sleeping, reading, personal communications	Separation of private crew quarters from • public view • sounds • vibrations • each other	1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One--Habitability Constance M. Adams, AIAA
Recognition of cultural differences	Social and psychological benefits	• Adopt common tools e.g. for leadership • Spatial expression for tradition and "holidays"	"Psychology of Spaceflight", Albert Holland, Human Spaceflight, Mission Analysis and Design p174

COMPONENTS			
Laundry	• Mass reduction of textiles • Psychological issue • Self-cleaning • Eatable/ biodegradable clothes • No clothes	Water requirements	
Permanent dining table	To prevent separation of the crew (eating places and hours)	Table for whole group	1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One--Habitability Constance M. Adams, AIAA
Laboratory-glove boxes	Contamination prevention	2 laboratories (one during the flight and one on Mars)	
Radiation shielding	Galactic Cosmic Rays (GCR) • Constant isotropic bombardment by GCRs poses a special problem, as mission planners are only beginning to recognize • High mass / cm2		AIAA-96-4467 Habitat Distinctions: Planetary versus Interplanetary Architecture Marc M. Cohen
	Solar Particle Event (SPE) Extra "satellite" for prediction of solar flares because Earth cannot measure accurately spaceship trajectory	Storm shelter must be included in the architecture	
Windows	Provide the ability to • observe specific things outside the habitat • look at space outside the confined environment • virtual windows for enhancing the physical space and environment and to provide some diversity in the confined space • What is the exact function. e-g- living or only sleeping CQ -> decides whether there is need for windows.	Cupola: observation of exterior of module, EVA and robotic operations Windows in private crewquarters with automatic shutters (radiation, micro-meteorite protection)	981800 Space Habitat Design Integration Issues Marc M. Cohen -----cosmonaut rec. Fred Smith in an interview with Barbara Imhof about BIOPLEX and the isolation test of 1997, RADIO ORANGE 26.8.2003
Doors	Provide • Privacy and separation • Sealable pressure port within habitat modules • Pressure port between habitat and deep space/Mars	To close hatches between volumes quickly and easily in case of emergency	

Exercise	• fitness • counter-measures against physical degradation	• Special area for functional and symbolical importance • Exercise in small groups (exercising together, social sport activities)	981800 Space Habitat Design Integration Issues Marc M. Cohen
	• Role-playing • Free exercise • Social benefit	Recreation area for whole group	1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One--Habitability Constance M. Adams, AIAA
	Exercise equipment readily accessible	Experience on Mir showed that equipment is not used or used less frequently if it is not readily accessible	1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One--Habitability Constance M. Adams, AIAA
Personal Hygiene	• Whole body cleansing in privacy • Changing clothes		1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One--Habitability Constance M. Adams, AIAA
Greenhouse	• Fresh chives • Keep the crew busy • The crew can take care of an organic thing which changes and grows etc. – feed-back	Benefits for psychology, scientific experiments, food add-ons	SAE 2001-01-2174 Mars Surface Habitats: Architectural designs and concepts for planetary outposts, Imhof/Schartner

Fig. 3.2.1 - 1

The following issues refer to the discipline of architecture and become especially relevant in studies dedicated to human long term missions such as a human mission to Mars or a permanent outpost on the Moon. The sub-themes such as adjacency and separation derive from the spatial position of the functions in relation to each other in the space of the spacecraft.

Architecture Configuration

Recommendation	**Rationale**	**Examples**	**Source**
ADJACENCY and SEPARATION			
Simultaneous crew activities to be located far enough apart	Reduce the change of accidental interference		"Human Factors of Crewed Spaceflight", Barbara Woolford, Robert Bond, Human Spaceflight, Mission Analysis and Design p151
Easy access to potential trouble spots (leak points, motors, valves, controllers)	Easy repair and adjustments	In an unpressurized environment repair is only possible by astronaut EVA	981800 Space Habitat Design Integration Issues Marc M. Cohen
Emergency routes in every part of the habitat		Emergency routes are kept clear of equipment	"Human Factors of Crewed Spaceflight", Barbara Woolford, Robert Bond, Human Spaceflight, Mission Analysis and Design p151
Protection from electromagnetic interference	Communications and computation equipment may be interfered	• Physical separation of power cables from computer systems and data cables • Layout of raceways	981800 Space Habitat Design Integration Issues Marc M. Cohen
Mechanical systems (motors, pumps, LSS, waste management, toilets) far away from crew quarters	Sound, vibration and smell control		981800 Space Habitat Design Integration Issues Marc M. Cohen
Separating waste management from food preparation and dining	Hygienic and aesthetic reasons		981800 Space Habitat Design Integration Issues Marc M. Cohen
Toilet far away from crew quarters	Noisiest item during sleep periods		"Human Factors of Crewed Spaceflight", Barbara Woolford, Robert Bond, Human Spaceflight, Mission Analysis and Design p151
Multiple volumes	• Fire • Contamination • Loss of pressure • Event x	At least two, separate, isolatable pressurized volumes within the habitat core allow the crew to move from one volume to the other in emergency situations.	981800 Space Habitat Design Integration Issues Marc M. Cohen

Fig. 3.2.1 - 2

FLEXIBILITY OF USE			
Crew autonomy			
Flexible design of workstations	Access to control systems from more points in any module	• Elimination of dedicated workstations with their displays and controls • Portable computers • More autonomous working	"Human Factors of Crewed Spaceflight", Barbara Woolford, Robert Bond, Human Spaceflight, Mission Analysis and Design p151

Fig. 3.2.1 - 3

Flexibility of use signifies that the interior space, which is basically the habitable volume has no inscribed function - it is multifunctional. This concept taken from the architecture discussion of the 1990's refers to the efficient use of spatial volume. On Earth for example, one could compare "one-person homes" and apartments to the Japanese style of living in extremely dense cities. Life style thus became synonymous of flexibly used spaces.

With long duration stays and the increase in crew stressors, communication with "home" becomes one of the major issues. Various studies - space mission reports or studies of humans living in extreme environments on Earth - have shown that good and efficient communication based on advanced technologies also indicates that more generous interior configuration will be crucial for mission success in long duration missions.

Communication

Recommendation	Rationale	Examples	Reference
Refresher Training	• Mission very long • Almost no cost in mass • Psychological factor • Training for 0g and xg	• Training-methods in principle • Virtual reality training • Training software during travel	"Human Factors of Crewed Spaceflight", Barbara Woolford, Robert Bond, Human Spaceflight, Mission Analysis and Design p143
2-way-communication	• Contact with home (family, children, friends) • Taking into account time delays – creating new ways of communication – recording • Extension by means of physical perceptions that do not require real-time data transfer	• Confidential, direct and simultaneous • Video conference, messaging • Alternative communication: auditory, tactile, sensory, etc	Human Spaceflight, p165 Interview Valery Polyakov (Modern Times Spezial, ORF)
Responsibility and authority for crew	Less ground support through increasing distance		"Psychology of Spaceflight", Albert Holland, Human Spaceflight, Mission Analysis and Design, p173
Psychological Support during whole mission	Prevention and optimization of performance dysfunction in crewmembers	• Private consultation • Self-sufficient psychological tools (no dependency on Earth-based resources) • Virtual reality stimulation	"Psychology of Spaceflight", Albert Holland, Human Spaceflight, Mission Analysis and Design, p151, 173

Fig. 3.2.1 - 4

The texture and materiality of interior spaces are considered to be a stimulating factor for crew's health and productivity. Noise reduction must be addressed in the design for future space habitats and must be solved in a way that noise levels get reduced to a level of comfort. Currently these levels are as high as on a four-lane highway. (On ISS there is approximately 60dB or sometimes even more. This equals the noise of cars on a four-lane highway.)

Lighting, Color And Sounds

Recommendation	Rationale	Examples	Reference
Visual stimulation	Psychological well-being	Through color, lighting, sounds	"Human Factors of Crewed Spaceflight", Barbara Woolford, Robert Bond, Human Spaceflight, Mission Analysis and Design p145
	Biorhythm	Create day and night/winter and summer	Bioplex study, "For a future life on extraterrestrial planets", Barbara Imhof (JSC-NASA, Flight Crew Support Division), 1997
	Different atmosphere	Sunny day, cloudy day, party mood	Bioplex study, "For a future life on extraterrestrial planets", Barbara Imhof (JSC-NASA, Flight Crew Support Division), 1997
	Noise reduction to a comfortable level especially in crew quarters		"Psychology of Spaceflight", Albert Holland, Human Spaceflight, Mission Analysis and Design, p155

Fig. 3.2.1 - 5

3.2.2 Design Drivers

Initial interior design drivers depend on the decision whether the THM should be a rigid cylindrical module or an arrangement of spheres, whether the structure was to be inflatable or a hybrid construction of inflatable and hard shell modules. The first sketch shows a cylindrical habitat opposite a sphere. The second sketch refers to an inflatable habitat, and the third shows a hybrid construction with options for deploying parts to enlarge the interior volume.

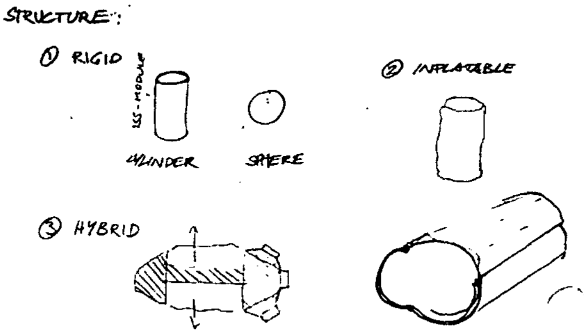


Fig. 3.2.2 - 1: Diagrams depicting structural options for spacecraft configuration

The first approach by the HMM study team was to organize and design a core cylindrical module where all the hardware, parts and functional spaces necessary for successful habitability of the required 450 m^3 should be incorporated. This decision directly implied another on how the module should be organized in terms of interior space and volume efficiency, mass efficiency, habitability, psychology, physiology and spatial architectural issues.

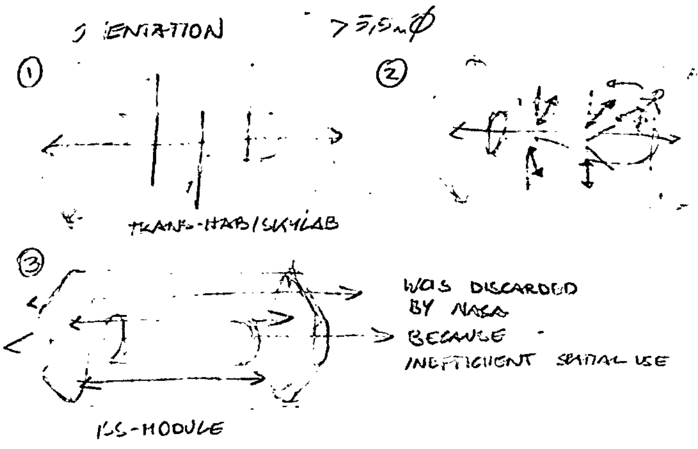


Fig. 3.2.2 - 2: Orientation options 1

1. This sketch shows a habitat layout with different levels (dark lines) as we know from NASA's Skylab (designed by Raymond Loewy and NASA engineers) and the new Transhab (designed by a small NASA crew of engineers and architects).
2. This shows an inner cylindrical core with a habitable surface of the outer surface of the inner cylindrical core.
3. This cylindrical module consists of an inner core for all technical infra-structure but orientates the habitable space along the axis of the hatches and connectors towards the other modules. NASA discarded this layout because of its inefficient use of space.

The diagram below summarizes the possibilities for orientation: sociologists have revealed that more complex spaces are required on long missions to keep the crew healthy and productive. Therefore the best option seems to be the 'mixed' option (right diagram) because it allows for a great variety of options in space perception and inhabitation by the astronauts. This option also requires a distinct orientation so that orientation is easy rather than confusing when floating through the modules.

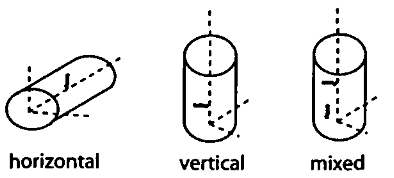


Fig. 3.2.2 - 3: Orientation options 2

The final choice was one fail-safe module with a hard shell and a mixture of Skylab and ISS orientation. The space with the centrifuge for artificial gravity adopted a new layout paradigm due to its construction.

3.2.3 Other Design Drivers

The following is a list of the other most important design drivers.

Mechanical issues:
- 1/5 of the volume has to be dedicated to ducts and pipes
- easy access to all ducts and pipes for maintenance is required, a well designed system and structure supports easy maintenance

Safety issues:
- In principal for safety reasons all systems (LSS, AOCS, etc.) should be modular – so to speak plug-and-play parts. In case a part fails in one place the astronaut can put it into another place.
- The storm shelter does not need to be air-tight if there are procedures and precautions for the following:
    - Toxicity
    - Fire/explosion
    - Contamination
    - Radiation (storm shelter)
    - Other biological hazards
- Enough fire detectors and isolation and recovery systems should be provided to enhance the safety of the crew

3.3 Concept and Development of THM Design

This part describes the process and development of the THM design and (interior) configuration in several steps. Commented sketches and drawings explain the individual development phases, including engineering feed-back.

3.3.1 Basic Concepts for a Transfer Habitat I

The first draft design included a cylindrical hard shell module concept (as opposed to an inflatable module) and focused on programmatic functions and their arrangement in the module. The first sketch in Fig. 3.3.1 - 1 outlines the entire configuration with the Mars Excursion Vehicle [MEV] (at the very left), the Earth Return Vehicle [ERC] (at the very right), the solar arrays, radiators and propulsion system. The red mark in the middle of the core module indicates the position of the storm shelter, a retreat for the astronauts during possible solar particle events. The shelter is designed to provide a safe haven for the crew for a minimum of 2 days.

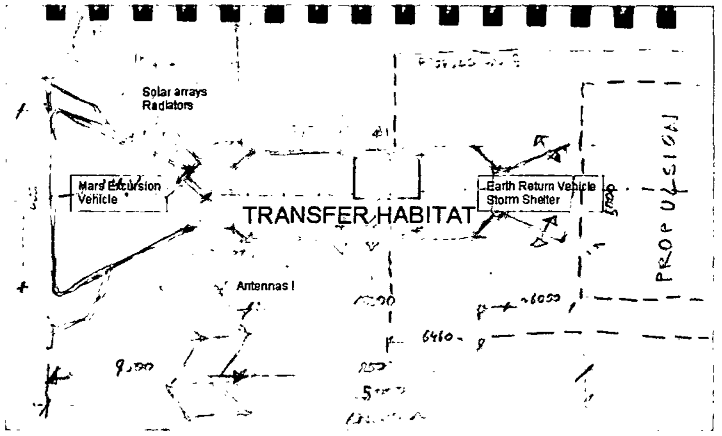


Fig. 3.3.1 - 1: Sketch of the Overall Configuration of the Transfer Habitat

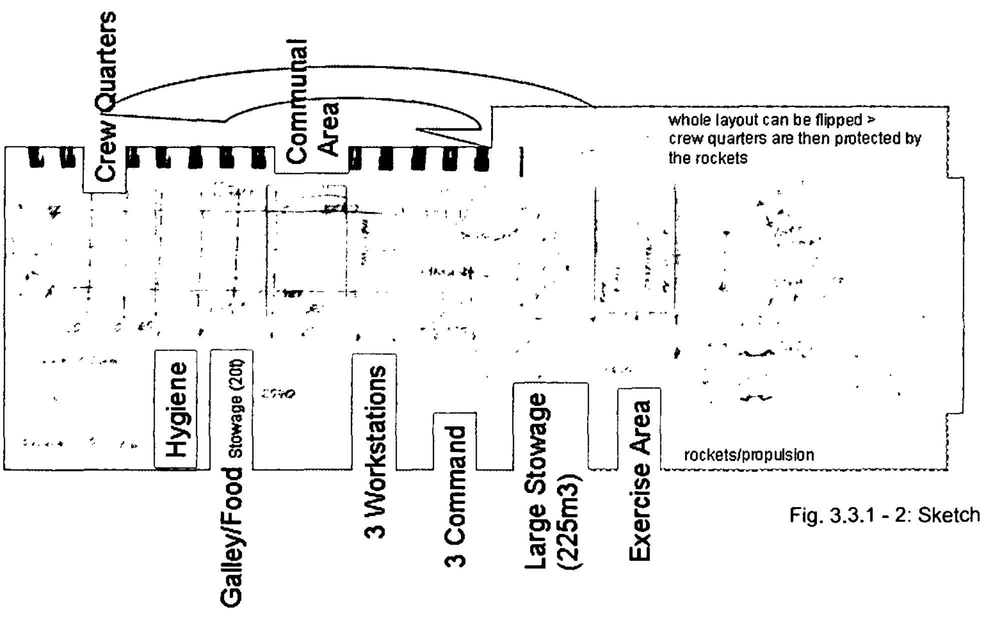


Fig. 3.3.1 - 2: Sketch - Zoning

Fig. 3.3.1-2 shows the layout for the different zones of the habitat. The crew quarters are situated at the very end to give the members enough privacy, the hygiene compartment separates the private area from the communal area, the galley and eating area. The command area is placed next to the communal area for easy access during emergencies. During normal every-day activity the station is controlled from different laptop stations all around the habitat. A large storage facility separates the noisy exercise machines and the training crew from the rest of the module. It was put at one end of the spacecraft close to the propulsion system to keep the centre of mass next to it. The exercise compartment will consist of several training facilities: a treadmill, an ergometer and a centrifuge for gravity simulation. This has a diameter of approx. 3.75-4.5 m and is as heavy as a middle class motorcycle (~200kg)

The worksheet with basic data gives a good first overview of volumetric figures.

	"width" [m]	"length" [m]	"height" [m]	**volume [m3]**	pieces	TOTAL		
Public Areas							101,82	S 1
Dinner/Conference	2,5	3	2,15	7,6	1	7,6		
workstation	0,9	1,01	2,05	1,86	6	11,16		
food stowage	3	3	2,15	20	1	20		
recreation	2,5	3	2,15	7,6	2	15,2		
exercise - treadmill	1	1,5		3,7	1	3,7		
artificial gravity/ergometer	4	1,5		18,8	1	18,8		
toilet	1,55	1,2	2,15	4,09	1	4,09		
hygiene	1,01	1,01	2,15	2,17	1	2,17		
	1,01	1,43	2,15	3,1	1	3,1		
pressure ports				4	2	8		
EVA				8	1	8		
translation	0,9	1,01	2,15	1,95				
Private Areas							11,52	S 2
crew quarter/sleeping	0,85	0,85	2,15	1,55	6	9,3		
changing clothes	1,01	1,01	2,15	2,17	0	0		
personal stowage	0,1	1,01	3,7	0,37	6	2,22		
[redacted]								S 1+2
Stowage/pressurized volume							272,17	S 3
food/prep	1,01	1,01	2,15	2,17	1	2,17		
other according to Human Factors engineer						270		
total VOLUME						385,51	385,51	S 1-3

Fig. 3.3.1 - 3: Worksheet: Volume Calculations

Here a very rough calculation of the status presented on the next page is given. The habitable volume is calculated including all facilities except the stowage areas. During the design process the calculation becomes more accurate. The habitable volume is less than one third of the total volume so that needed to be modified completely as the relation should be one third stowage and two thirds habitable volume.

Habitable volume approx.	113 m3	<< 2/3 of total volume
Pressurized stowage volume approx.	272 m3	>> 1/3 of total volume
Total volume	385 m3	

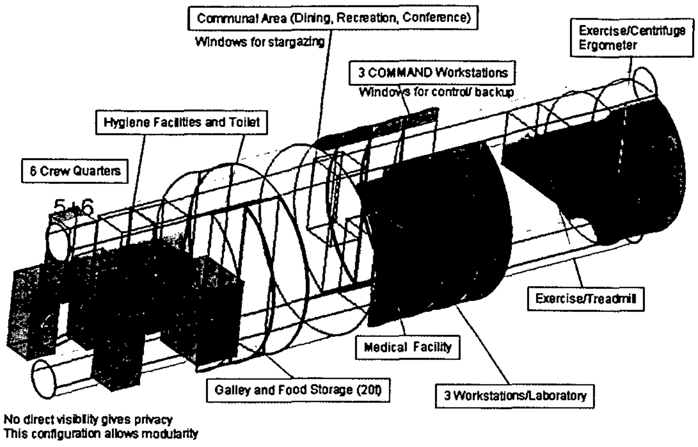


Fig. 3.3.1 - 4: CAD-Drawing of overall configuration

Fig. 3.3.1 - 4 provides an overview of the layout with minimum required volumes for different facilities as described in the previous table. An important consideration was:

- Few larger installation ducts for easy maintenance. Previous missions showed that maintenance takes a lot of the crew's time and is a daily duty in the life of an astronaut. Therefore it is suggested that when planning a human mission in more detail infrastructure parts such as ducts should be accorded major importance.

After review by the engineers and author, this configuration was discarded for the following reasons:

- One module with only one compartment is not considered safe enough for such a long trip.
- Each crew member should be separated from each other, have a window and a bit more space of their own - even if this space is also used for other purposes. (Feed-back of ESA astronaut Frank de Winne on habitation issues)
- The hygiene facilities are too noisy and too dirty, they should not be situated near the crew quarters. (Feed-back of ESA astronaut Frank de Winne on habitation issues)
- The centrifuge with this position spinning around the axis of the spacecraft would have obstructed the translation pass to the Earth Return Vehicle. Although this pass would not have been used much, security standards say that the exercise infrastructure has to be re-arranged.

The CAD drawing in Fig. 3.3.1 - 5 shows measurements for the discarded module concept, which form the basis for the following design options.

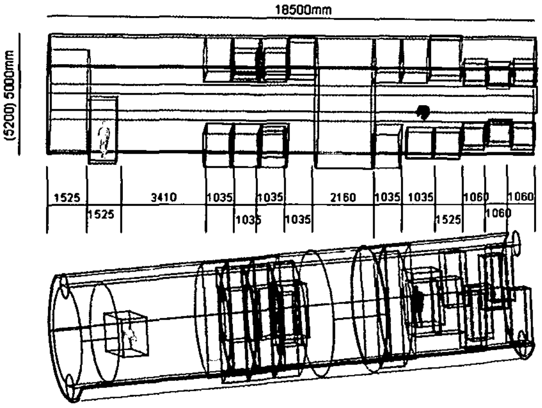


Fig. 3.3.1 - 5: CAD Drawing – Measurements of the Transfer Habitat

3.3.2 Architectural Recommendations

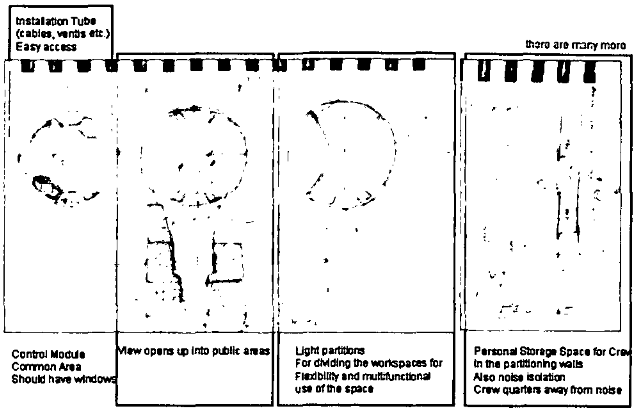


Fig. 3.3.2 - 1: Sketches of habitual considerations of the Transfer Habitat

The sketch in Fig. 3.3.2 - 1 shows examples for architectural recommendations on habitability:

Far left:

- Plan of an effective system for the installation ducts
- Windows for the common area, given that star gazing is the primary recreation activity for astronauts
- Command part should have direct visibility outside the spacecraft in case the remote cameras fail.
- To improve radiation protection it was suggested that the crew quarters should not have windows.

Center left:

- Racks/structures for hardware differ in size to create a mix of more open and denser spaces for in/visibility.
- Thus the habitable space becomes more differentiated in its function and allows easier orientation because of spatial distinction between the areas.

Middle right:

- In addition to the commonly used rack structure, light flexible partitions are introduced to keep the use of the habitat space flexible and give the crew opportunities to modify their own space whenever they feel the need for it.
- This also means that areas can be protected for better sound insulation during work time, and can be opened up during recreation times to provide a larger open area like in Skylab. It is known that Skylab astronauts always looked forward to spending some time in this area during the day.

Right:

- Thicker partitions can be used as personal storage space for the crew while also providing sound insulation between the individual spaces and from the rest of the spacecraft.

3.3.3 Basic Concepts for a Transfer Habitat II

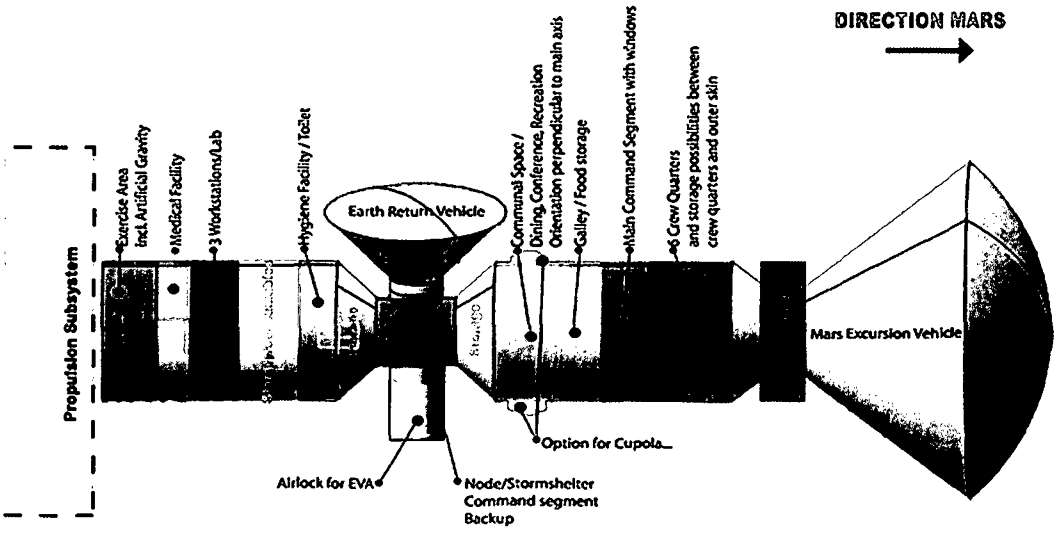


Fig. 3.3.3 - 1: CAD Drawing – overall configuration of THM

In Fig. 3.3.3 - 1 the personal area with the medical, exercise and hygiene facility is located in the back module, the social area with the private area of the crew quarters is located in the front part, and the storm shelter in the node. These designs brought up the following issues regarding functionality:

- Redundancy: in case one module is not functioning there is another fully functioning module – this implies replicating other infrastructure for backup, e.g. another hygiene facility.
- Storm shelter: the size of the storm shelter depends on how long such a solar particle event is expected to last. The agreed length for minimum protection is two days. In Fig. 3.3.1. the storm shelter is at the center where it is additionally sheltered by the surrounding mass of the modules. The node in itself already has a higher mass than a standard module, therefore it already provides more protection.
- Exercise facility: The exercise facility with the artificial gravity machine, the centrifuge, is located at the end because with its large diameter of 3.74 to 4.5 meters it cannot possibly be accommodated elsewhere. Nevertheless, there is no optimum solution for the configuration of the centrifuge as yet. Possible approaches could be:

1. Design a larger module with a diameter comparable to Transhab (approx. 7.8 meters). In a large inflatable module it would be easy to integrate such a large piece of hardware.
2. Design a novel artificial gravity facility. With the centrifuge spinning around the axis of the spacecraft, more propulsion power is currently required to keep the spacecraft in its position.
3. In case of emergency it would be a good idea to have some flexible exercise equipment. During an internal EVA this equipment can be taken out so the crew can still go on with its training.

- The hygiene facility is located near the node far away from all other functions. Therefore it is secluded for privacy and sound insulation. At the same time, this area is easily accessible from all other parts of the habitat.

3.3.4 Basic Concepts for a Transfer Habitat III

The configuration and habitat layouts dealt with the issues of optimized habitability standards and safety issues. Introducing more than just two modules allows for increased differentiation between the individual (private, personal, social/communal), as they could be established in one module each. This approach produced a variety of design ideas:

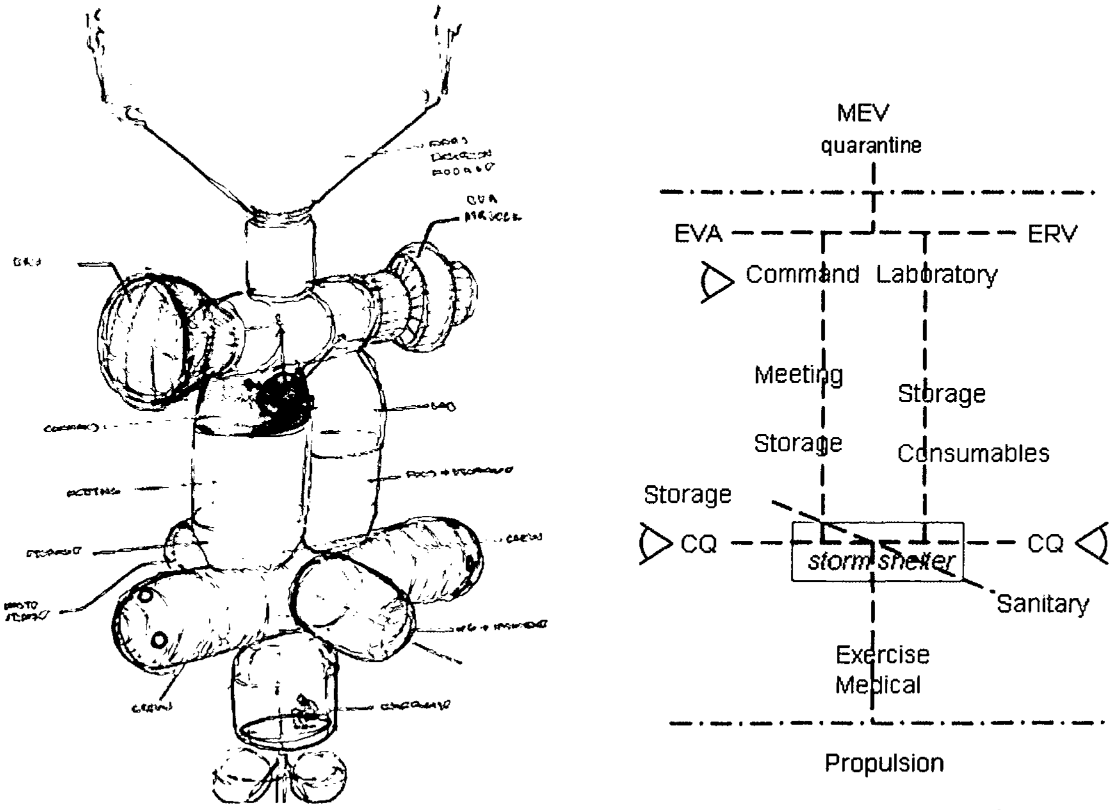


Fig. 3.3.4 - 1: THM Configuration 1

In Fig. 3.3.4 - 1 the diagram at the right illustrates the sketch at the left, focusing on the arrangement of the different zones. It is easy to recognize the location of the crew quarters (CQ) in respect to the hygiene facility (sanitary), and the exercise and medical facilities located in a separate module.

Further other options follow. For comparative reasons the design is displayed in the same fashion with a sketch and a diagram. In general, the social zones including dining area, galley, laboratory, and command are in the core module structure, while all other facilities are separated into smaller node-type modules to provide better sound insulation and more privacy.

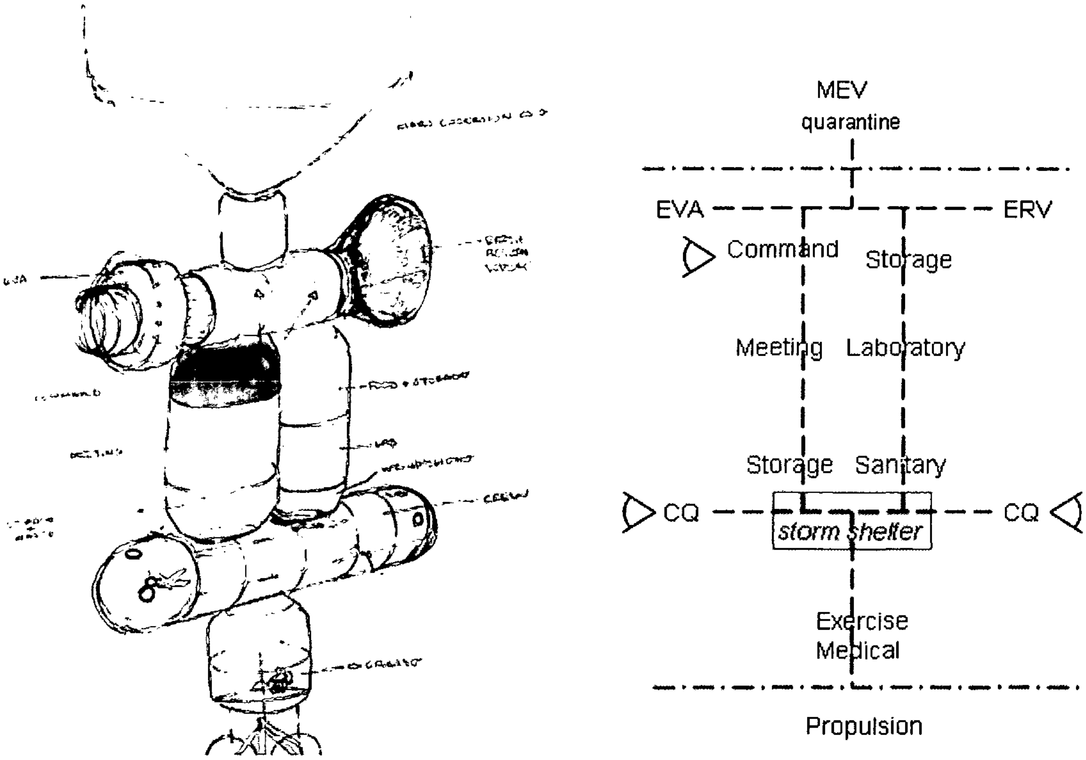


Fig. 3.3.4 - 2: THM Configuration 2

Considerations included a quarantine facility for the 3 crewmembers returning from Mars to guarantee planetary protection standards. – See top right in Fig. 3.3.4 - 2

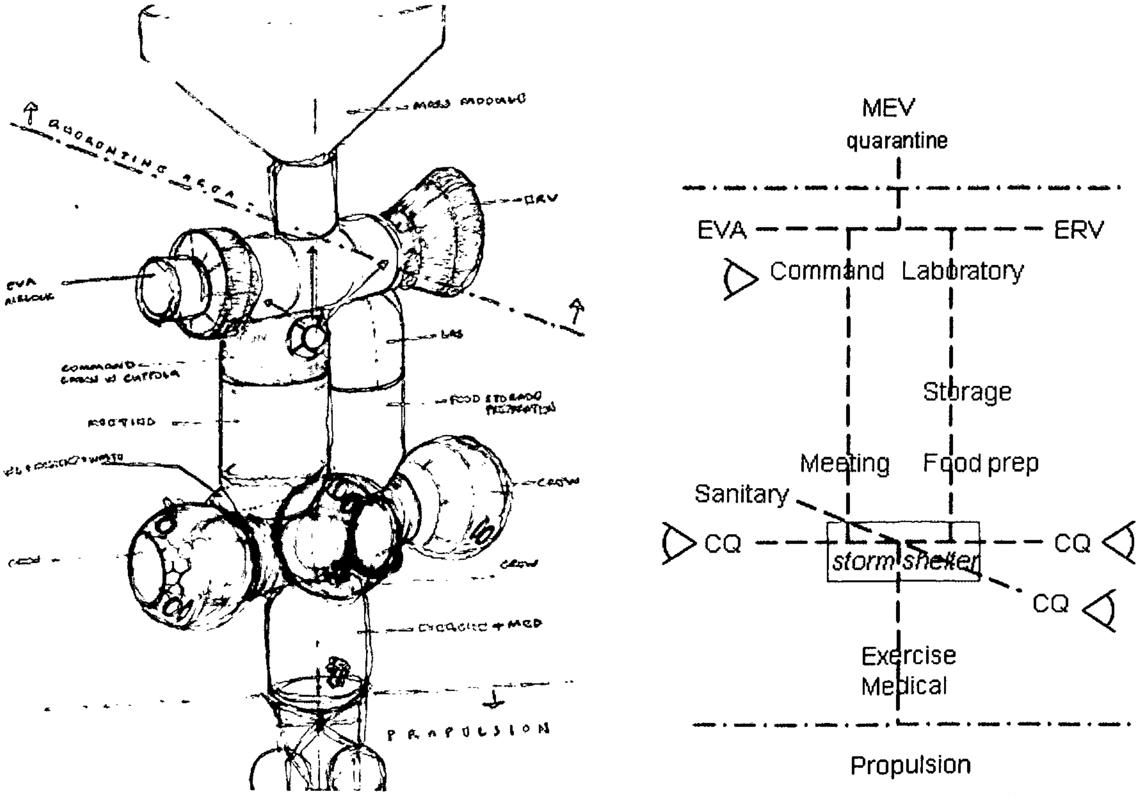


Fig. 3.3.4 - 3: THM Configuration 3

Each of the various configurations was briefly reviewed. It was hard to tell the advantages and disadvantages at this point because many major engineering factors were not defined then.

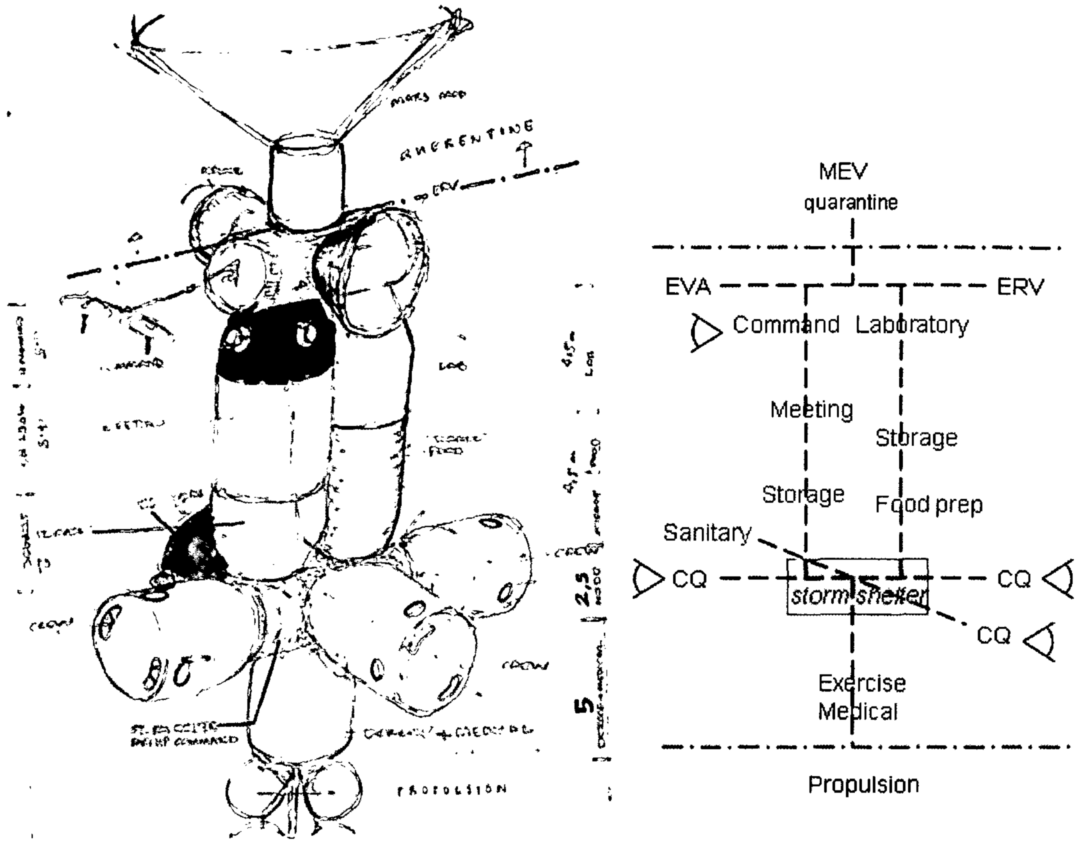


Fig. 3.3.4 - 4: THM Configuration 4

After CDF feedback, configuration 5 in Fig. 3.3.4 - 5 was selected by the author as the optimum solution among all configurations. The main advantages:

- The crew enjoys a maximum of privacy - two crewmembers share one node-type module, and all the crew quarters (CQ) have windows

- The hygiene facility (sanitary) is in a separate node-type module on its own, close to the crew quarters (CQ) and easy to reach from all other areas

- The command deck has an integrated cupola so the astronauts have a clear view over the spaceship and the airlock. Although having remotely controllable cameras, direct visibility can never fail in case of emergency.

In general, increasing the number of modules provides more possibilities for redundancy, which in turn increases crew safety. At the same time, having more spatial diversity increases the crew's productivity and well-being.

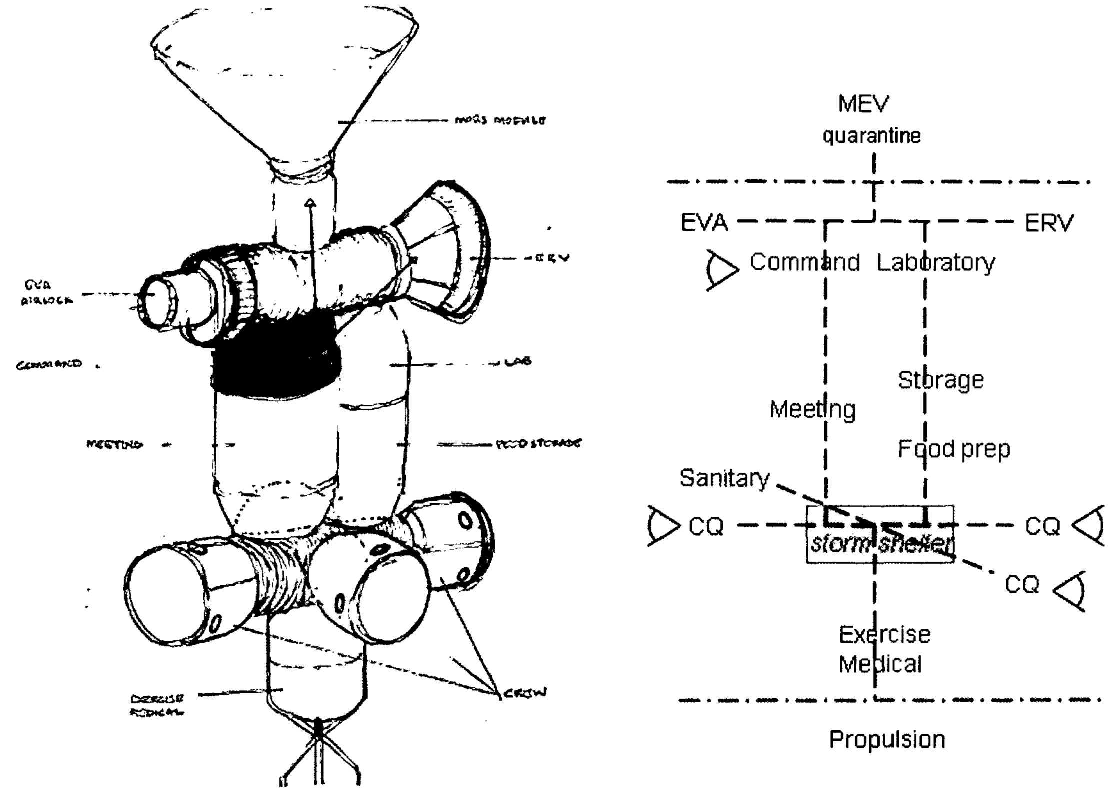


Fig. 3.3.4 - 5: THM Configuration 5

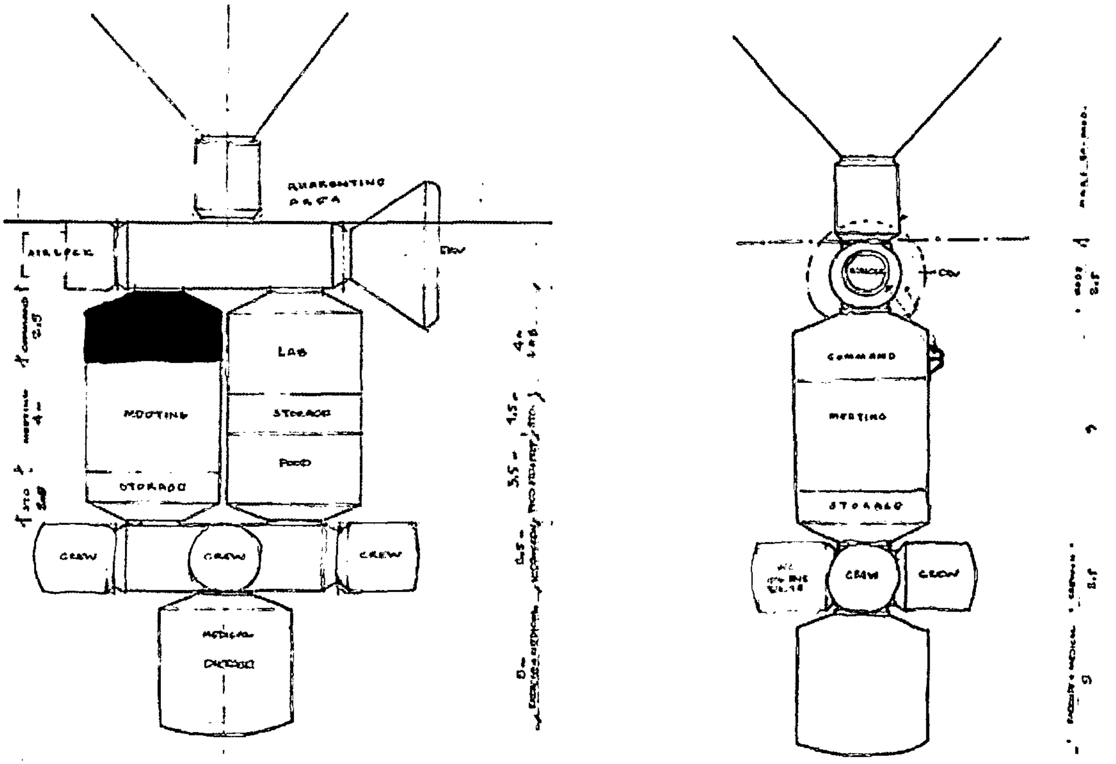


Fig. 3.3.4 - 6: THM Configuration 5 – side views

Fig. 3.3.4 - 6 shows two side elevations with approximate dimensions - size and length.

A cross configuration was discarded because of the excessive torque force the cross-modules would apply on the entire system architecture and structure.

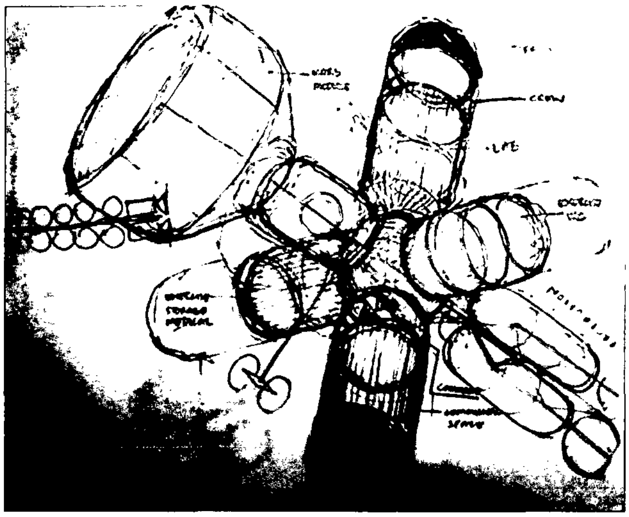


Fig. 3.3.4 - 7: THM Cross - Configuration

3.3.5 Safety

Before closing the chapter 3.3.4. "Basic Concepts for a Transfer Habitat III" the safety issue should be discussed due to its relevance for architectural design:

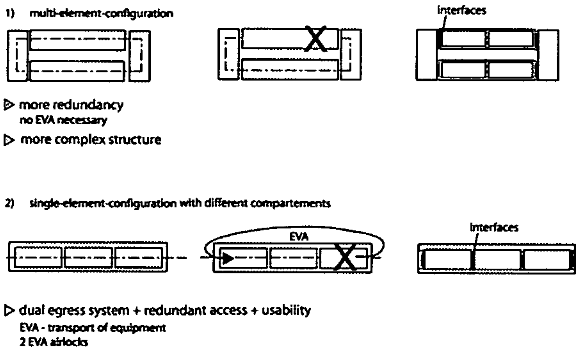


Fig. 3.3.5 - 1: Safety issues of a multi-element and single-element configuration

The first diagram - Fig. 3.3.5 - 1 shows a multi-element configuration and discusses issues such as translation, isolation of one module and back-up compartmentalizing.

Top left: in this configuration the astronauts are able to translate very well in two directions from one module to the other.
Top center: an emergency case – one module is malfunctioning (e.g. contaminated, depressurized). It is easy to shut this module off and travel safely into the others. If another module fails there are still modules left for contingency.
Top right: Compartments with hatches need to be introduced to make modules safe.
This is also applicable to a one-module-configuration as shown in the three diagrams below. By means of external or internal vehicular activities the malfunctioning part of the module can be shut off from the rest to eliminate danger.

3.3.6 Basic Concepts for a Transfer Habitat IV

The following configuration was derived from the analysis of the design steps shown above: a three-module configuration with two nodes connecting to the Earth Return Capsule (ERC), the airlock and the Mars Excursion Vehicle (MEV) – see Fig. 3.3.6 - 1. This had many reasons; the most obvious being that configuration 5 of the previous chapter in Fig. 3.3.4 - 5 and 3.3.4 - 6 needed to be simplified in order to allow for a reduction of torque forces acting on the entire spacecraft: the node-type modules housing the crew quarters and hygiene facility had to be removed and incorporated into the core module. Due to this reduction in the number of modules, the configuration in Fig. 3.3.6 - 1 was lighter than in the previous concepts.

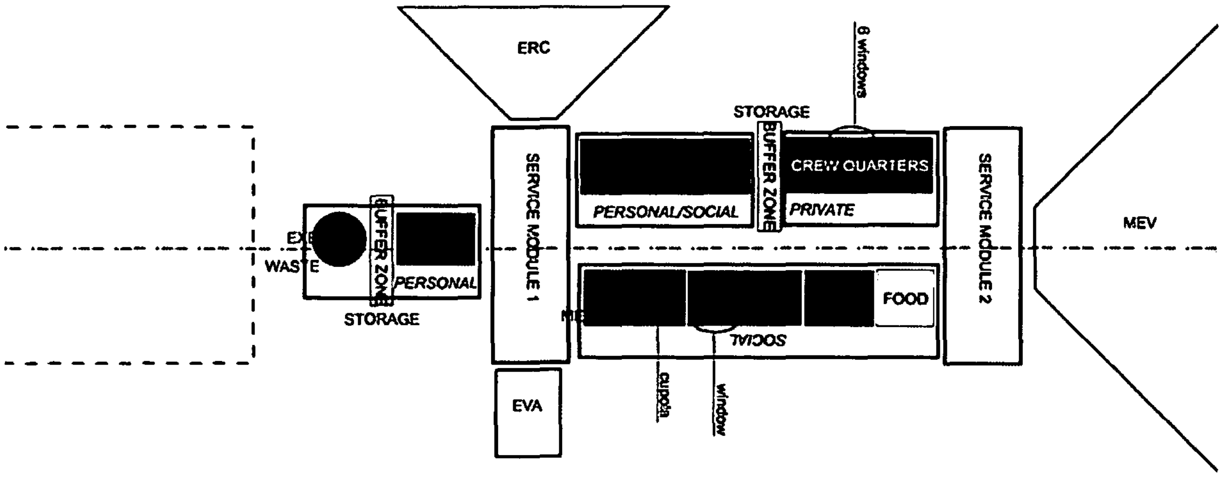


Fig. 3.3.6 - 1: Interior Configuration Overview – 2 module / 2 node configuration

With the following configuration option in Fig. 3.3.6 - 2 the starting point for the foundation for the overall configuration design emerged: the CDF team decided on one hard shell module cylinder, which is fail-safe and is subdivided into compartments. It was concluded that this is the best option for the present Human Mission to Mars study based on today's knowledge of technology and conservative assumptions. The main reasons for this decision were the launch weight, the number of launches and the associated costs. Subsequently the architecture of the interior configuration could be investigated into more detail.

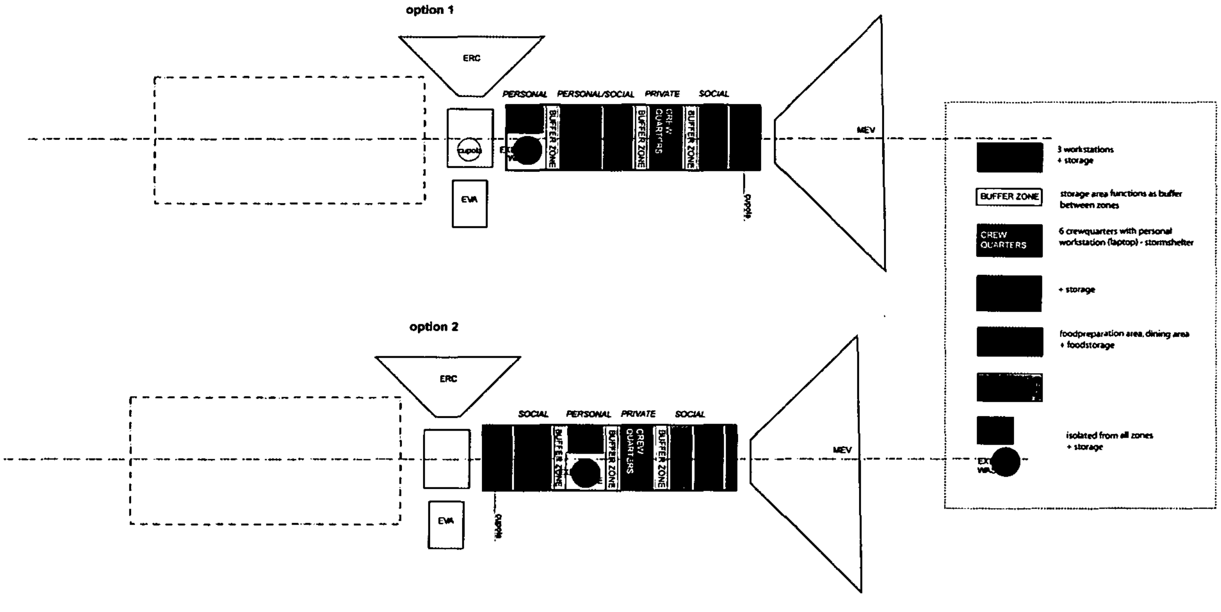


Fig. 3.3.6 - 2: Configuration Options THM – one module / one node configuration - 2 options

The two options in Fig. 3.3.6 - 2 deal with the different options of arranging the different habitat zones (personal, private and social/communal). In option 1 there is a greater mix of the three different zones, which is not appreciated because quiet and noisy zones alternate too often, making it more difficult to keep one zone quiet. In option 2 the different zones are organized more coherently. Before a final decision on the overall configuration was taken, an investigation into the details of possible interiors was needed.

3.3.7 Interior Configurations - a Primary Investigation Into Options

The basic spatial distinction between quiet zones and more noisy, busy zones is based on a differentiation into three zones:

I. Private zone - crew quarters: each crew member has his/her own reserved space where they can also retreat from the others.

II. Personal zone - hygiene facilities, exercise facility, work stations, laboratory racks: these are places which all astronauts share but on an individual basis. The exercise facilities will allow two crewmembers to train together but in general the time allocated for each crew member is defined by individual training. The same applies to the other facilities and areas. The hygiene facility is shared by all members but is essentially a place of intimacy.

III. Social/communal zone - galley, recreation, dining, and command: in these areas all crewmembers spend their time together. Key elements are the galley, a table for gatherings, and infrastructure for video communication back home. The diagram of the social module below shows that the different functions are divided by storage racks, which allows for a clear distinction between different functions. The overall orientation is comparable to that of ISS. The many storage racks are necessary to store the Life Support Systems, consumables, maintenance equipment and many more things, which are listed in chapter 3.5. "Tables of Volumes". The command area has a cupola which can also be used by the astronauts as a place of recreation to spend their spare time. At the same time this point provides a good view of parts of the outside of the spacecraft.

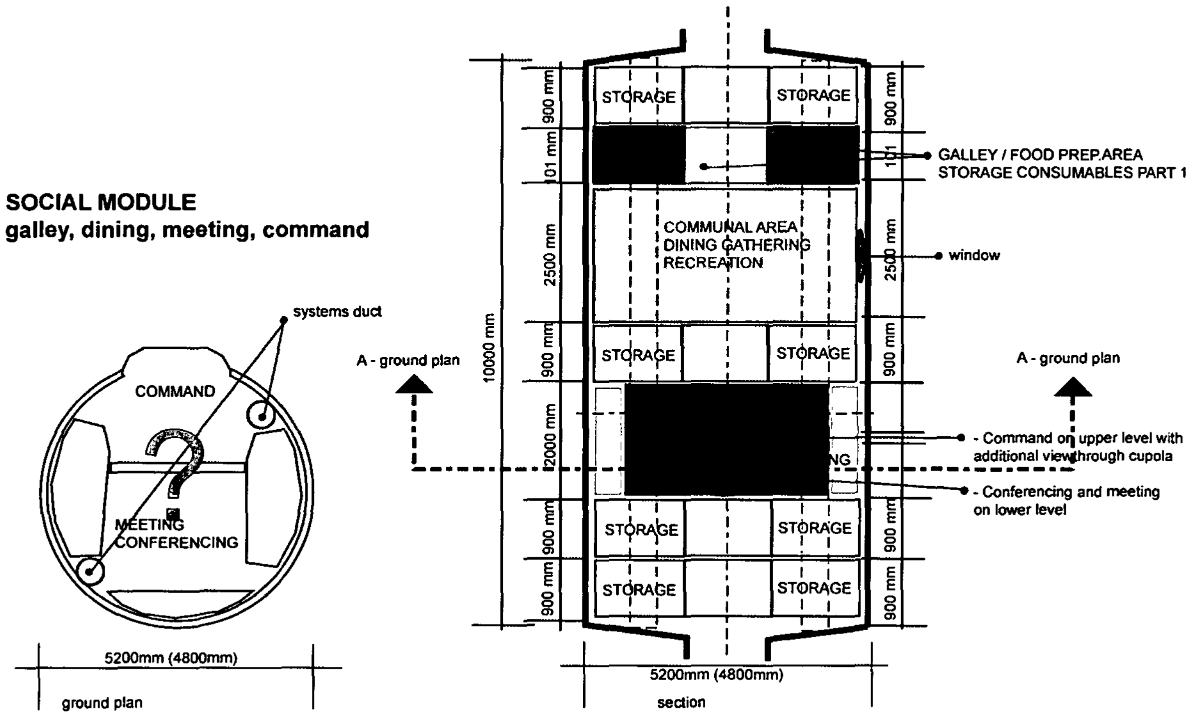

SOCIAL MODULE
galley, dining, meeting, command

Fig. 3.3.7 - 1: Interior Configuration - Social Module which can also be seen as one compartment within a module

As a great amount of storage space is required, an efficient method of storing and using the space has to be developed. The diameter of 4.8 meter is slightly more than on ISS so the rack system used efficiently on ISS cannot be applied to this mission. A proposal is to implement moveable racks, which are accessible sideways and leave a narrow translation pass in the middle. In this way the storage areas can be very dense and equipment can be placed efficiently. The architectural space receives its own rhythm and a differentiation, which facilitates orientation for the astronauts, reduces fatigue and stimulates the senses through the possibility to put storage racks into different positions when not in use. Through this, the space and its perception changes.

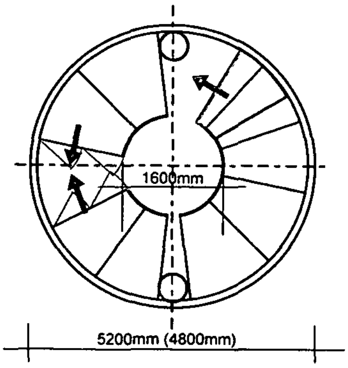


Fig. 3.3.7 - 2: Interior Configuration - Storage

Ad I. Private zone – crew quarters: The crew quarters will become a very important design issue, given that the crew constitutes a critical mission system whose well-being and productivity is a success factor. Therefore a more detailed investigation was considered valuable. In the diagram of Fig. 3.3.7 - 3 two options are proposed:

- Option 1 introduces a public translation path in front of a private sector and distribution area, which is the entry to the crew quarters. It has a height of two levels because this orientation implies different "vertical levels", like Skylab or Transhab. Thus an optimum of privacy can be achieved.

- Option 2: a public translation zone was set above the private zone. It is entered from above and has a distribution and entry space for the crew quarters. From here all six crew cabins are reached. For the baseline design the first option was taken because it allowed translating more easily through the module seen within the overall configuration.

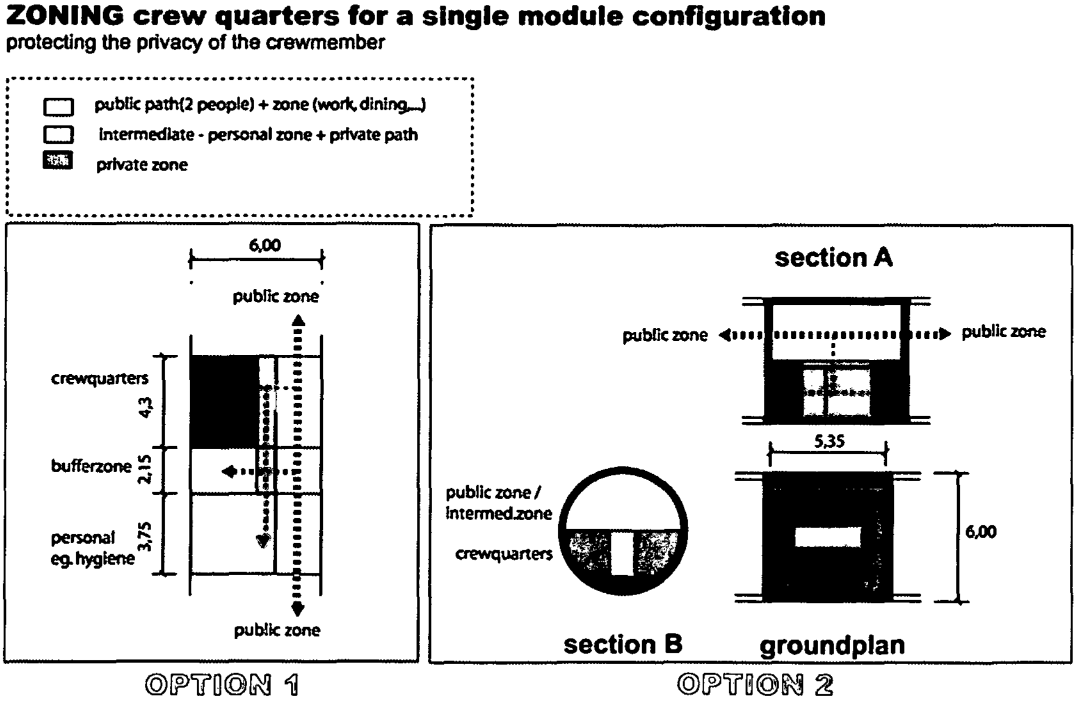
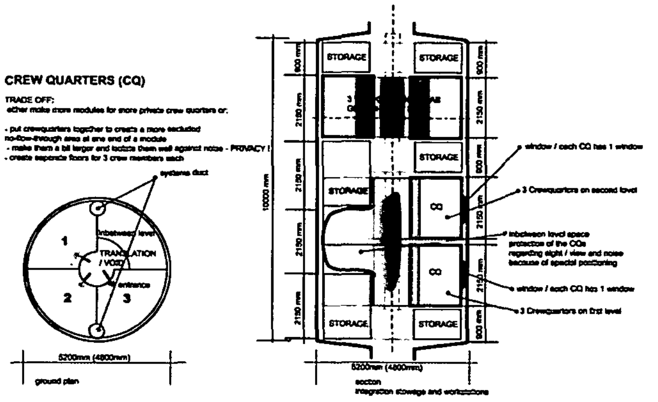


Fig. 3.3.7 - 3: Zoning crew quarters

Option 1 was investigated further: having a public and a private translation space seemed to take too much space so alternatives were searched for: The argument moved towards having slightly larger crew quarters with thicker partitions for adequate privacy and discarding the additional transfer space. The orientation stays as it was in Skylab and the crew quarters are situated on two different levels (three crew cabins on each level) to maximize the distance between them. A similar solution had previously been recommended by ESA astronaut Frank de Winne.

Opposite the entrance of the cabins a special dedicated space was designed as recreation area. The exterior walls of the cylindrical habitat create the basis for a set of curved wall-furniture. (see Fig. 3.3.7-4) Due to the lack of gravity, humans look for other spatial orientation. Walls become important surfaces for reference and a recreation space can "ground" and relax the astronauts, which supports their well-being on such a daring mission.



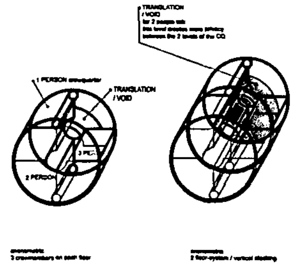


Fig. 3.3.7 - 4: Interior Configuration – Crew Quarters

Fig. 3.3.7 - 5: Interior Configuration - Translation

In Fig. 3.3.7 - 5 an axonometric view of the crew quarters is shown.

Taking account of all issues discussed above, and considering all advantages, the following reference for the baseline design was developed. It integrates all requirements, research points, trade-offs and processes in this study:

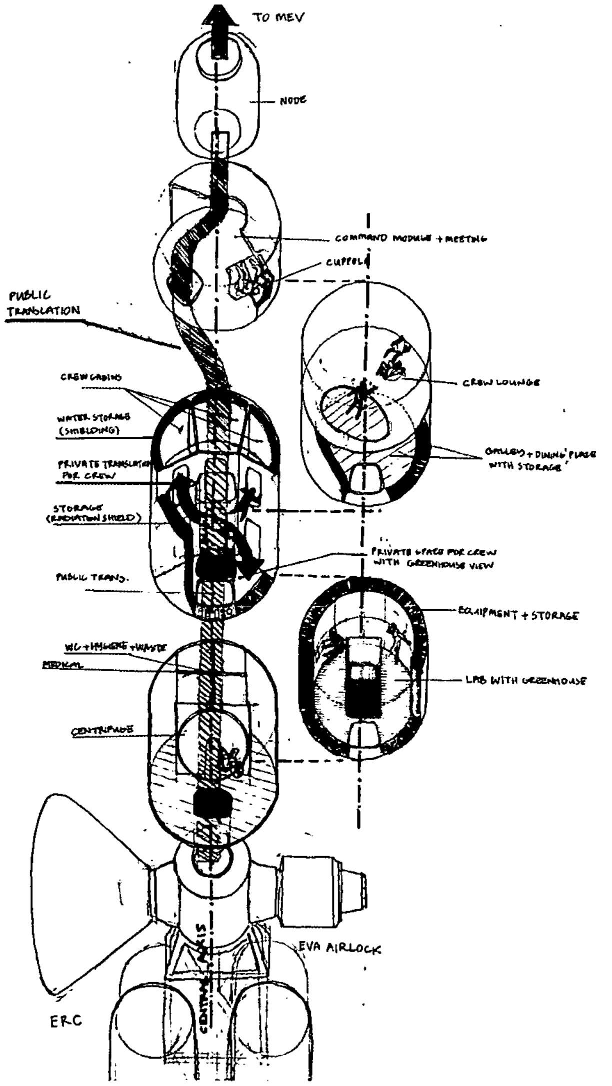


Fig. 3.3.7 - 6: Axonometric view of the draft baseline design

In Fig. 3.3.7 - 6 shows the first approximation towards the final base-line design for the Transfer Vehicle (THM). It is characterized by the easy but sense-stimulating translation path through the module and the "vertical-level" (Skylab-type) orientation which only changes in the exercise module due to the centrifuge. The centrifuge with a diameter of 3.75 meters spins around an axis perpendicular to the spacecraft's main axis. This reduces the forces acting on the entire configuration. The hygiene facilities are located in this area, too. "Above" is the level of the laboratory, the medical and maintenance racks. Further "up" the crew quarters can be found as described in the previous chapter, followed by the galley, gathering area and communication/command area on the very "top" end of the module.

3.4 Baseline Design for the THM

The drawing showing the baseline design for the THM is depicted in Fig. 3.4 - 1:

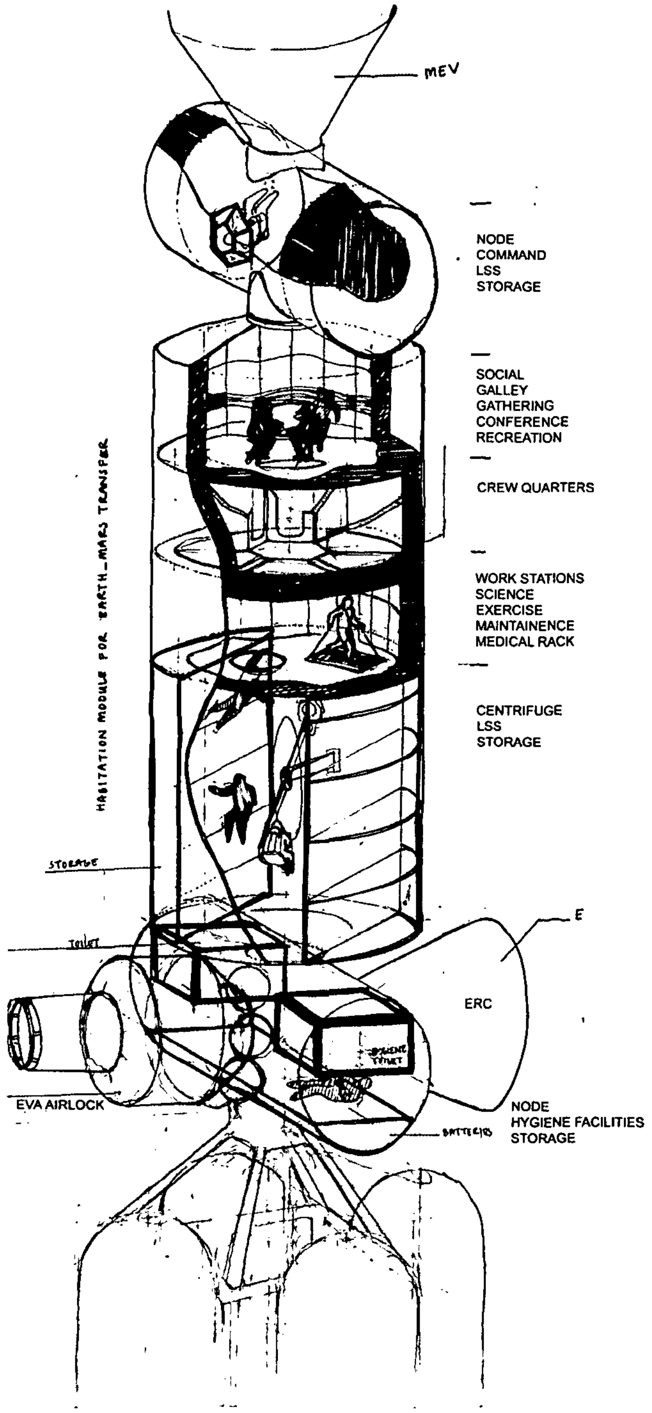


Fig. 3.4 - 1: Axonometric view of the final baseline design

The final configuration consists of a fail-safe module with a length of 14.00 m and 5.90 m inner diameter (outer diameter is 6.00 m). On the extremes of the module two nodes are connected, which allow to interface with additional habitable modules:

- The EVA airlock and the ERC (Earth Return Vehicle) connected onto the back node (the "lower" one in the drawing), and,
- The MEV (Mars Excursion Vehicle) connected at the upper end.

The total habitable volume is 485 m^3; where 1/3 of the volume is used for storage, and the remaining 2/3 are the habitable volume. Approximately 5% of the total volume has to be considered for the module structure. The minimum volume requirement amounts to 450 m^3 but according to the standards of human factor engineers this is not sufficient.

The following sections will describe the overall interior layout in further detail, based on Fig. 3.4 - 2

Detailed Interior Configuration
Diagrams including measurements were drawn to develop this study into a prototype concept with detailed information. The nodes have a length of 5.10 m, with a diameter of 3.60 m (slightly smaller than ISS modules, which are 4.00 m in diameter). As described before the module has a length of 14.00 m with an inner diameter of 5.90 m (outer diameter is 6.00m). It is assumed that this module will be launched on the Energia rocket, which has an approximate capacity of 80 metric tons (Tm), 38 m length and 6 m diameter. For further details, please see general AURORA HMM study report.

VOLUMES

Total volume = 480 m3
Main module = 382 m3
2 Nodes = 98m2

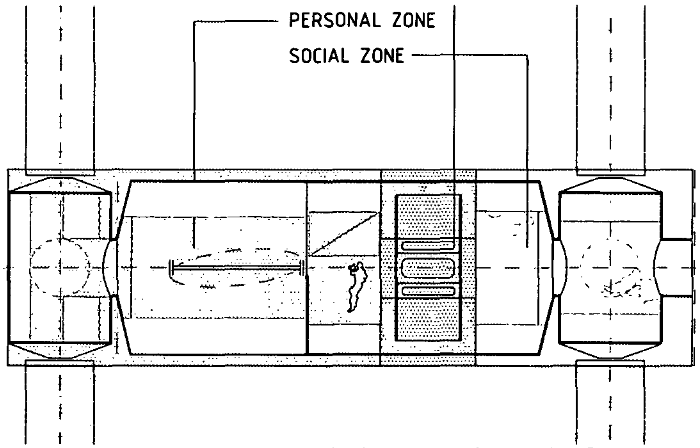


Fig. 3.4 - 2: Baseline Design Overview - Drawing

Fig. 3.4 - 3 describes the 3 basic habitation zones and the main translation movement, which is demonstrated through red arrows.

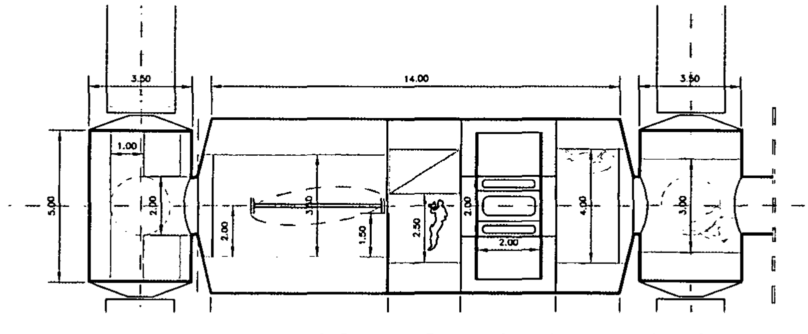


Fig. 3.4 - 3: Baseline Design Overview – Drawing of Measurements

An idea of the total volume can be obtained from Fig. 3.4 - 3, where the approximate dimensions are given.

General safety issues:
Two main aspects have been taken into consideration with regard to safety:
The overall configuration is based on a fail-safe main module. Only the storm shelter has airtight hatches for radiation protection. The main cylinder is already partitioned into three zones, which can be used independently in case of emergency. Furthermore the use of the MEV and the ERC nodes provide additional safe compartments.
Special precautions have to be taken with respect to fire, toxic contamination etc. It is therefore assumed that a fire detection system, a fail-safe isolation and recovery system is implemented. Batteries should be placed outside, adjacent to the solar panels, and the oxygen/nitrogen tanks should be arranged around the airlock.

Node - Personal Zone - Hygiene Facility
The back node is mainly a translation space to the ERC. The airlock stores three space suits, two in case of EVA and one for contingency. This habitable node is considered as more isolated than other spaces therefore the hygiene facilities are located here (personal zone). There are two hygiene facilities, one for daily use and the other for backup. The space in direction of the propulsion is used as storage space although all AOCS systems, batteries, and propulsion tanks are arranged outside to prevent the inhabited space from being polluted by dangerous fluids or gases. The spherical tanks are fixed around the EVA hatch for easy access in case of an emergency. The dimensions of the node with an ISS-type layout allow a maximum use of the space. Additionally the complex hygiene facilities used on the ISS today can easily be improved without inventing new hardware with latest technology.

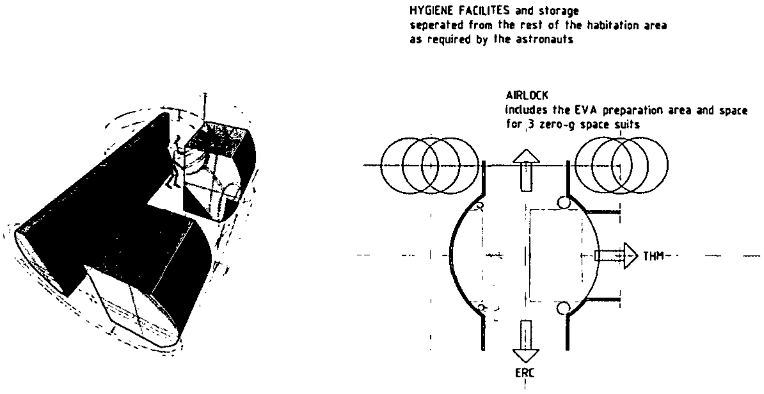
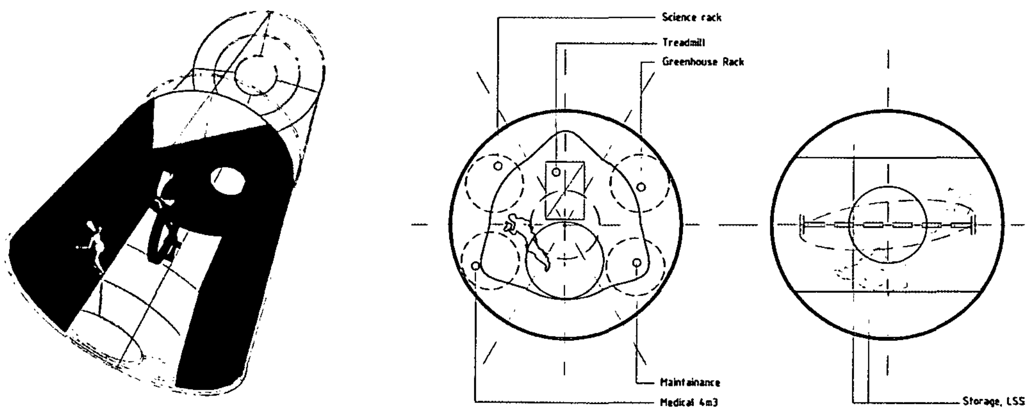


Fig. 3.4 - 4: Baseline Design Back Node - Drawing

Module part 1+2 - Personal Zone
In the following Fig. 3.4 - 5 the exercise area with the centrifuge and how the astronauts translate from one area to another is depicted.


Centrifuge

Laboratory - section

Centrifuge - section

Fig. 3.4 - 5: Baseline Design Personal Area - Drawing

The large exercise facility with the centrifuge (personal zone) is located in the back end of the main cylinder. It is spinning along the axis of the spacecraft. The other space is used for translation of the crew and for the life support system, which altogether requires approximately 55 m^3. This space has an unusual orientation, which is neither Skylab-type nor ISS-type due to the spinning centrifuge. It is very well used by arranging the LSS in this part because of its easy access for maintenance.

Furthermore it has a large volume that may be used by the astronauts in their leisure time for some "floating" experiments, as they did on Skylab. The adjacent compartment is the laboratory, workstation and maintenance level (personal zone), which has a Skylab-type orientation due to the proportions of the module. For efficient use of space this is the most adequate orientation. It is the level for the treadmill, a medical, science and greenhouse rack and three workstations with computers in addition to each astronaut's fully equipped laptop computer.

Module part 3 - Private Zone

In Fig. 3.4 - 6 the following compartment is shown, which has light hatches. It houses the crew quarters (private zone). It has a 0.5 m thick protection wall all around the compartment, stuffed with consumables and water for radiation protection in case of a solar particle event. This storm shelter protects the crew for two days. Inside, 6 crew quarters are equally distributed with a translation path wide enough for large packets to be passed.

Crewquarters: 10m3 (incl. a thick partiti oning wall for noise reduction)

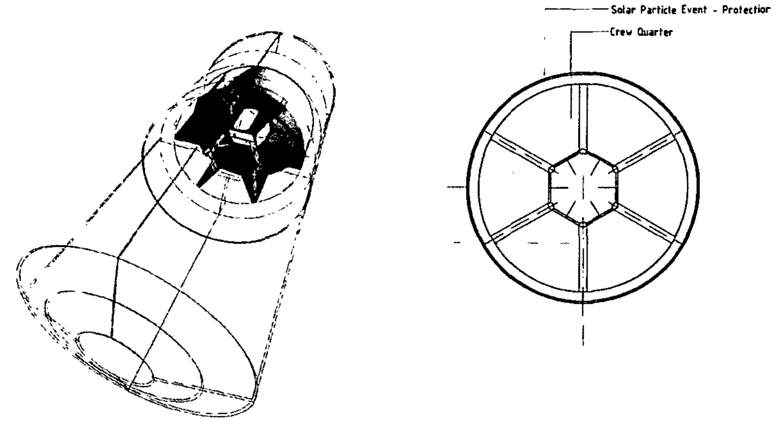
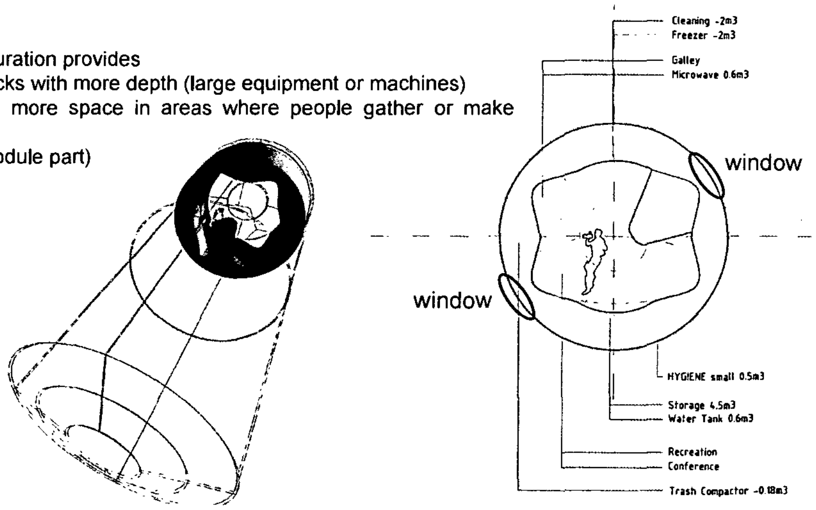


Fig. 3.4 - 6: Baseline Design Private Zone - Drawing

Module part 4 - Social Zone

The "top" part of the main module is occupied with the social zone; that is the galley, the gathering area, the conference infrastructure and some space for recreation. There should be at least two windows to look outside.



Star-shape configuration provides
more space for racks with more depth (large equipment or machines)
and gives way to more space in areas where people gather or make experiments/tests
(see laboratory module part)

Fig. 3.4 - 7: Baseline Design Social Zone – Drawing

Node - Command Area

The front node has the same dimensions as the back node, which is the translation path to the MEV (Mars Excursion Vehicle) and houses the command part with the cupola for a good overview of the spacecraft. The cupola faces the same direction as the airlock, so during an EVA, the remaining crew can view their colleagues during a space walk. Additional storage racks are placed in this node as well.

The orientation is adjusted to the functional program (see Fig. 3.4 - 8, right): there is an extra command level put in between to connect the cupola with the main command to distinguish the space "below" as different from the one above. In the "upper" command area six seats can be installed for use during the spacecraft's acceleration when taking the course towards Mars. Therefore a fixed level becomes imminent. Below there is the free main translation path to the MAV (Mars ascent vehicle) – part of the MEV (Mars Excursion Vehicle).

Storage

Storage is a big issue for long travels and long duration missions. This was already identified in previous long-term missions on MIR. Tools for maintenance and spare parts have to be taken into account.

The overall storage space of the THM is 37.6 m³ (excl. LSS, and personal stuff, consumables or related stuff) with the possibility of adding 8 to 10 m³ for additional storage. The storage space in the overall configuration is distributed as follows:

NODE 1	5.1 m³
Module part 1+2	23.5 m³
Module part 3	(4.5 m³ all consumables or personal stowage crew - not in calculation)
Module part 4	(4.5 m³ all equipment for housekeeping, cooking etc. - not in calculation)
NODE 2	9.0 m³

Cupola provides only an overview over part of the overall spaceship and enhances psychological support

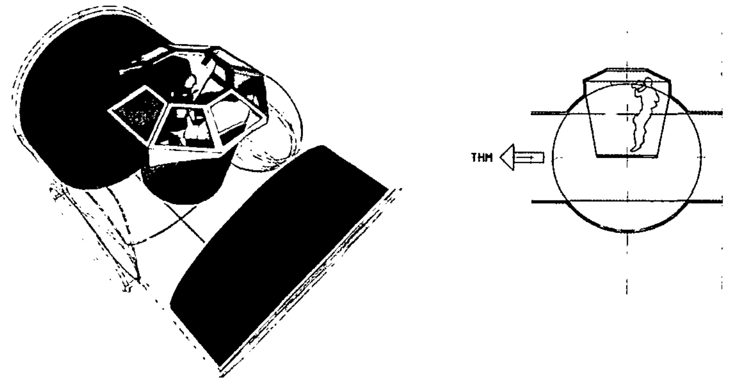


Fig. 3.4 - 8: Baseline Design Front Node - Drawing

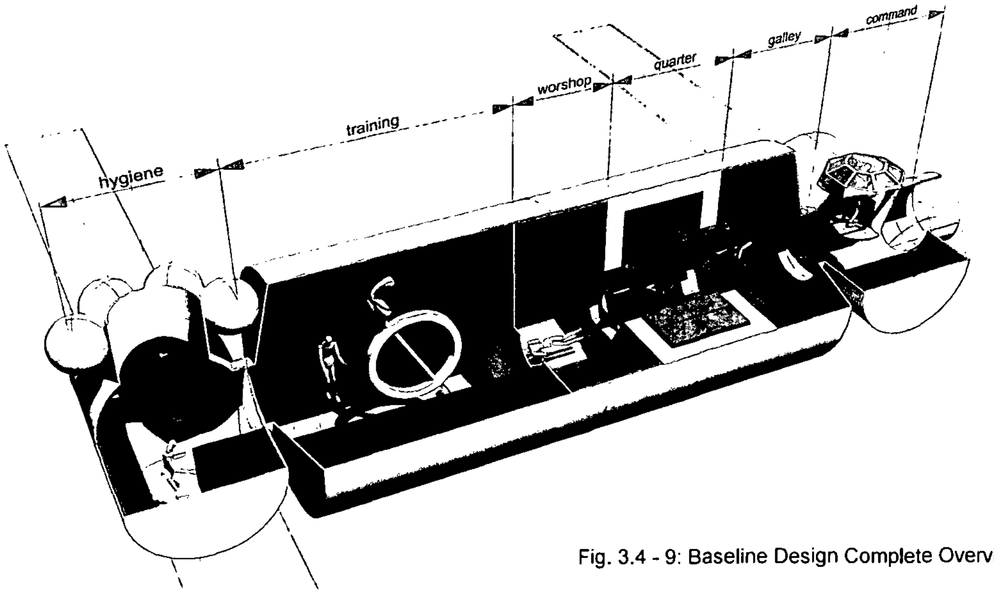


Fig. 3.4 - 9: Baseline Design Complete Overview

3.5 Table for Volumes of the THM

			Volume [m3]	[m3]	[m3]	[m3]	[m3]	[m3]	
		comments	habitable space	storage space	equipment	structure 5%	other	**TOTAL**	zoning
ELEMENT	NODE 1	with airlock and ERC docked	28	6	13	2		49	personal zone
	toilet 1				4				
	toilet contingency				4				
	behind toilet x2				1				
[m3]	below/above toilet x4	space for equipment			4				
MODULE TOTAL	other habitable space		28						
371,90	MODULE part 1		86	18	51	8		162	personal zone
	exercise - centrifuge	space above the centrifuge inc. structure			24				
	LSS	fuel/cell water storage, water/urin recycling etc.			27				
	other habitable space		86						
	MODULE part 2		44	0	20	3		67	personal zone
	treadmill		4						
	science/greenhouse/maintainance				16				
	medical				4				
	other habitable space		40						
	MODULE part 3		47	10	0	3		60	private zone
	crewquarters x6		25						
	storage			5					
	clothes	radiation protection			0				
	water	radiation protection		1					
	storage	radiation protection		4					
	translation		6						
	other habitable space		16						
	shielding 2 sides of crewquarter						20	20	
	MODULE part 4		40	5	16	3		63	social zone
	galley				14				
	Hygiene facility small				1				
	storage			5					
	water				1				
	other habitable space		40						
	NODE 2	with MEV docked	28	0	18	3		49	social zone
	Command								
	LSS				13				
	food				5				
	other habitable space		28						
	AIRLOCK						3	3	
	TOTAL		272	38	117	23	23	**473**	

Fig. 3.5 - 1

Distribution space

Requirement:		in THM of the HMM	
1/3 stowage and equipment	150m3	>> 1/3 stowage and equipment	201m3
2/3 habitable volume	300m3	<< 2/3 habitable volume	272m3
TOTAL ca.	450m3	TOTAL ca.	473m3

assumption 5% of total volume for structure

3.6 Appendix to Part 3

The Appendix shows 3-D drawings, diagrammatic plans and and a section of the THM to give a more detailed overview.

Overview THM / section

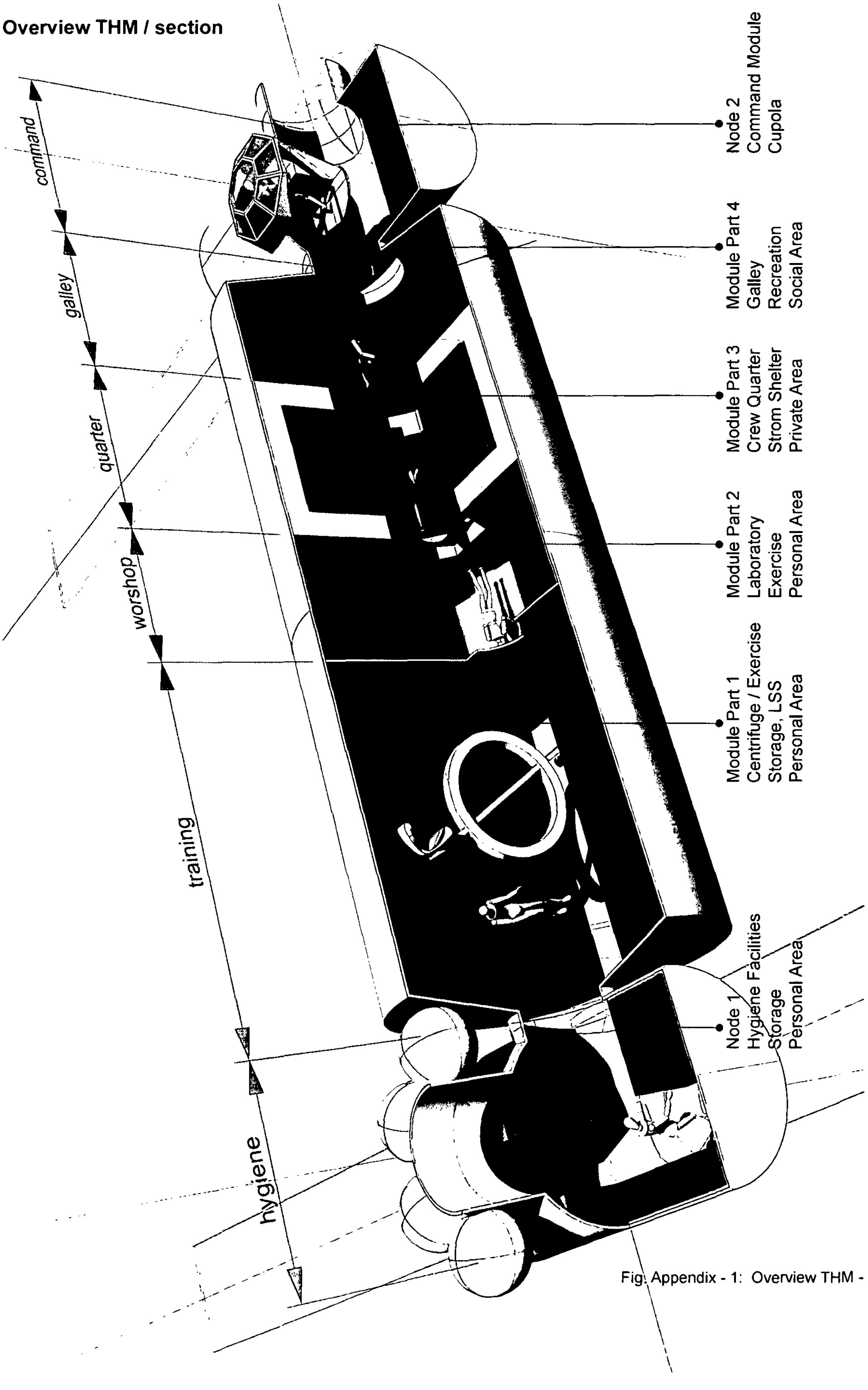


Fig. Appendix - 1: Overview THM - section

THM section

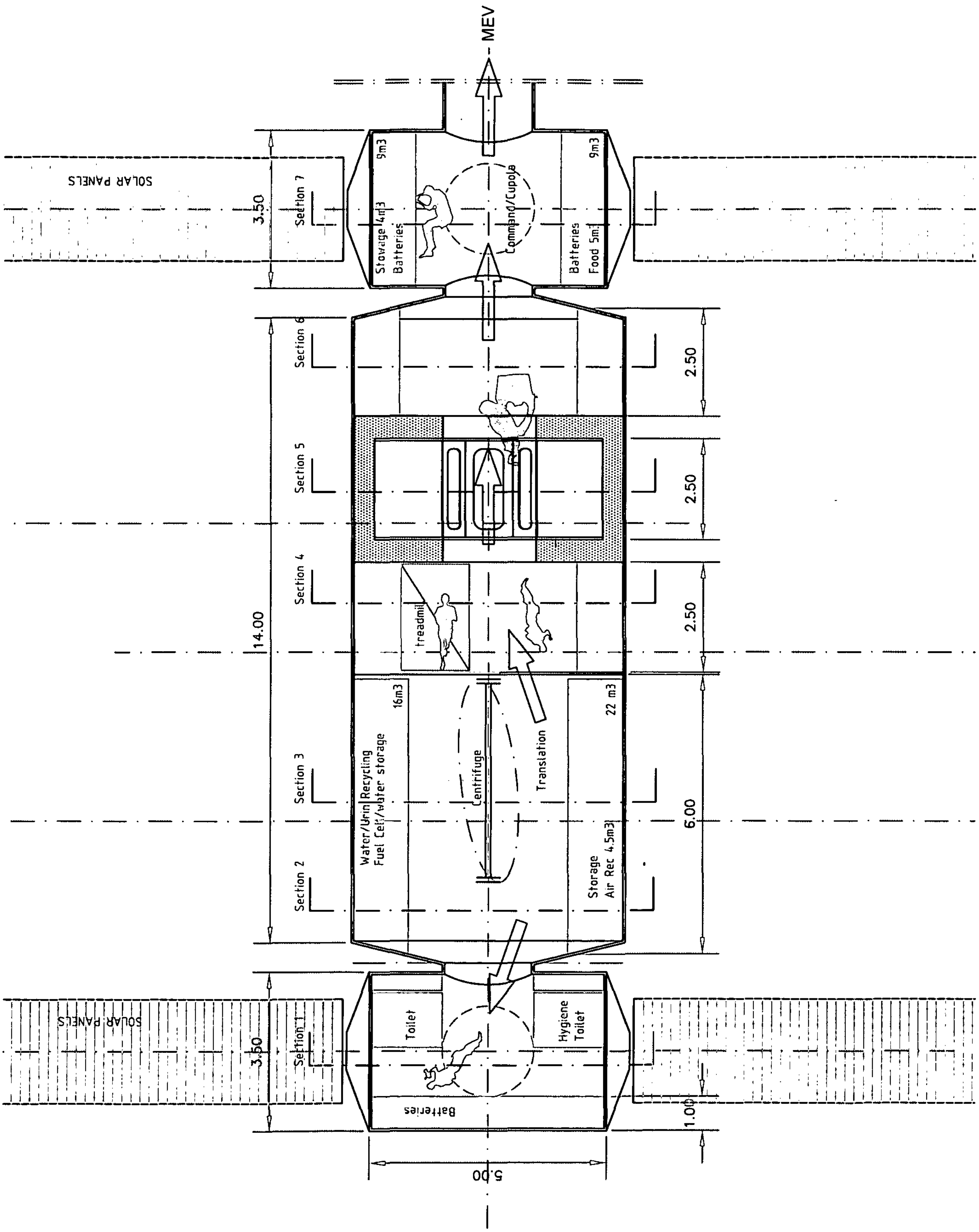


Fig. Appendix - 1-1: THM Section

Node 2 - Command Module

In Node 2 the core command interface is located. A cupola allows large visibility for command and control reasons (EVA visibility, possible spaceship damage etc.) and also for purposed of research (star observation) - (below Section 7)

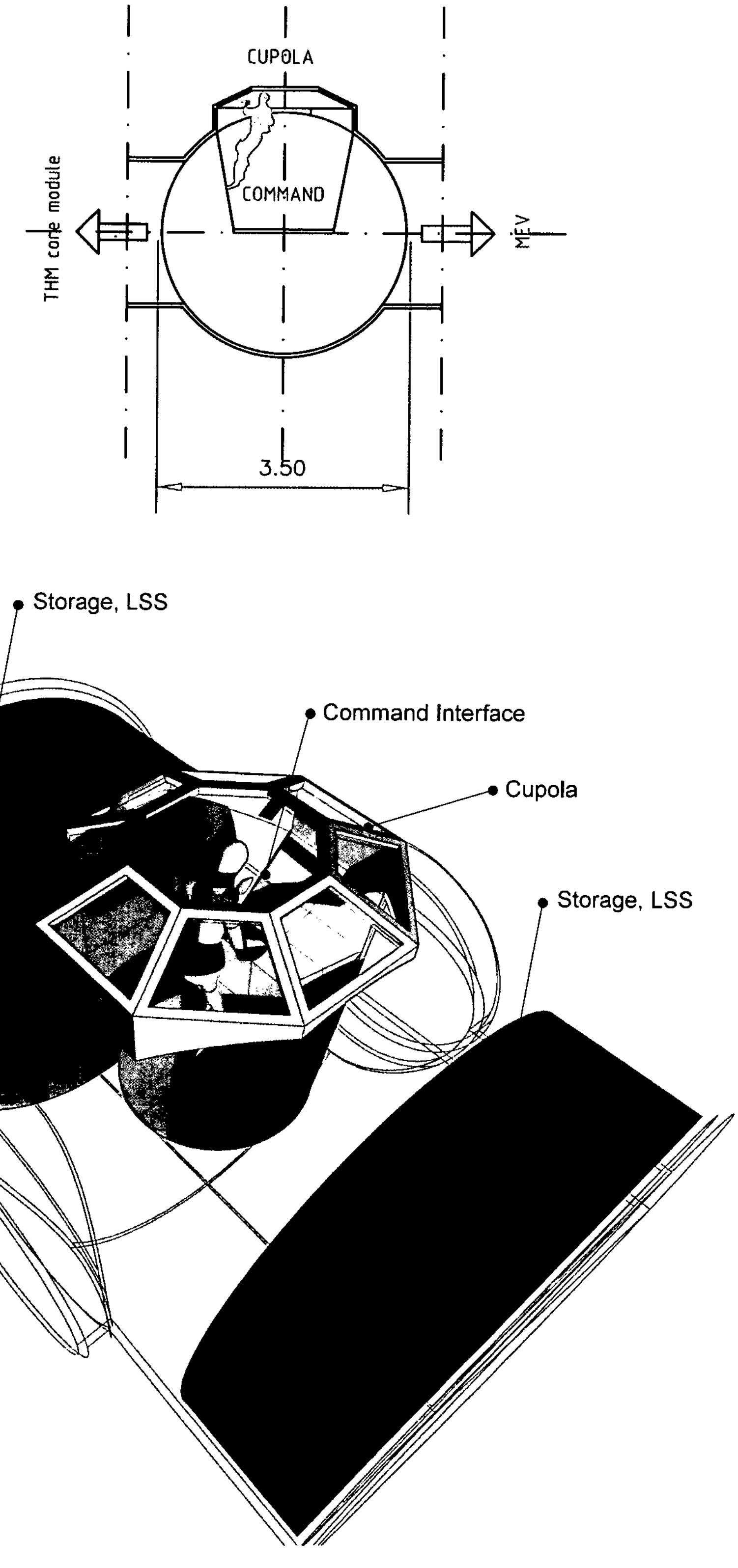


Fig. Appendix - 2: Node - Command Module

Galley - Recreational Zone

In the Module Part 4 the galley is situated. It is a social space and functions as a zone for gathering, recreation and communication with Mission Control and the families.
(left Section 6)

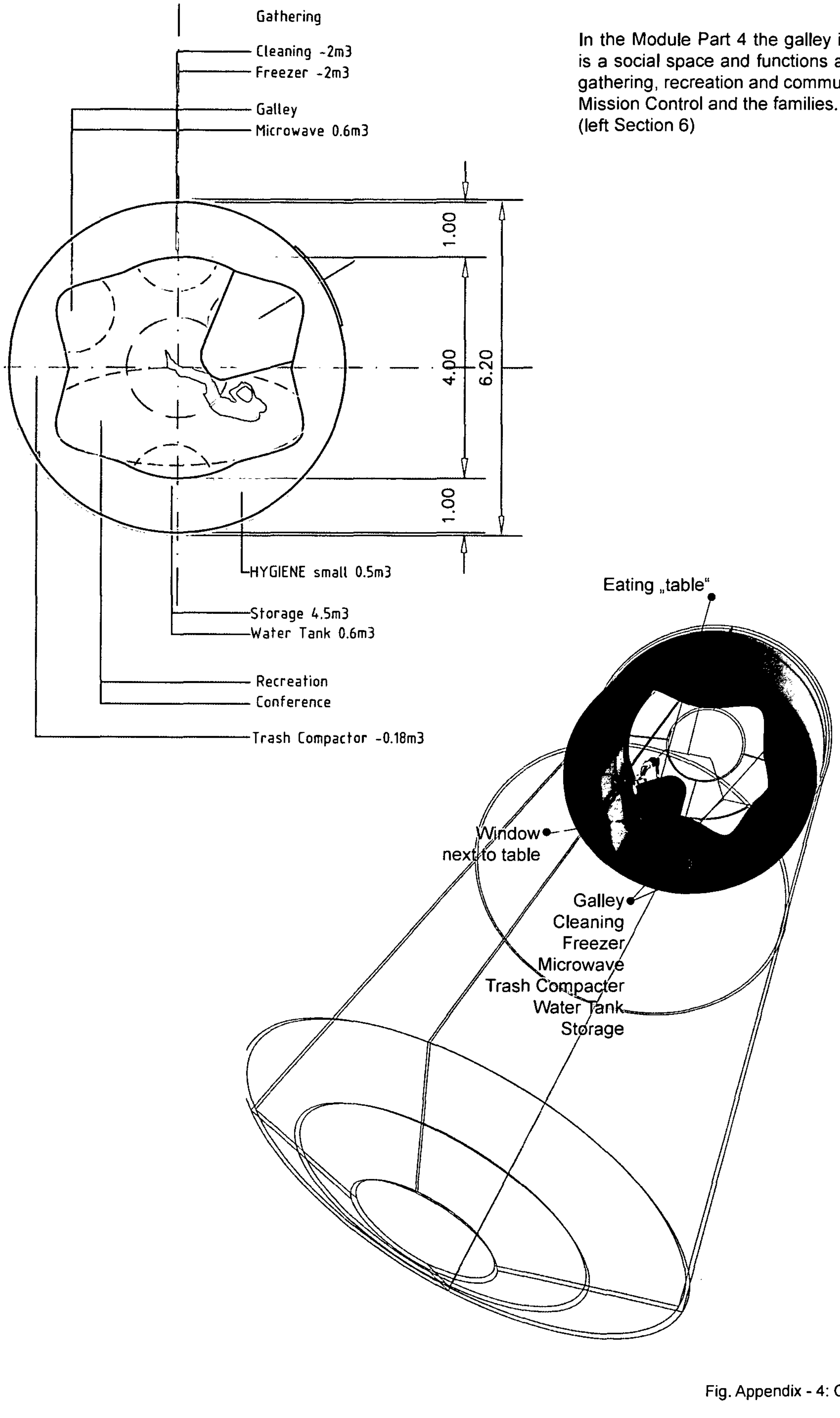


Fig. Appendix - 4: Crew Quarters

Crew Quarters - Storm Shelter

In the Module Part 3 the six crew quarters are arranged. They are protected by a 50cm wall holding water and food storage and serving as a safe zone in case of a solar particle event. The crew quarters are private areas with a central circulation zone for semi-private communication. (below Section 5)

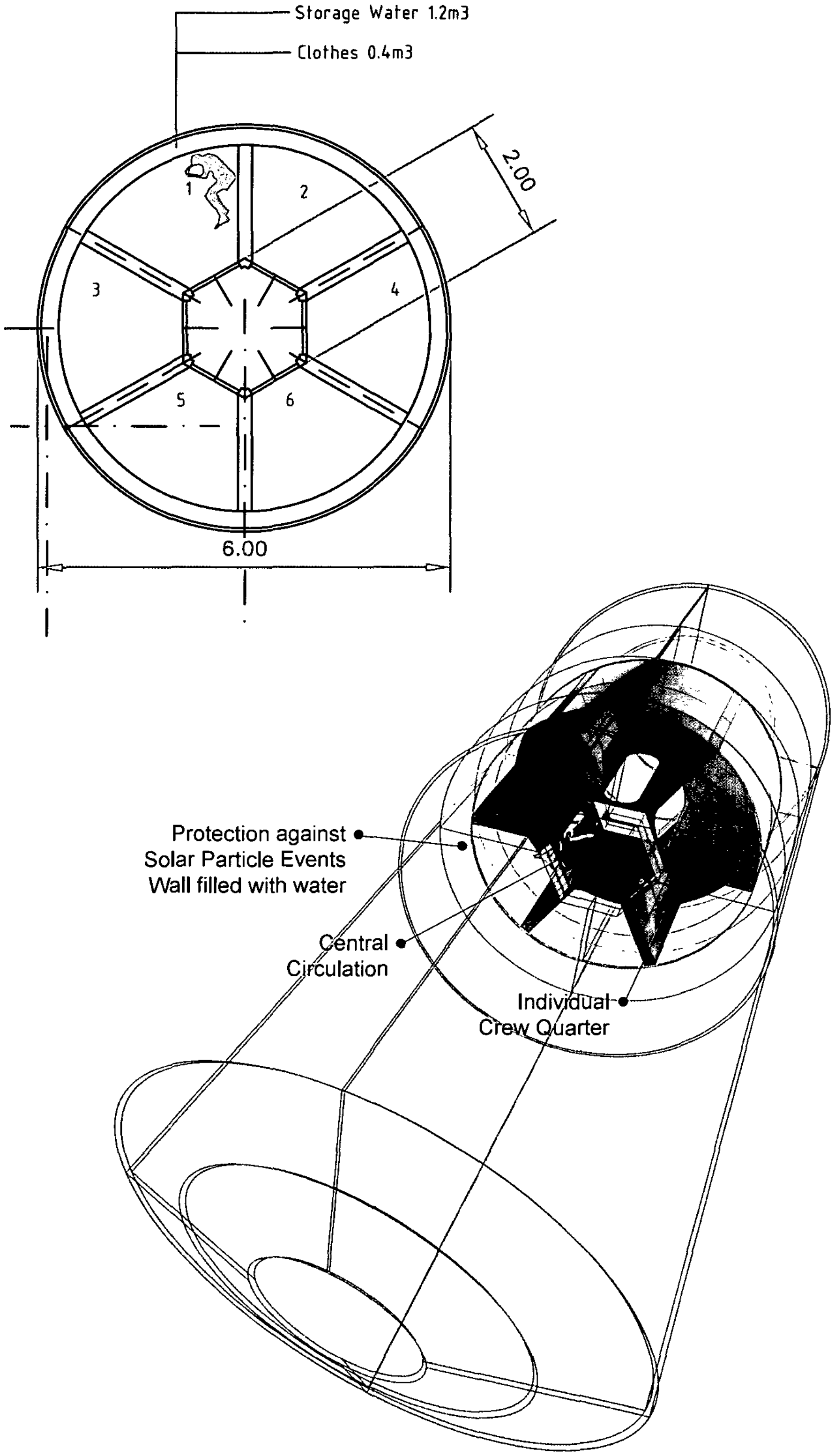


Fig. Appendix - 4: Crew Quarters

Science - Exercise

Module Part 2 consists of the personal area which includes the research laboratory and the exercise area. It houses training facilities such as treadmill or ergonometer. (below Section 4)

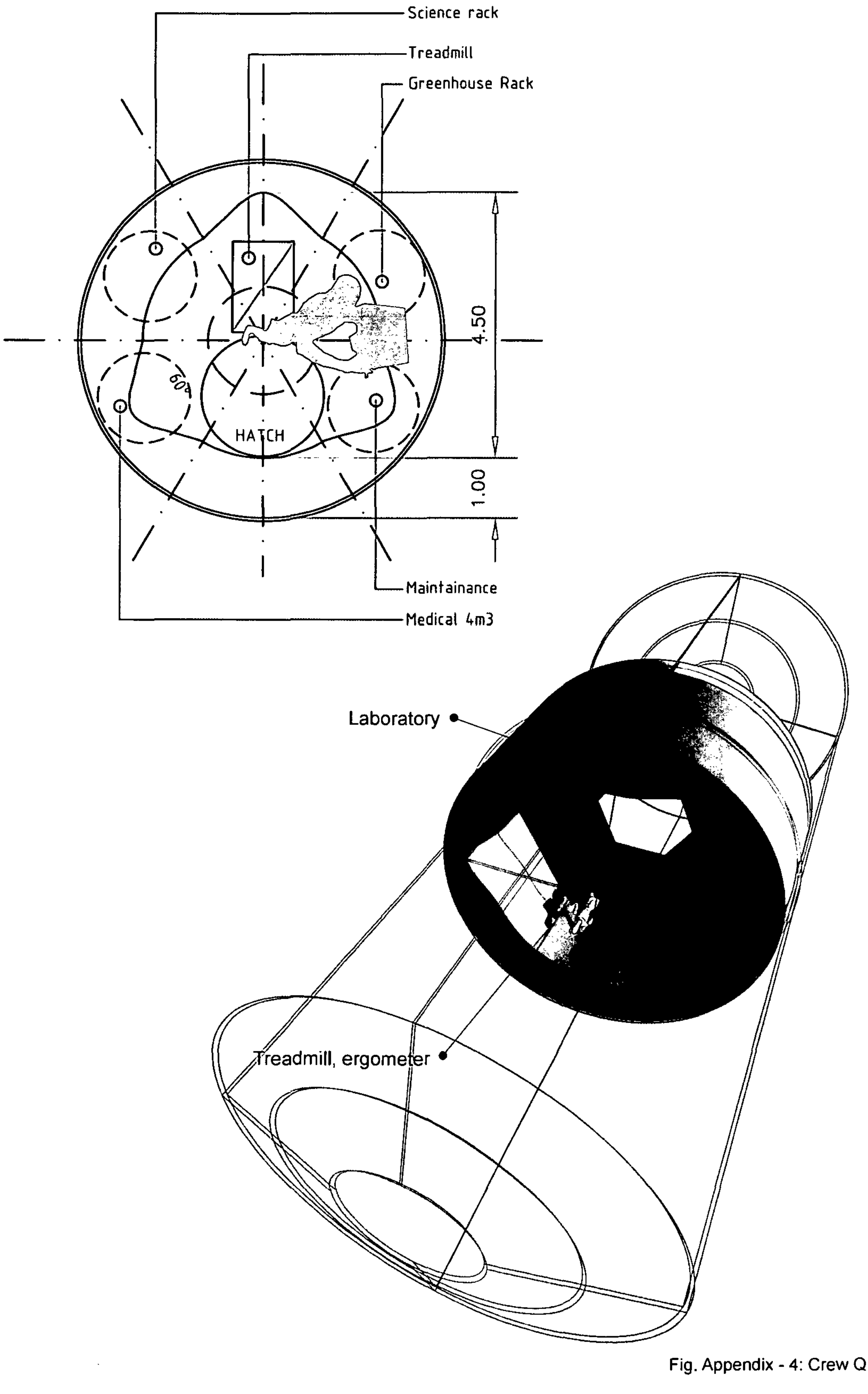


Fig. Appendix - 4: Crew Quarters

Training Zone - Centrifuge and Storage

Module Part 1 consists of the centrifuge area and the main part of the LSS, oxygen and nitrogen tanks and storage space. (below Section 2/3)

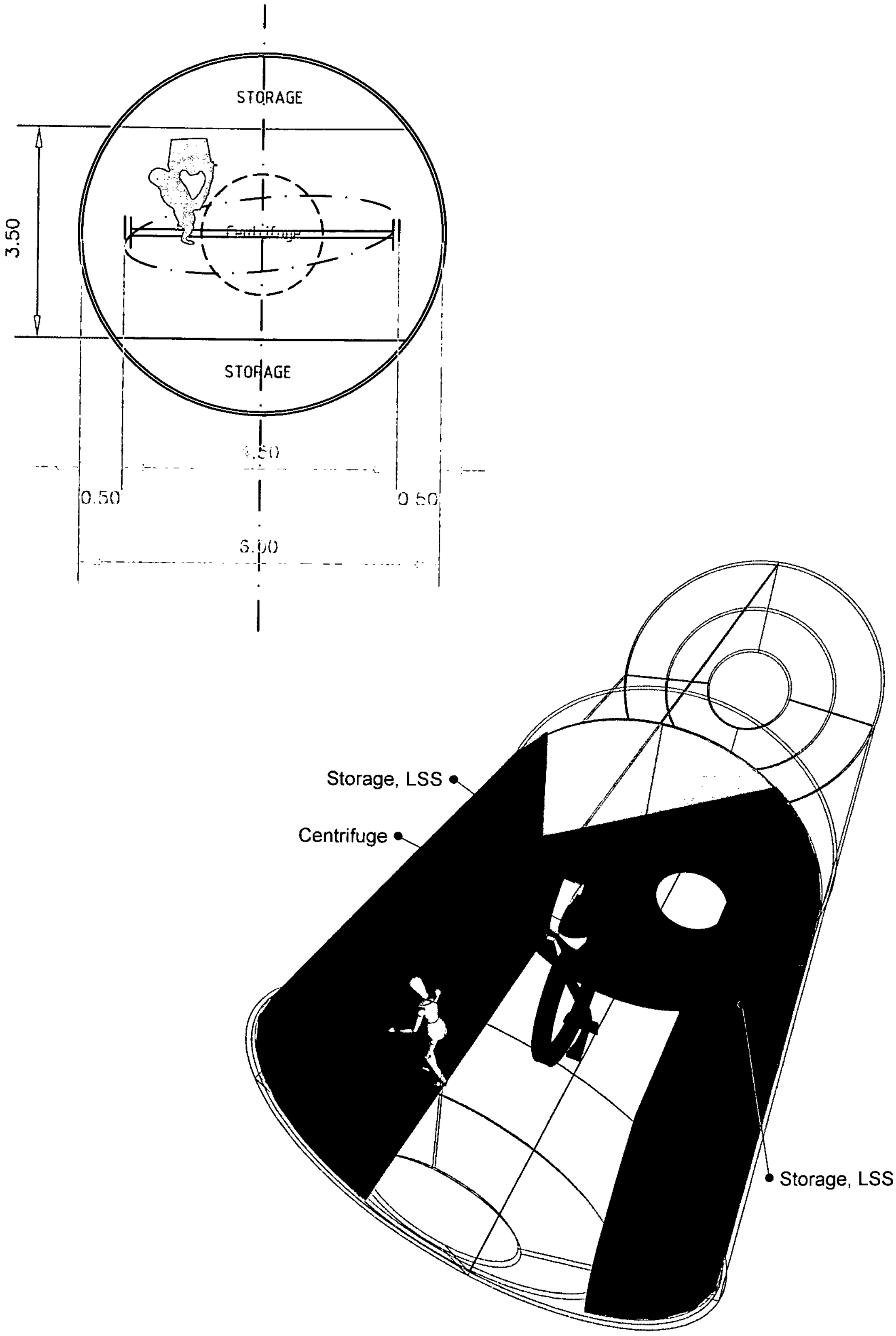


Fig. Appendix - 5: Training Zone

Hygiene Facilities

In Node 1 the the hygiene facilities are located. It is a personal area used by every crewmember. This area is noisy when used therefore it is in distance to the crew quarters but in vicinity to the exercise facility for comfortable use after training. Additional general storage space is foreseen. The node to the airlock and to the ERC are opposing each other on two sides of Node 1. (below Section 1)

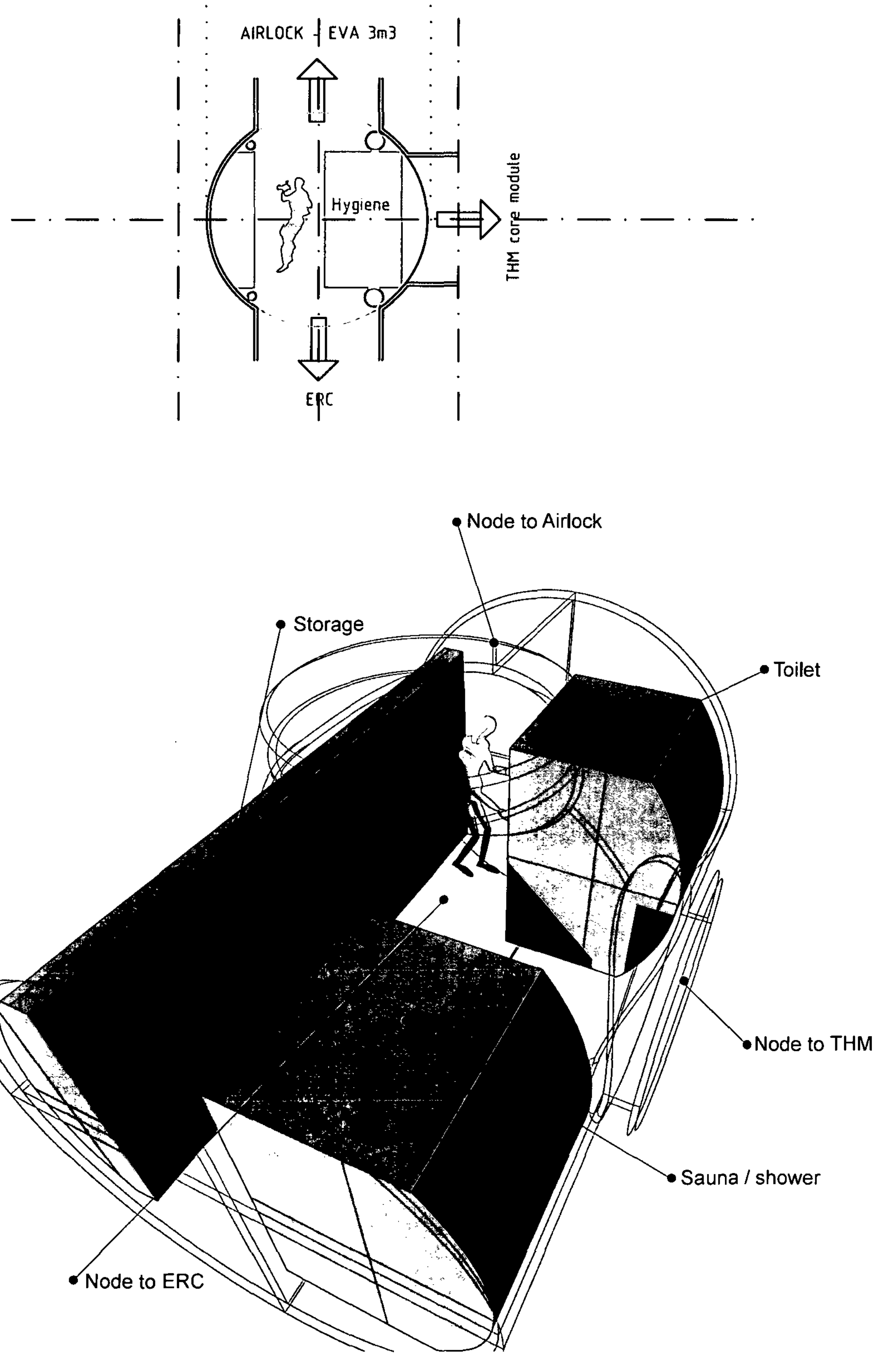


Fig. Appendix - 6: Hygiene Facilities

3.6 References - Part 3

Adams, C.; The Human System as a Primary Driver in Long-Duration Vehicle Architecture. Life Support and Biosphere Science, Vol. 7 No. 1, 2000. p. 97

Adams, C.; McCurdy, M. R.; Habitability as a Tier One Criterion in Advanced Space Vehicle Design, Part One: Habitability (SAE 1999-01-2137). 29th International Conference on Environmental Systems (ICES), Denver, Colorado, USA, 12-15 July 1999.

Adams, C.; Four Legs in the Morning: Issues in Crew-Quarter Design for Long-Duration Space Facilities (SAE 981794). 28th International Conference on Environmental Systems (ICES), Danvers, Massachusetts, USA, 13-16 July 1998.

Cohen, M. M.; Habitat Distinctions: Planetary versus Interplanetary Architecture (AIAA 96-4467). Space Programs and Technologies Conference, Huntsville, Alabama, USA, 24-26 September 1996. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Cohen, M. M.; Space Habitat Design Integration Issues (SAE 981800). 28th International Conference on Environmental Systems (ICES), Danvers, Massachusetts, USA, 13-16 July 1998

Anderson, B.; The Greenhouse Effect - Living with Plants in Other Worlds, http://www.lpi.usra.edu/publications/newsletters/lpib/lpib85/plants.html

Connors, M.; Harrison A.; Living Al oft: Human Requirements for Extended Spaceflight, Government Printing Office, 1985, http://history.nasa.gov/SP-483/ch1-4.htm

Drysdale, A. E.; Maxwell, S.; Systems Analysis of Life Support for Long-Duration Missions, 2000-01-2394, Proceedings of the 30 th International Conference of Environmental Science (ICES)

Eckart, P.; Space Flight and Lifesupport and Biospherics, Kluwer, Microcosm, Inc., Academic Space Technology Library, March 10, 1997

Gruber, C., Leben und Arbeiten im All, Wissenschaft und Technik Verlag, Berlin, 1996

Harrison, A.; Clearwater Y.; McKay, C.P.; From Antarctica to Outer Space - Life in Isolati on and Confinement, Springer Verlag, 1991

HUMEX, Study on the Survivability and Adaptation of Humans to Long-Duration Interplanetary and Planetary Environments, ESTEC/Contract No. 14056/99/NL/PA

Imhof, B.; In the Simulator (Architecture, Technology and Innovation), Interview with Fred Smith, Simulation Astronaut, NASA, 26.08. 2003, Radio Orange

Imhof, B.; Schartner, H.; Mars Surface Habitats: Architectural Designs and Concepts for Planetary Outposts (SAE 2001-01-2174). 31st International Conference on Environmental Systems (ICES), Orlando, Florida, USA, 9-12 July 2001

Kring, J.; Human Consideration in the Design of Closed Environmental Systems, Life Support and Biosphere Science, vol. 7, no. 1, 2000

Larson, W.; Pranke, L.; Human Spaceflight, Mission Analysis and Design, The McGraw-Hill Companies Inc., Space Technology Series, 1996

Lucid, S.; Flight Crew Support Division Debrief Transcript on Habitability on Mir, 10/15/96, NASA, JSC

Man-System Integration Standard, Vol. 1, NASA STD 3000, Rev.B (1995), NASA-Johnson Space Center, Houston, TX

NASA Mars Exploration Study Team, Human Exploration of Mars, Johnson Space Center, Houston, Tx, 1997

Space Architecture, Architectural Design, Wiley-Academy, Vol.70, No 2, March 2000 London, GB

University of Houston, SICSA Outreach, Manned Missions to Mars: Planned Bold Journeys into Tomorrow, Saskawa International Center for Space Architecture, vol.3 1990

4 The Development of the Surface Habitat Mars (SHM)

4.1 Architectural and Habitability Requirements and Recommendations for a Partial Gravity Surface Habitat

4.1.1 Requirements: Mass and Volume Calculations

The requirements are based on volumetric and mass standards, which have been established by NASA, ESA and RSA throughout the years of their experience. This forms the basis for the architecture/ interior configuration part of the SHM.

4.1.2 Recommendations

To complement the requirements and figures, a number of recommendations has been developed. Some are based on interviews of ESA astronaut Frank de Winne, RSA cosmonauts and NASA simulation/isolation experts, some derived from the book "Human Spaceflight – Mission Analysis and Design" (referred to as „Human Spaceflight"), and others taken from papers or interviews referenced below. At the same time, the following tables reflect personal work experience with the architecture/interior configuration part of human space missions. As long duration human spaceflight requires a new set of spatial conditions due to the critical success factor of human survival, the emphases of the following guidelines include issues of psychology and perception of interior space, as well as the relationship between the human inhabitant and the inhabited space.

In addition to the NASA Standards 3000 (STD), the recommendations for the SHM and the respective sources are listed in the table below (some of the recommendations are similar to those of the THM and appear here again, some are specific only to the SHM and the 30-day surface stay of the crew):

Architecture General

Recommendation	**Rationale**	**Examples**	**Reference**
GENERAL			
Anthropometric design and layout	• Different muscular effort in 1/3g	Different design requirements for workstations, clothing and equipment 1/3g	Human Spaceflight, p147
Socialization	• Support social cohesion • Reduction of interpersonal tension • Short term stay on Mars	• Areas designed for group interaction (dining, wardroom, group work sites)	1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One-- Habitability Constance M. Adams, AIAA
Privacy	Individual crew activities such as sleeping, personal communications	Separation of private crew quarters from • Public view • Sounds • Vibrations • From each other	1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One-- Habitability Constance M. Adams, AIAA
Recognition of cultural differences	Social and psychological benefits	Adopt common tools e.g. for leadership	Human Spaceflight, p174
COMPONENTS			
Clothes	• Mass reduction of textiles • Self-cleaning clothes • No clothes	Short term stay on Mars	
Permanent dining table	To prevent separation of the crew (eating places and hours)	Table for whole group	1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One-- Habitability Constance M. Adams, AIAA

Laboratory-glove boxes	Contamination prevention, immediate research	2 laboratories (one during the flight and one on Mars) to keep the crew active with meaningful work	
Radiation shielding	Galactic Cosmic Rays (GCR) • Constant isotropic bombardment by GCRs poses a special concern, which mission planners are only beginning to recognize • High mass / cm2		AIAA-96-4467 Habitat Distinctions: Planetary versus Interplanetary Architecture Marc M. Cohen
	Solar Particle Event (SPE) Extra "satellite" for prediction of solar flares because Earth cannot accurately measure the Spaceship's trajectory	Storm shelter	
Windows	Provide the ability to • observe specific objects and activities outside the habitat • look beyond the confined environment. • Virtual windows enhance the physical space and environment and provide diversity to the confined space • The need for windows depends on exact function of CQ – i.e. to live in or only sleep in.	Observation of exterior of module, EVA and robotic operations Windows in private crew quarters with automatic shutters (radiation, micro-meteorite protection?)	981800 Space Habitat Design Integration Issues Marc M. Cohen -----cosmonaut rec. BIOPLEX (Fred Smith in an interview)
Doors	Provide • sealable pressure port within habitat modules • pressure port between habitat and deep space/Mars	To close hatches between volumes quickly and easily in case of emergency	
Exercise	• Fitness • countermeasures • Social benefit • Short term stay on Mars	• Exercise in small groups (exercising together, social sport activities)	981800 Space Habitat Design Integration Issues Marc M. Cohen
Personal Hygiene	• Astronauts can perform part of their body hygiene in privacy • Changing clothes		1999-01-2137 Habitability as a Tier One Criterion in Advanced Space Vehicle Design: Part One--Habitability Constance M. Adams, AIAA
Greenhouse	• Fresh chives • Keeps the crew busy • Crew can take care of organic creatures and get feed-back, i.e. plant changes, grows etc.	Benefits for psychology, scientific, experiments, food add-ons	SAE 2001-01-2174 Mars Surface Habitats: Architectural designs and concepts for planetary outposts, Imhof/Schartner

Fig. 4.1.2 - 1

The following issues referring to the discipline of architecture become especially relevant in studies dedicated to human long term missions, such as a human missions to Mars or a permanent outpost on the Moon. The sub-themes such as adjacency and separation derive from the spatial arrangement of the individual functions in the Mars Surface Habitat.

Architecture Configuration

Recommendation	Rationale	Examples	Source
ADJACENCY and SEPARATION			
Simultaneous crew activities to be located far enough apart	Reduces the probability of accidental interference		Human Spaceflight, c. 6/p.133
Easy access to potential trouble spots (leak points, motors, valves, controllers)	Easy repair and adjustments	In an unpressurized environment repair is only possible by astronaut EVA	981800 Space Habitat Design Integration Issues Marc M. Cohen
Emergency routes at every stage of the habitat		No equipment blocking emergency routes	Human Spaceflight, c. 6/p.133
Protection from electronic magnetic interference	Communications and computation equipment may be interfered	• Physical separation of power cables from computer systems and data cables • Layout of raceways	981800 Space Habitat Design Integration Issues Marc M. Cohen
Mechanical systems (motors, pumps, LSS, waste management, toilets) far away from crew quarters	Sound ,vibration and odor control		981800 Space Habitat Design Integration Issues Marc M. Cohen
Separating waste management from food preparation and dining	Hygienic and aesthetic reasons		981800 Space Habitat Design Integration Issues Marc M. Cohen
Toilet far away from crew quarters	Noisiest item during sleep periods		Human Spaceflight, c. 6/p.133
Multiple volumes	• Fire • Contamination • Loss of pressure • Event x	At least two separate, isolatable pressurized volumes within the habitat core so crew can retreat from one volume to the other in contingency situations.	981800 Space Habitat Design Integration Issues Marc M. Cohen
FLEXIBILITY OF USE			
Crew autonomy			
Flexible design of workstations	Access to control systems from more points in any module	• Elimination of dedicated workstations with their displays and controls • Portable computers • More autonomous working	Human Spaceflight, c. 6/p.133

Fig. 4.1.2 - 2

For the Surface Habitat on Mars flexibility of use is important but also hard to fullfill within such a restricted space of only 75 m3 for 30 days for three people. Here it might be the little things which will matter in this respect, e.g. a foldable table might make a difference in the end.

With long duration stays and the increase of the crew's stressors, communication with "home" becomes one of the major issues. During a Mars surface stay there will be a communication delay with Earth between 20 and 40 minutes so ,live'communication is not possible. There need to be other means such as video documentary to send via satellite communication or other interactive communication interfaces which are not dependent on time.

Communication

Recommendation	Rationale	Examples	Reference
2-way-communication	• Contact to home (family, children, friends) • Solving the problem of time delays – creating new ways of communication / recording Adding elements of with physical perception that need no real time data transfer	• Confidential and direct and simultaneous • Video-conference, messaging • Alternative communication channels: voice and other auditory information, tactile, sensory, others	Human Spaceflight, p165 Interview Valery Polyakov (TV program "Modern Times Spezial", ORF)
Responsibility and authority for crew	Ground support decreases with increasing distance		Human Spaceflight, p173
Psychological support during entire mission	Prevention and optimization of performance dysfunction in crewmembers	• Private consultation • Self-sufficient psychological tools (no dependency on Earth-based resources) • Virtual reality stimulation	Human Spaceflight, p151, 173

Fig. 4.1.2 - 3

The texture and materiality of interior spaces is considered to be a stimulating factor for the crew's health and productivity. The problem of noise must also be addressed in the design for future space habitats, and is to be solved in a way that ensures noise levels are reduced to a level of comfort.

Lighting, Color And Sounds

Recommendation	Rationale	Examples	Reference
Visual stimulation	• Psychological well-being • Performance	Through color, lighting, sounds	Human Spaceflight, p145

Fig. 4.1.2 - 4

4.1.3 Design Drivers

- 1/5 of the volume has to be dedicated to ducts and pipes

- Easy access to all ducts and pipes for maintenance is required, a well designed system and structure supports easy maintenance

- For safety reasons, all systems (LSS, AOCS, etc.) should be modular in principle; plug-and-play parts, so to speak: if a part fails in one place the astronaut can transfer it to a different place.

- Enough fire detectors and isolation and recovery systems should be provided to enhance crew safety.

- The LSS of the Mars Ascent Vehicle (MAV) should function independently from the Surface Habitat (SHM) so there are two air-tight compartments:
  1. MAV
  2. SHM

4.2 Process of the Design Concept for the SHM

In the following the flow of concepts were analyzed (during CDF consecutive sessions):

4.2.1 Basic Configuration Options for the SHM

The whole architecture, which will land on Mars – Mars Excursion Vehicle (MEV) – consists of two parts: the Mars Ascent Vehicle (MAV) and the surface Habitat (SHM).

In the Mars orbit, the crew will transfer from the Transfer Habitat (THM) to the MAV. Having landed on the surface, the crew uses the tunnel or an EVA to reach the SHM. This depends on the configuration of the whole MEV.
In the following chapter, two initial configurations are described in more detail: a configuration with and one without a transfer tunnel.

4.2.1.1 Configuration 1

A transfer tunnel leads from the MAV to the upper level of the habitat (marked as red zone). This implies changes in the size of the propulsion tanks for the first and second stage. Four tanks per stage with dm = 1750mm each instead of 6 tanks dm = 1540mm.

Advantages of having the crew transfer from the MAV to the SHM via a tunnel are as follows:
There is no need for 6 airlocks (because each crew member needs one suit and needs to dock first from the MAV and then to the SHM when transferring) - therefore it is assumed that mass for the airlocks is saved in using a transfer tunnel. If something happens to the Mars suits the crew can still stay on Mars for 30ays, which would not be possible if they were unable to leave the MAV (Mars Ascent Vehicle) They could do useful work, e.g. picking samples with a robotic arm. Emergency access to the Ascent vehicle is faster via a tunnel than an EVA – a better escape possibility.

For the internal layout, a 3-compartment-configuration with a vertical orientation was chosen:
The upper level (marked in red) with the crew quarter (private zone) and the hygiene facilities can serve as a storm shelter. It requires less mass for protection than housing the whole habitat.
The main level (below the red zone) is the main social and working area (social/communal zone) and provides space for food preparation and dining.
The EVA level with the airlock at the bottom provides a safe shelter for the suits and propulsion, making the EVA preparatory space a safe compartment (personal zone)

All the compartments are not air-tight and sealed, but in case of emergency they provide a certain protection from each other.

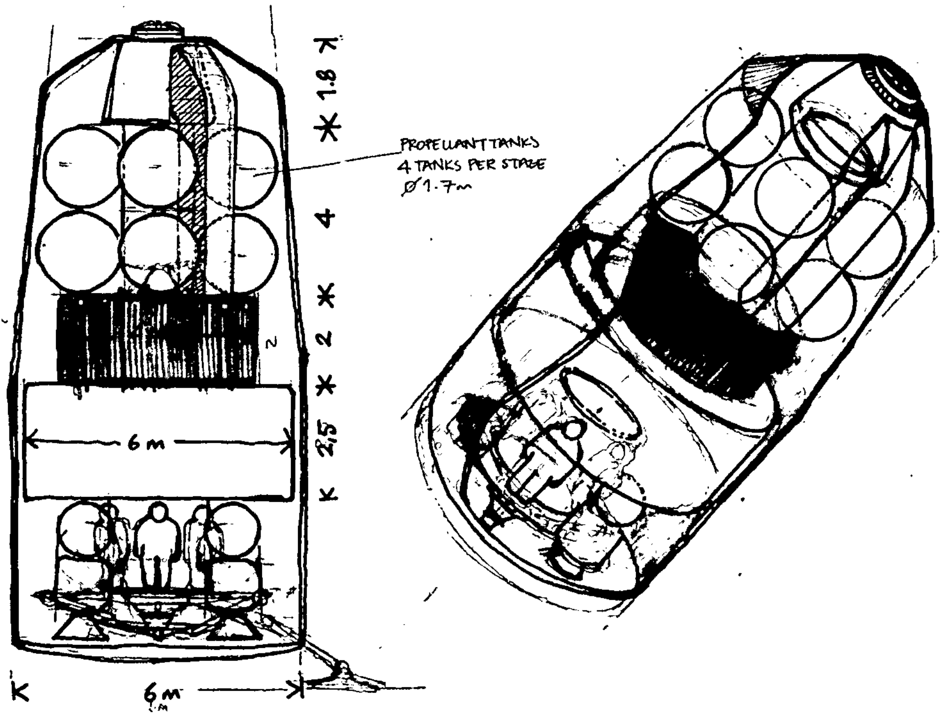


Fig. 4.2.1.1 - 1: left: section, right: axonometric view, Configuration 1

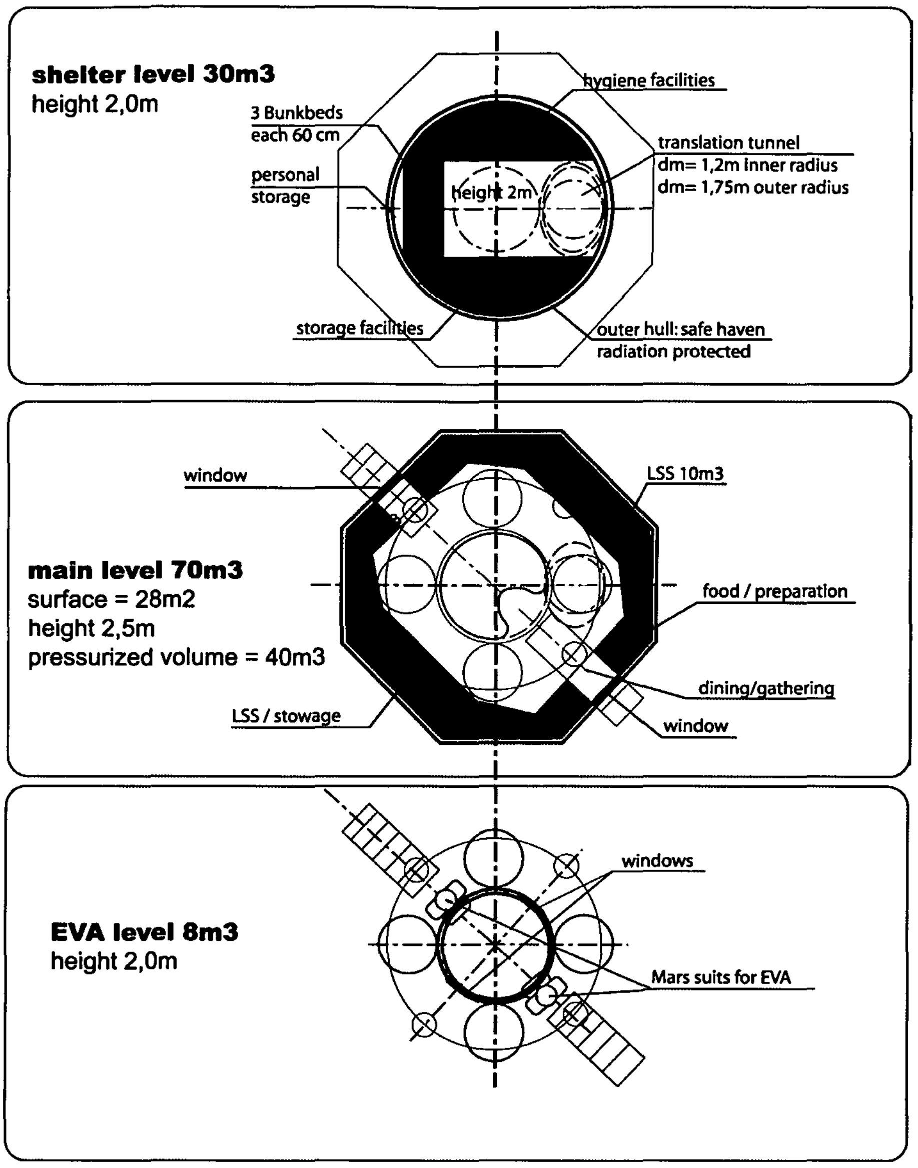


Fig. 4.2.1.1 - 2: Configuration 1 – internal layout of all 3 levels

4.2.1.2 Configuration 2

This option has no transfer tunnel. The crew translates in their Martian suits from the MAV to the SHM. In case the SHM has a failure the crew could still get some rock samples from the surface and go back to the orbiting THM.
This option does not decrease the total mass because not only three, but 6 airlocks are needed to dock the suits first to the MAV and then to the SHM. Both systems, especially the MAV would become heavy. The configuration has to be failure save. In this option the crew has to escape by getting into the suits and then to the MEV in case of an emergency event.

Basic ideas as to whether the structure should be a hard shell module or hybrid with inflatable parts were investigated: all the equipment and infrastructure was accommodated in the hard shell, which makes maintenance easier for the exhausted crew and requires no additional crew training. In the inflated parts there is space for the crew quarters and some training options. The Core-Habitat is sheltered. In case of a storm the habitat folds together.

Using a hybrid structure would allow slightly more space for the same amount of mass, considering the fact that inflatables are lighter. This still needs to be investigated better and proved on an engineering level.

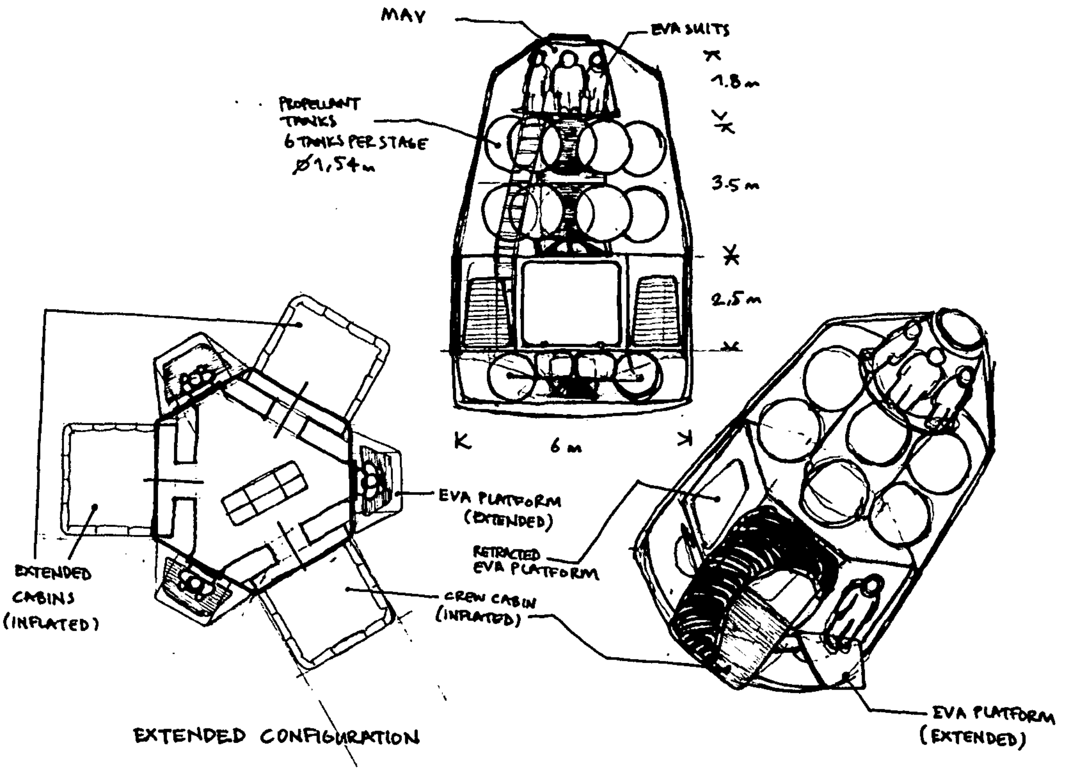


Fig. 4.2.1.2 - 1: plan with deployed parts (left) and section top right, far right: axonometric view - Configuration 2

The Mars suits would be fixed to foldable platforms. During an EVA the platform folds down to allow the astronaut to climb down to the surface. In this one-floor module design three inflatable cabins are located next to the EVA platforms. The hexagon shape was considered to be more space efficient for the main module.

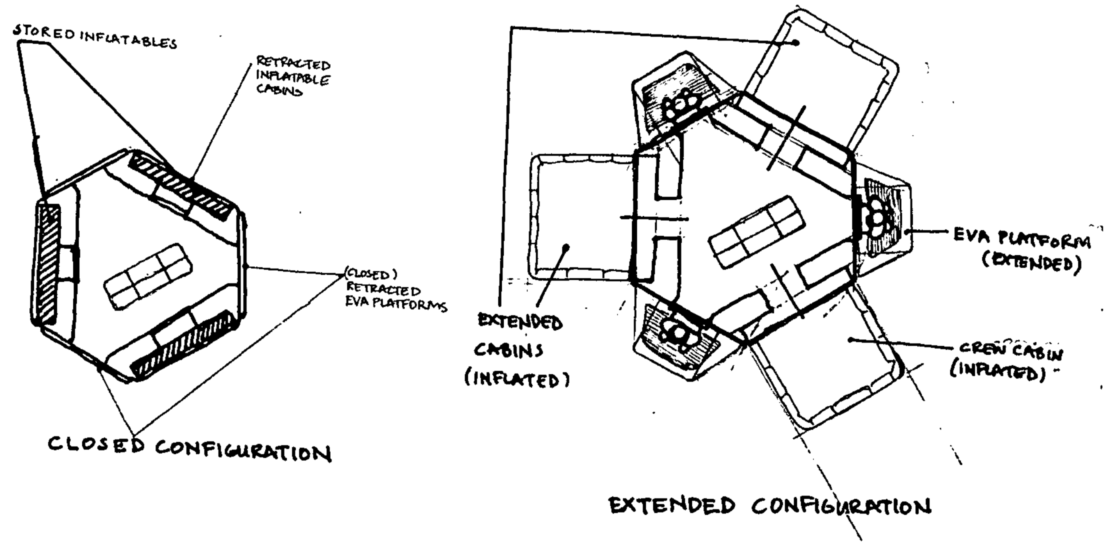


Fig. 4.2.1.2 - 2: plans - left: closed configuration, right: extended

Finally this kind of configuration was discarded because of the external transfer from the MAV to the SHM and the problems of airlock mass, procedures and emergency.

4.2.2 Interior Configuration for the SHM

The next step was to consider the possibilities of using inflatables and deployable structures to extend space to profit from a lighter structure and to ensure better habitability standards. Several options are listed here: (The transfer was always using a tunnel, which connected the MAV to the SHM.)

4.2.2.1 Option 1

The Core-habitat has one possible extension.

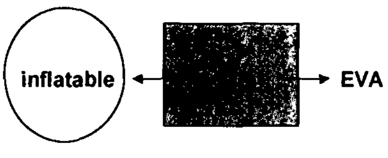


Fig. 4.2.2.1 - 1: Diagram - Option 1, paradigm: one-side expanding

One inflatable "arm" provides additional space for private crew quarters. The inner core serves as storm shelter and bears the main infrastructure such as the LSS, the hygiene facilities, the storage and the galley. two EVA suits are fixed to the outer shell.

The total habitat is 37 m3, which is far too little according to the assumed minimum volume. Later in the study progress it was decided that the minimum surface is 20 m2, with a minimum ceiling height of 2.5 m, which adds up to approximately 75 m3. The distribution of space should have the relation of 1/3 of stowage space (25 m2) and 2/3 of habitable space, which adds up to 50 m3. So Option 1 was discarded because of the lack of volume.

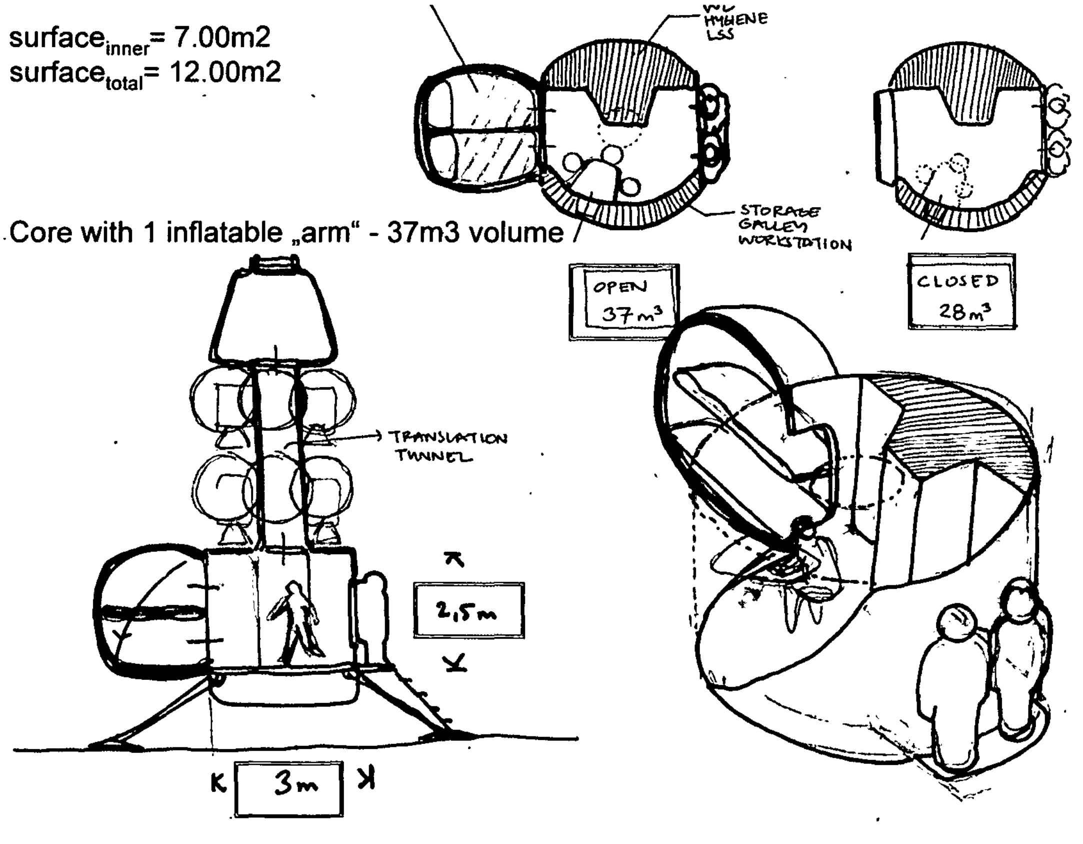


Fig. 4.2.2.1 - 2: Sketch (left: sectional sketch, top right: plans of main deck with and without inflated extension, bottom right: axonometric view) - Option 1

4.2.2.2 Option 2

The Core-habitat has a two-storey possible extension at the side.

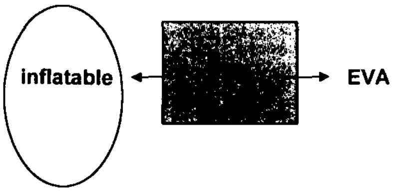


Fig. 4.2.2.2 - 1: Diagram - Option 2, paradigm: 1-side and below - expanding

The total habitat volume is ~ 50 m3. The inflated space is divided into two levels. The upper level houses the private crew quarters and the lower level provides additional working space. The inner core serves as storm shelter and bears the main infrastructure such as the LSS, the hygiene facilities, the storage and the galley. Also this option was discarded because it provides too little volume. These investigations provided the basis for defining volume requirements for the actual volume.

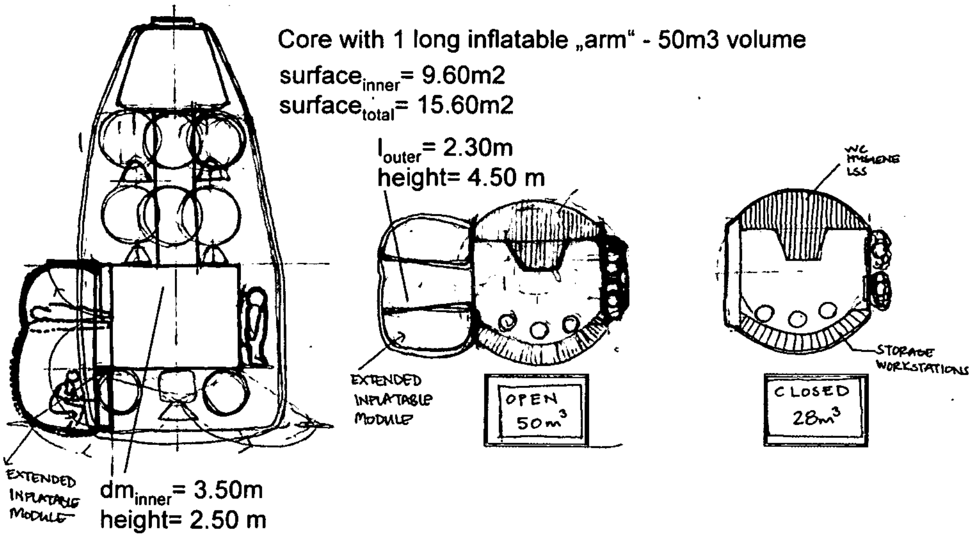


Fig. 4.2.2.2 - 2: Sketch (left: sectional sketch, right: plans of main deck with and without inflated extension) - Option 2

4.2.2.3 Option 3

The core habitat has three possible extensions, two at the sides and one below for EVA.

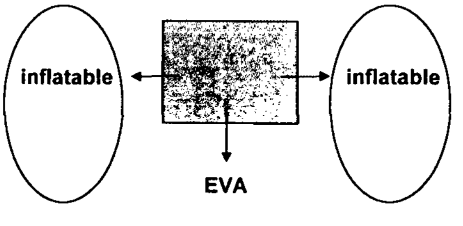
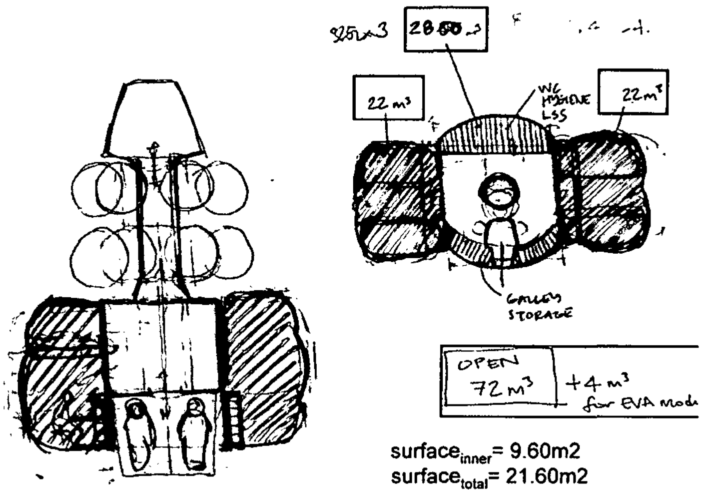


Fig. 4.2.2.3 - 1: Diagram - Option 3, paradigm: 2-side expanding, EVA below

The 28 m³ Core can be expanded to 72 m³. The process of developing towards the finally required 75m³ becomes obvious. The two two-storey extensions are used as private crew-quarters and additional working space. The inner core serves as storm shelter and bears the main infrastructure such as the LSS, the hygiene facilities, the storage and the galley. EVA access is from below to create a semi protected zone for the Mars suits from sand storms.



Center Core with 2 inflatable volumes - 72m3 volume

Fig. 4.2.2.3 - 2: Sketch (left: sectional sketch, right: plan of main deck) - Option 3

4.2.2.4 Option 4

The inflatable module deploys all around the core module, the EVA-access is below.

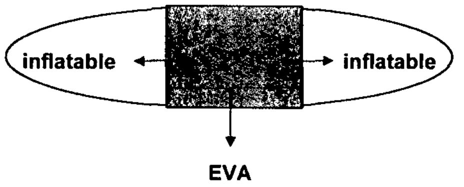


Fig. 4.2.2.4 - 1: Diagram - Option 4, paradigm: all-around expanding, EVA below

The whole habitat is deployed through inflating a torus-shaped volume. When inflated it provides translation space and crew quarters. The infrastructure is installed in the core, which is a hard-shell element. It serves as a storm shelter and bears the main infrastructure such as the LSS, the hygiene facilities, the storage and the galley. To perform an EVA, the astronauts get into the pre-breathing chamber below the core-habitat before exiting onto the surface in their suits.

Center Core with inflatable „torus" - 70m3 volume

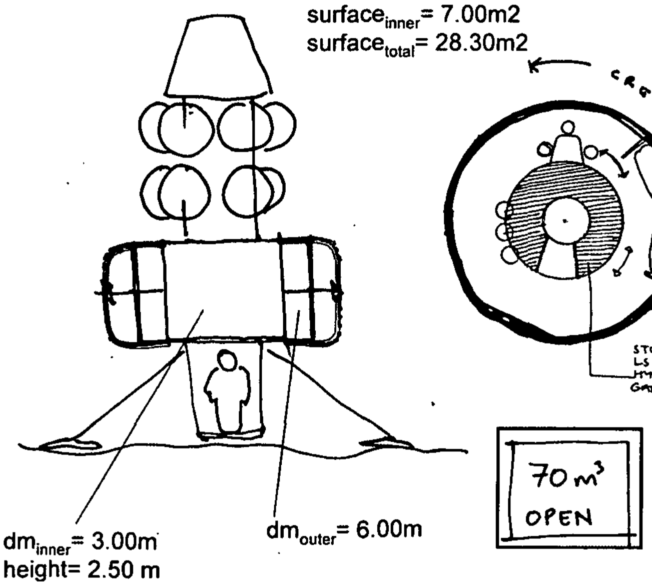


Fig. 4.2.2.4 - 2: Sketch (left: sectional sketch, right: plan of main deck) - Option 4

4.2.2.5 Option 5

This option has one possible extension for the habitat and one for the EVA area.

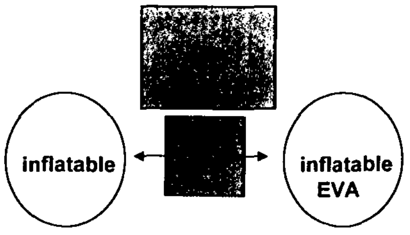


Fig. 4.2.2.5 - 1: Diagram - Option 5, paradigm: 2-side expanding with EVA on lower level

At the lower level is the EVA area, the pre-breathing chamber and an inflatable workstation module. The upper level comprises the private crew quarters and the main social and working area. The total volume is 71 m³ with a surface of 21 m². The upper level has a total volume of 53 m³ with a surface of 12.5 m², while the lower level has a volume of 18 m³ with a surface of 8.5 m².

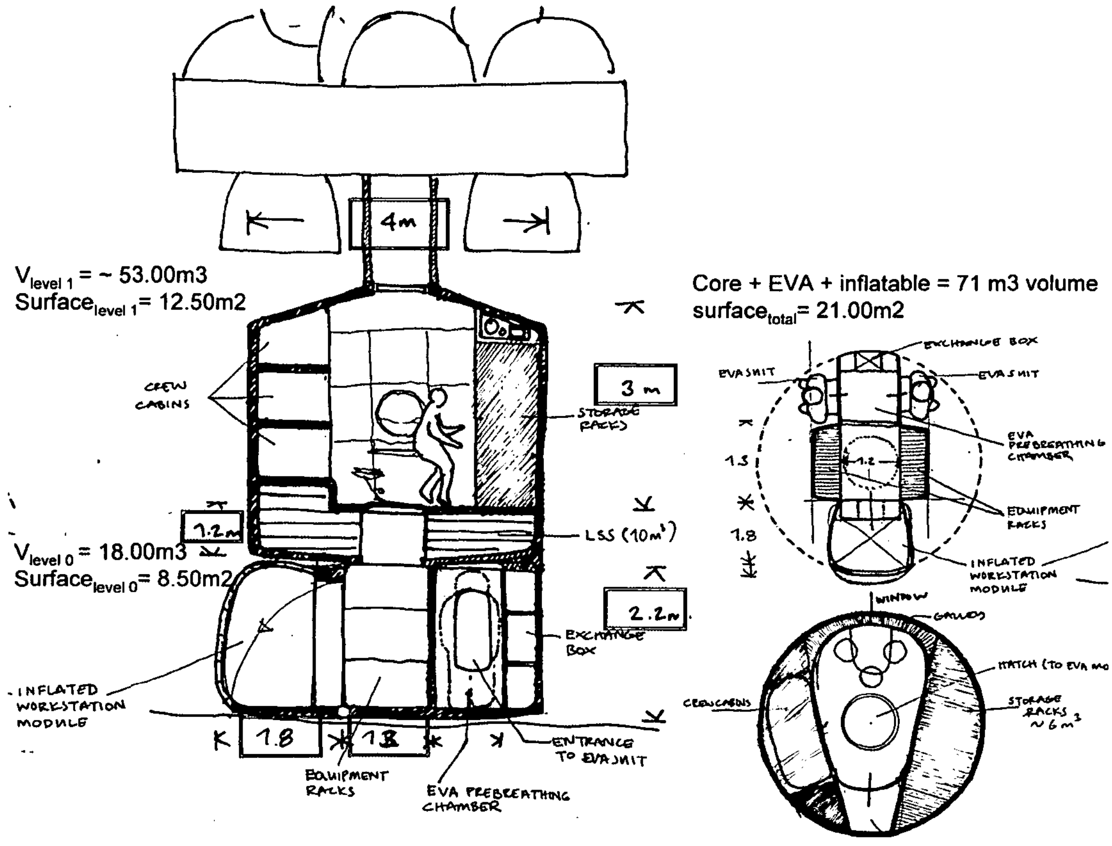


Fig. 4.2.2.5 - 2: Section (left) and plans (top right: lower level, bottom right: upper level) for Option 5

The LSS are located between the levels for easy access and maintenance. Also they provide sound insulation from the lower level, where all the preparation work for the surface walks need to be done. While part of the crew are working downstairs, other crewmembers can relax on the upper level. Additionally the two compartments provide more protection in case of emergency than a single open compartment would.

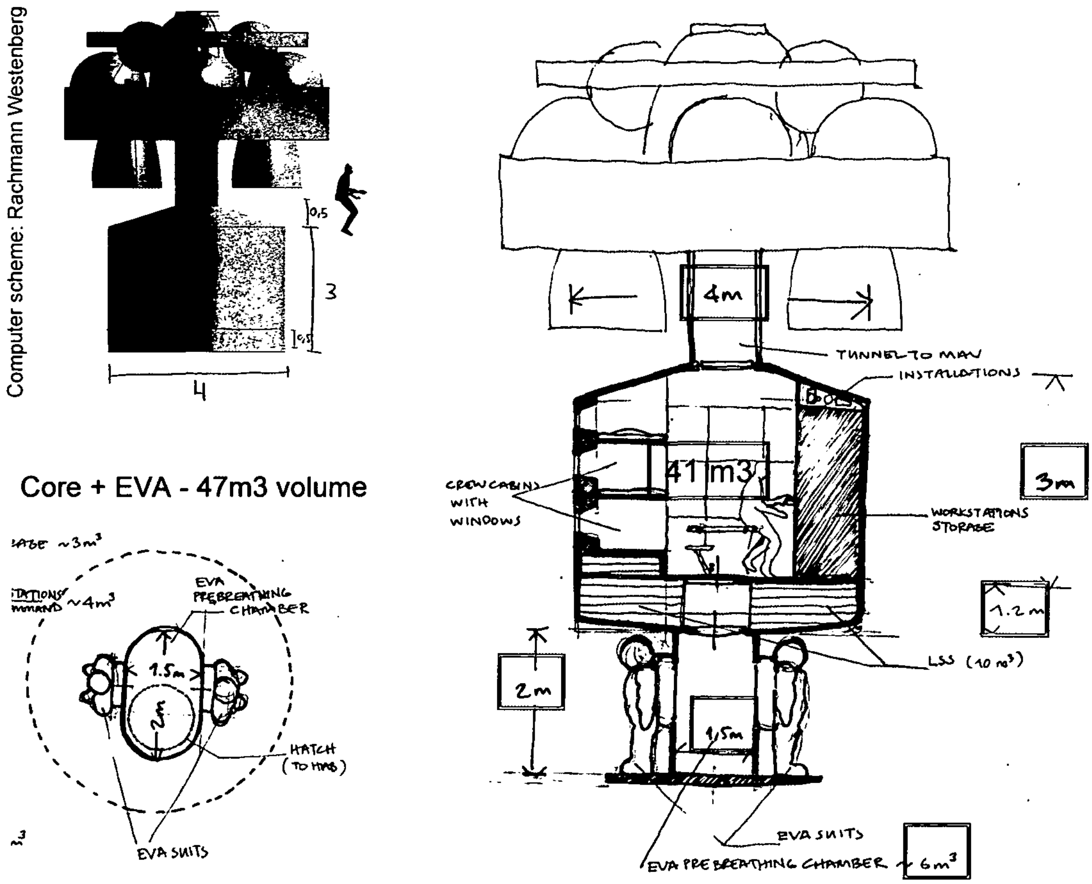
It was decided not to use inflatables for three reasons:

1. It is uncertain whether, if from today's point of view, this technology is really lighter than others, although the author believes that inflatables are lighter referring to the Transhab project.
2. Additionally this technology has not been proven in flight very much so using this in the HMMstudy creates even more uncertainty regarding safety and technical issues. Therefore finally the use of inflatables was discarded.
3. Using this technology at a really remote point a far away planet, endangers the safety and success of the mission due to possible malfunctioning.

As this option integrates inflatables, it was discarded later.

4.2.2.6 Option 6

This option derived from the final review with the system and configuration engineers. The SHM is basically a rigid cylinder with the EVA area below. In the core habitat there are the private crew cabins and the main social and working area. The private crew cabins are mainly used for sleeping and resting, and have a window with allowing crew to see outside. With a total volume of 47 m3 this configuration is far too small.



Computer scheme: Rachmann Westenberg

Fig. 4.2.2.6 - 1: Plan showing the lower level with airlocks (left) and section right - Option 4

All six options were developed for one CDF session so the line of argument should be seen within this context. Even if they do not seem to be in a line here, they represent different options and varieties even within one configuration.

4.3 Preparing the Baseline Design

4.3.1 Further Investigations into the Interior Configuration of the SHM

In the following the final steps of the SHM design development is described:

The final diameter for the SHM is 3.60 m derived from the limitations of the launch vehicle /diameter of 6.00 m) and the safety distance required between the thrust of the MAV during take-off and the ground or the habitat.

Where and how to locate the LSS optimally still remains an open issue. Three options for its positioning were considered: on the top level of the habitat, in the middle, and at the bottom. The option with the LSS on the top level was discarded because the mass of the LSS would have been too high, considering the fact that the MAV with the propulsion tanks already has substantial weight within the overall MEV configuration. Before drawing up a final conclusion in this vein, the following two options were developed:

4.3.1.1 Option 1 - Life Support System (LSS) in the Middle of the Habitat

SHM - cylinder:	
Height:	7.00m
Diameter:	3.60m
LSS: 10 m^3 in the middle of the habitat	

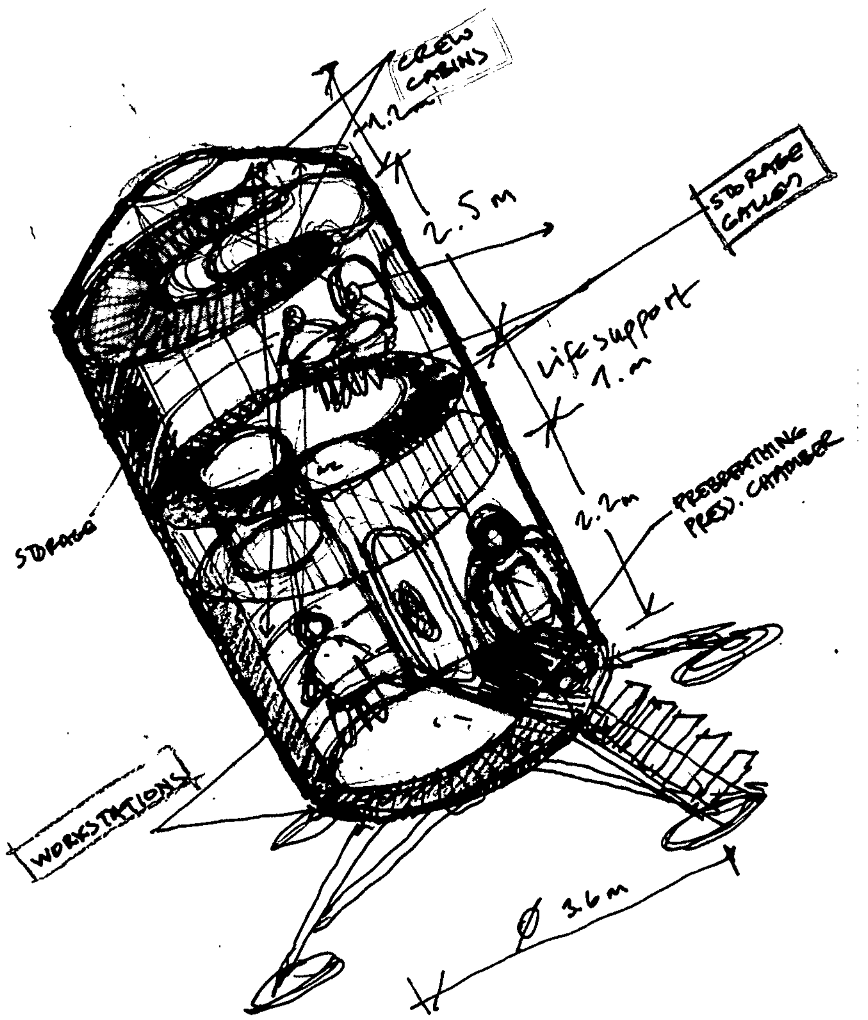


Fig. 4.3.1.1 - 1: Axonometric sketch of option 1 with LSS in the middle of the SHM

Rationale:

- Better access for maintenance for LSS
- Divides the habitat into compartments
- Increases structural rigidity of the shell
- Sets a distinction between private, personal and social space

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Fig. 4.3.1.1 - 1 shows the interior configuration for option 1. Placing the LSS in the middle of the SHM creates a natural distinction between zones. The main working zone is situated at the bottom next to the EVA area. Above the LSS are the private and personal spaces with the sleeping quarters at the top, close to the emergency exit into the MAV. This distinction creates distance while still having the possibility to overlook the entire module from the private quarters.

Nevertheless the best place for the LSS is close to the bottom so the centre of mass is as low as possible, which is optimal for landing. As the MAV with the propulsion system already is a very heavy part of the SHM, the LSS should be located at the bottom.

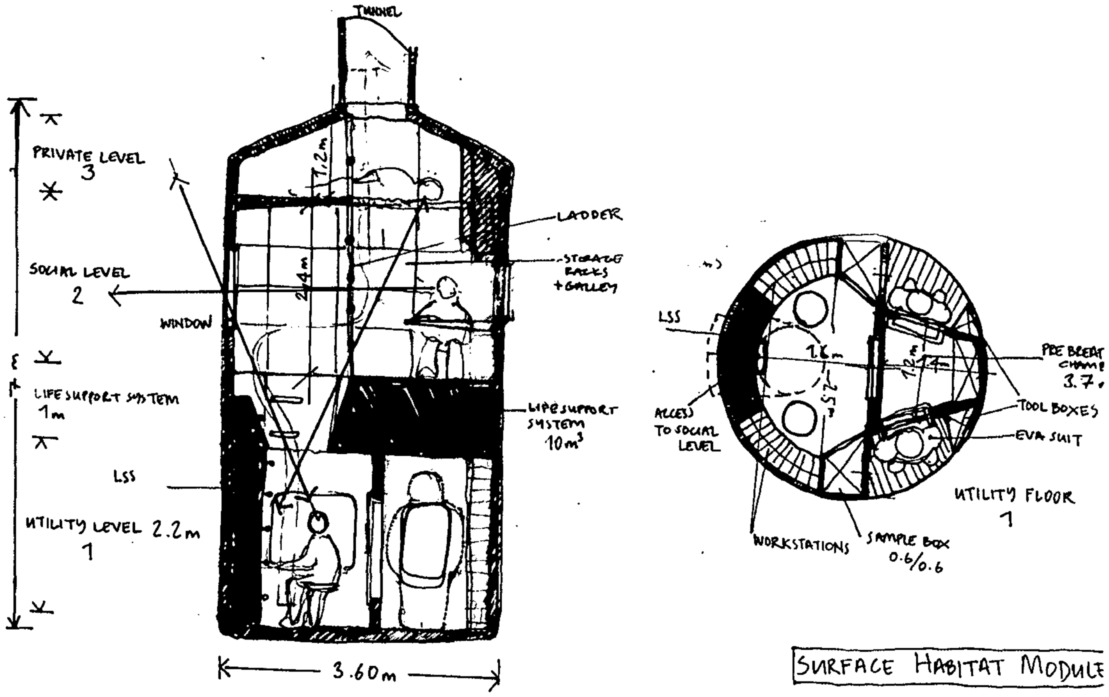

Fig. 4.3.1.1 - 2: left: section through the SHM, right: plan of the lower level - workspace and EVA access

The left section in Fig. 4.3.1.1 - 2 shows the different zones of the habitat. The upper part of the habitat is the private zone with some cocoon-type crew quarters (bunk beds) and below the social zone with the galley, the hygiene facilities, a table to accommodate all three crewmembers and the stowage area (marked in green). Arrows point out the line of sight to enlarge the space on a perceptive level. Even from the lower level one can view outside through the window placed near the table. The curved yellow arrow points towards the emergency exit - an easy path to follow, and also in the line of sight.

The plan on the right of Fig. 4.3.1.1 - 2 shows the lower level with the workstation, the sample exchange box and the EVA suits docked to the SHM.

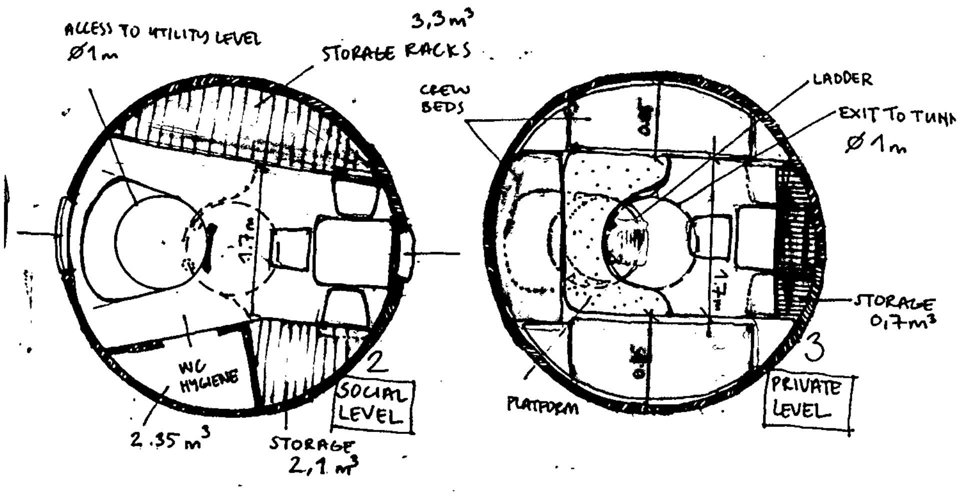

Fig. 4.3.1.1 - 3: left: section through the SHM, right: plan of the lower level - workspace and EVA access

The two plans in Fig. 4.3.1.1 - 3 are a detailed description of the main level with the social area and its functions, indicating the location of the crew cabins (marked in orange) on the right.

4.3.1.2 Option 2 - Life Support System (LSS) as the Bottom Base

SHM - cylinder:
Height: 7.00m
Diameter: 3.6 m - 4.4 m (bottom level)
LSS: 10 m³ at the bottom of the habitat

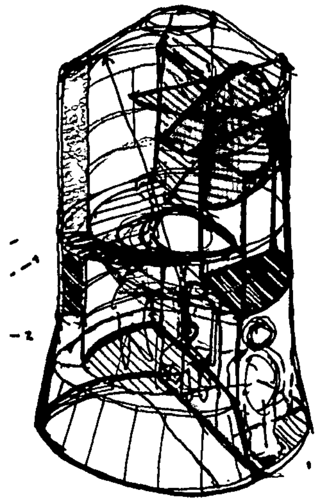

Fig. 4.3.1.2 - 1: Sketch of Option 2 with LSS at the base

Rationale:

- Preserves visual axis towards emergency exit
- Creates safe orientation points and good overview of habitat
- Visual axis makes the space look bigger and gives the astronaut an opportunity to look outside
- Centre of mass is at the bottom

Placing the LSS at the base (marked blue) of the SHM facilitates orientation and a good overview of the habitat. The section on the left shows that the working area is placed in a split level between the EVA area (marked red) and the main social zone. From here the astronaut can overlook the whole habitat, without interfering with the private space of fellow astronauts (marked orange).

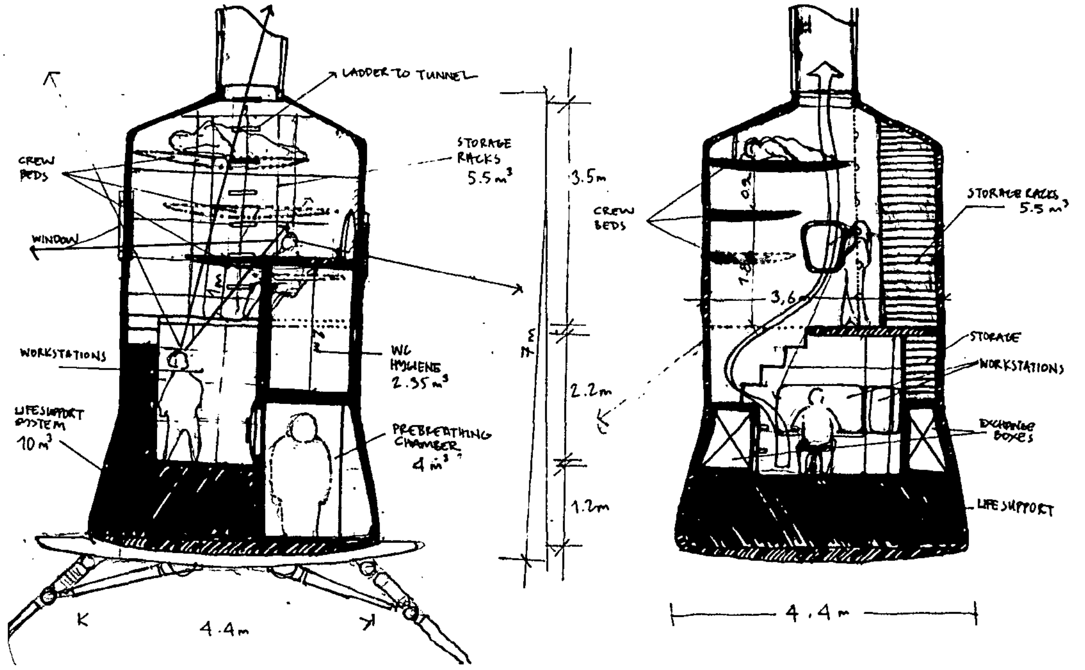

Fig. 4.3.1.2 - 2: Sectional drawings of Option 2

The two sections explain in detail the different zones, functions and infrastructure of the habitat. On the left the different visual axes are symbolized by black arrows. They enlarge the space on a perceptive level. An overview of the habitat is possible from each point of view. Through introducing split levels zoning is made possible and therefore creates a distinct set of different spaces allocated to different functions and crew performance.

The upper part of the habitat is the private zone with some cocoon-type crew quarters (bunk beds) which can be also used as stairs for a secondary option of circulation. The hygiene facilities, a table to accommodate all three crewmembers, a window and the stowage area (marked in green in the right section) are located below the social zone with the galley. The yellow curved arrow on in the right section points towards the emergency exit - an easy path to follow and also in the line of sight. This translation path is spacious and free of obstacles.

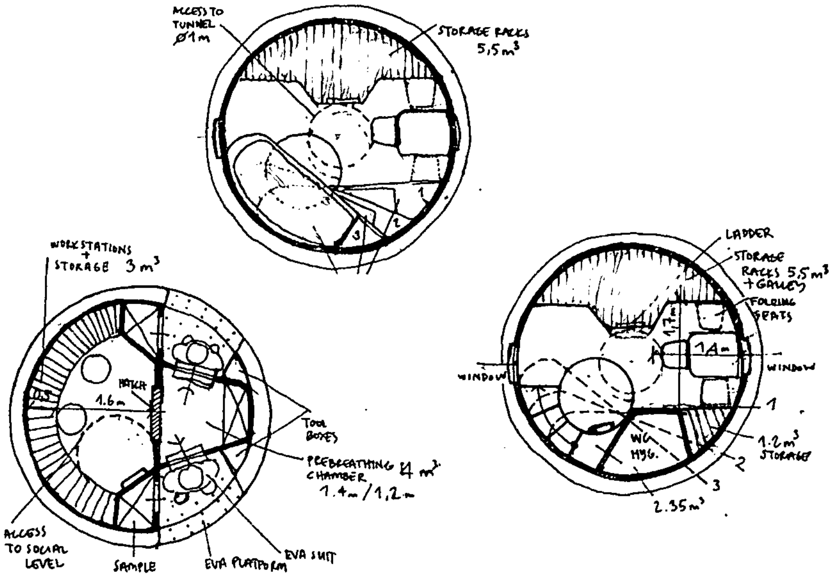

Fig. 4.3.1.2 - 3: from left to right: plan of lower level, upper level and mid level

The three plans in Fig. 4.3.1.2 - 3 show the different levels with their functional program. The diagram at the bottom left corresponds to the lowest level. It shows how the workstation, the sample exchange box, the toolboxes and the EVA suits docked to the SHM can be integrated. The right diagram is the social level indicating the relation of the window and the table, the galley and the circulation, the hygiene facilities and the stairs coming up from the EVA deck.

This design approach was finally selected because the heaviest part the LSS sits at the bottom of the habitat. Also the spatial design has the most advantages, and different layers of perception and habitability make the habitat user friendly. The entire process of examining different options produced this one option. It integrates all the advantages and important factors investigated earlier.

4.3.2 Baseline Design for the SHM

The following design concludes the research topics and the consecutive meetings at the CDF. This baseline design was developed from the original proposal, which had been taken further in its conceptual detail and design:

Zoning of the SHM is defined by functions such as working, EVA, private areas (marked orange) and achieved by a careful spatial planning. The LSS is placed at the bottom of the SHM, allowing free translation throughout the habitat. Below there is a large axonometric view of the habitat, which is self explanatory and gives and overview of the SHM configuration.

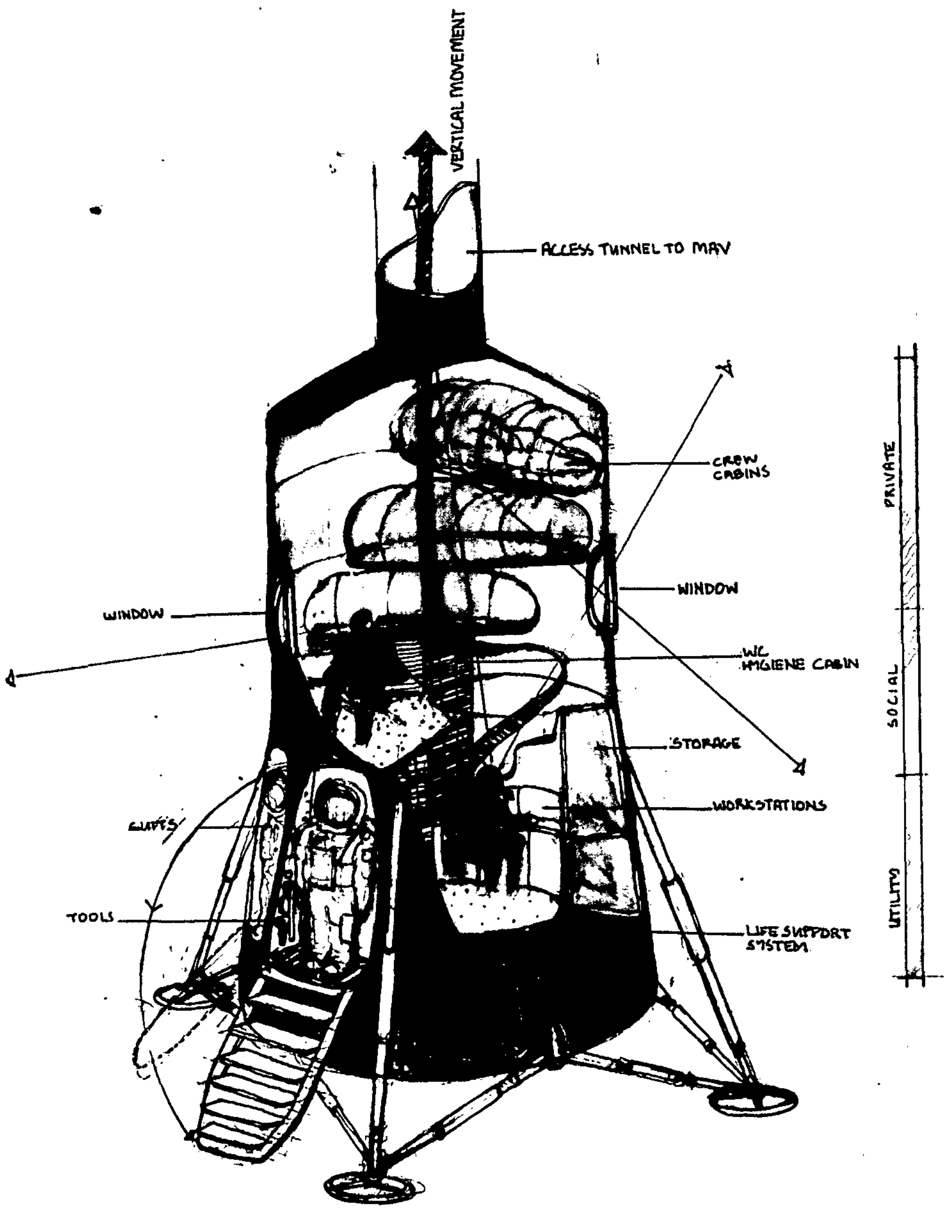

Fig. 4.3.2 - 1: Axonometric view of the final design status

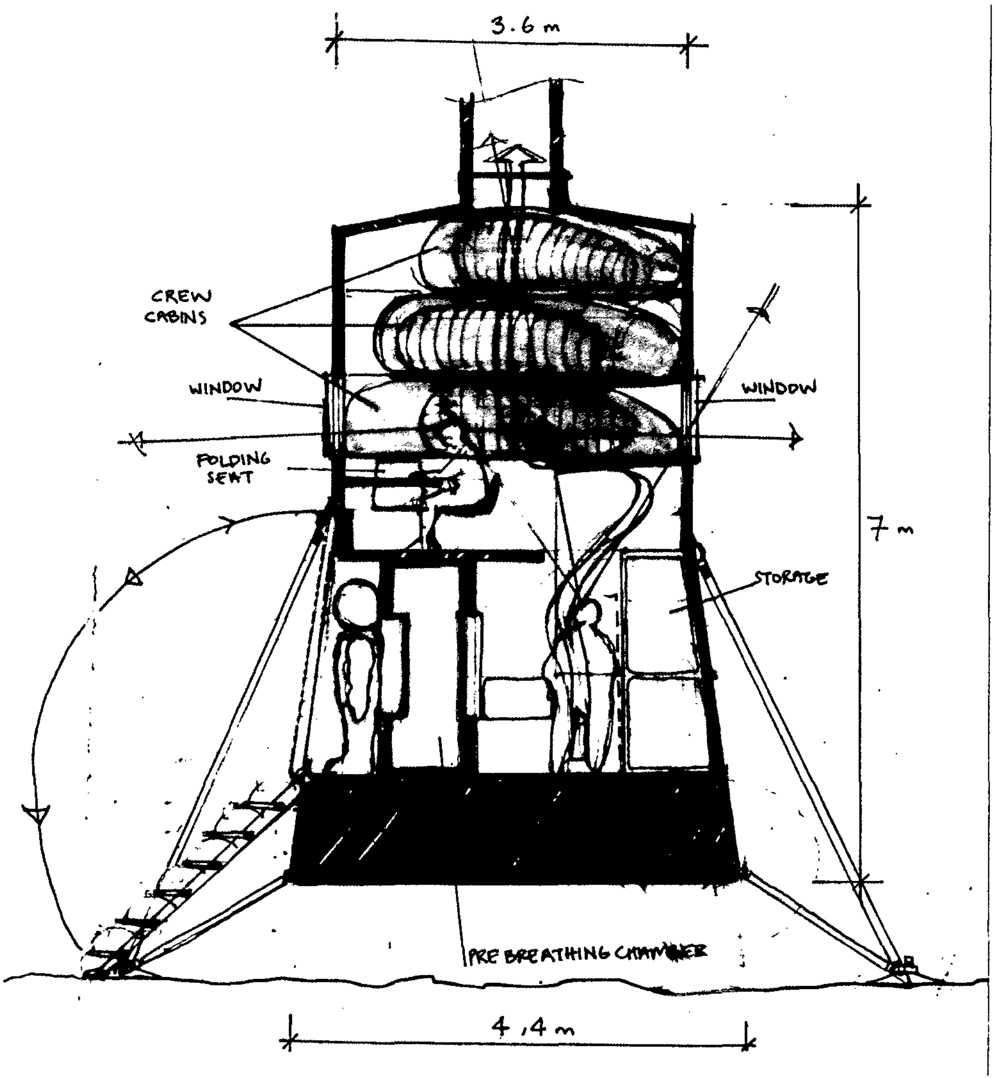

Fig. 4.3.2 - 2: Section of the final design status

In Fig. 4.3.2 - 2 the different zones of the private crew cocoons (marked orange), the social level (near the table and the window) and the working zone below are visible. Visual axes and translation paths are marked with arrows.

This configuration is conical towards the top and allows integrating the LSS on the bottom. The centre of mass is therefore in the right place.

Lower Level

On the lower level is the EVA area, a decompression chamber for returning crewmembers from the Mars walks in case they need it. The EVA system allows quick access from the inside to the outside. One spacesuit for each crewmember is provided. We assume that two astronauts go on EVA together. The third suit is for contingency. On the side there are the toolboxes and the sample exchange box. The hygiene compartment is on a split-level between the main deck and the lower level.

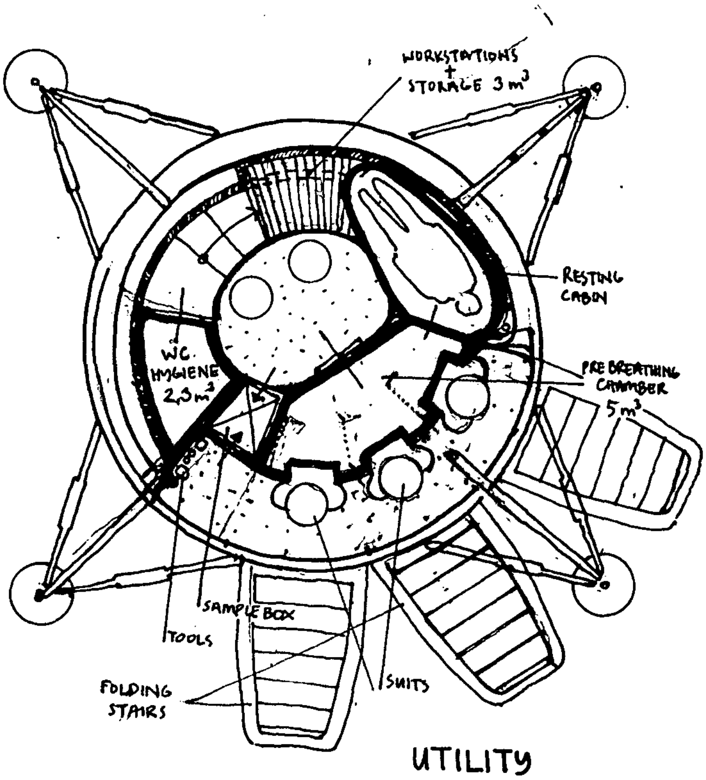

Fig. 4.3.2 - 3: Plan of Lower Level

Fig. 4.3.2 - 3 explains the sequences for EVA. The mars walker returns to the base and connects the suit to the inner hatch. The inner hatch is opened together with the back of the mars suit. This system prevents contamination and only a small volume of gas has to be pumped away.

When going for a walk on the Martian surface, the procedure is turned around and after pre-breathing the protection covers for the spacesuits fold down and reveal a ladder for the Mars walker to climb down.

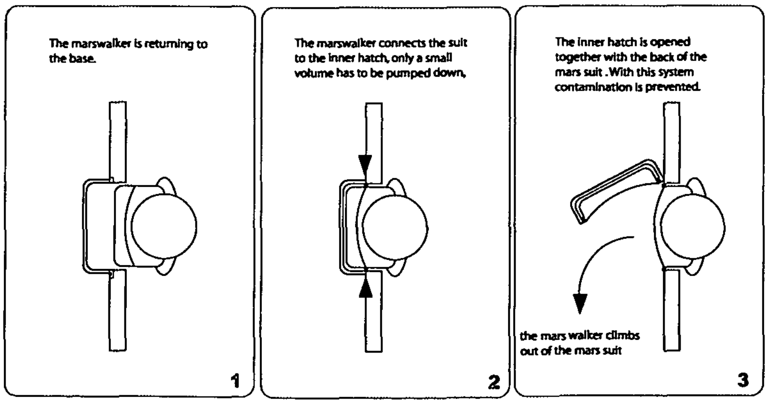

Fig. 4.3.2 - 4: "Airlockless"-Airlock System, currently further developed at EADS, Germany
© Drawing Sandra Häuplik

Main Level

This level is depicted in Fig. 4.3.2 - 5. It provides the main social area with a table to accommodate all crewmembers with folding chairs. A window at the table allows for an overview of the EVA area outside, enabling the crew to observe EVA and other activities. A second window is placed opposite.

While sitting at the table the crew has an excellent overview of the whole habitat, as well as over the Mars site and outside activities. The table is used for gathering, conferencing, observation and recreation. A galley and necessary infrastructure – all marked in green – is located here and an easy access to the hygiene facility is ensured. The stowage system (marked green) on this level ensures quick and rational access.

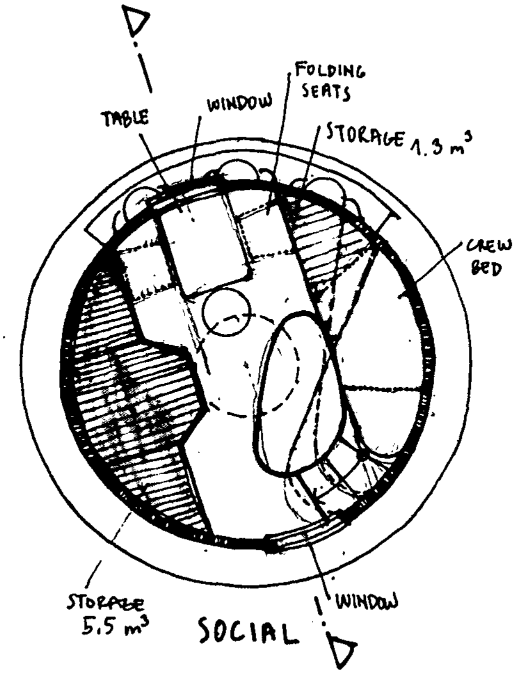

Fig. 4.3.2 - 5: Plan of Mid Level

Top Level

The crew cabins (marked orange) are accommodated in the very top of the SHM – see Fig. 4.3.2-6 One rationale for this decision: it places the crew cabins near the escape tunnel to the MEV. While resting the crewmember are able to observe the whole habitat, with the possibility to create a private zone by cocooning themselves. Also the protection against radiation is better here because the crew quarters are right underneath the MAV with its propulsion tanks.

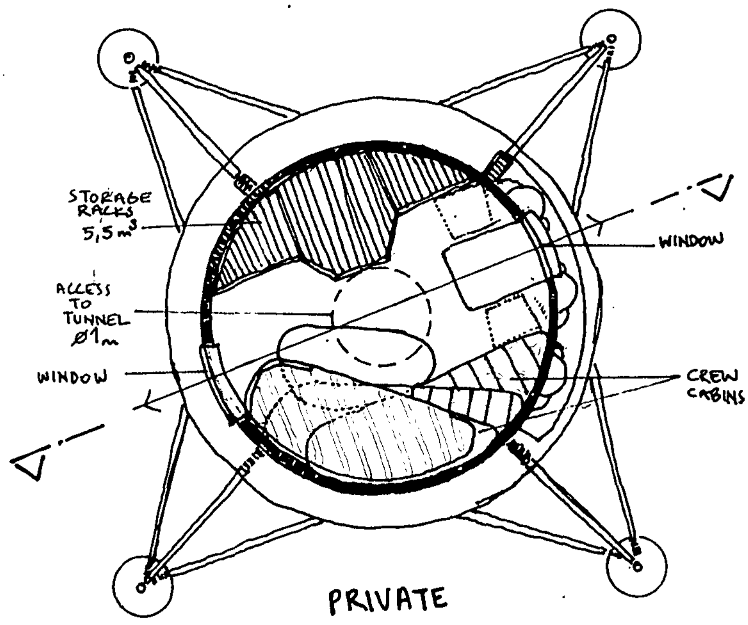

Fig. 4.3.2 - 6: Plan of Top Level

4.3.3 Table for Volumes of the SHM

4.3.3.1 Volume Calculations for Option 1 - LSS Middle and Option 2 - LSS Bottom

		Volume [m3] habitable space	[m3] storage space	[m3] equipment	[m3] structure 5% of TOTAL	[m3] TOTAL	zoning
DESIGN	OPTION 1- LSSmiddle	46	7	15	4	72	
	Crewquarterspace	6					private zone
	storage		0.7				private zone
	galley/stowage			3			social zone
	storage		2				social zone
	Storage/science		3				personal zone
	LSS			8			
	Additional subsystems		2				
	Prebreething chamber			4			personal zone
	Other habitable spaces	40					
	OPTION 2 - LSSbottom	44	12	14	4	74	
	Beds 3x	4					private zone
	Racks galley/food etc.		6				personal zone
	Hygiene			2			personal zone
	Galley storage		1				social zone
	Storage/science		3				personal zone
	Additional subsystems		2				
	LSS			8			
	Prebreething chamber			4			
	Other habitable spaces	40					personal zone

Fig. 4.3.3.1 - 1: Volume Calculations for Option 1 and 2

Distribution of the space

Requirement:		in SHM of the HMM	
1/3 stowage and equipment	25m3	>> 1/3 stowage and equipment	30m3
2/3 habitable volume	50m3	<< 2/3 habitable volume	44m3
TOTAL ca.	75m3	TOTAL ca.	74m3

(assumption 5% of total volume for structure)

4.4 References - Part 4

Adams, C.; McCurdy, M. R.; Habitability as a Tier One Criterion in Advanced Space Vehicle Design, Part One: Habitability (SAE 1999-01-2137). 29th International Conference on Environmental Systems (ICES), Denver, Colorado, USA, 12-15 July 1999. Warrendale, Pennsylvania, USA: Society of Automotive Engineers

Cohen, M. M.; Habitat Distinctions: Planetary versus Interplanetary Architecture (AIAA 96-4467). Space Programs and Technologies Conference, Huntsville, Alabama, USA, 24-26 September 1996. Reston, Virginia, USA: American Institute of Aeronautics and Astronautics.

Cohen, M. M.;. Space Habitat Design Integration Issues (SAE 981800). 28th International Conference on Environmental Systems (ICES), Danvers, Massachusetts, USA, 13-16 July 1998. Warrendale, Pennsylvania, USA: Society of Automotive Engineers

Connors, M.; Harrison A.; Living Al oft: Human Requirements for Extended Spaceflight, Government Printing Office, 1985, http://history.nasa.gov/SP-483/ch1-4.htm

Idea One, The First International Design for Extreme Environments Assembly, Final Conference Proceedings Report, University of Houston, 1991

Imhof, B.; Mohanty S,; Rombaut, H. J.; Van Susante, P. J.; Volp, A.; Lunar Base Design and Operation study (LB-DAOS 1) Earth-Like Planets and Moons , Proceedings of the 36th ESLAB Symposium, 3-8 June 2002, Noordwijk, NL, ESA-ESTEC SP-514

Imhof, B.; Mission to Mars - Long-Duration Missions: Notes on Psychological and Spatial Aspects, ALLDESIGN, Leben im schwerelosen Raum“, Museum für Gestaltung Zurich, 2001, p.62

Imhof, B.; Schartner, H.; Mars Surface Habitats: Architectural Designs and Concepts for Planetary Outposts (SAE 2001-01-2174). 31st International Conference on Environmental Systems (ICES), Orlando, Florida, USA, 9-12 July 2001

Imhof, B.; In the Simulator (Architecture, Technology and Innovation), Interview with Fred Smith, Simulation Astronaut, NASA, 26.08. 2003, Radio Orange

Larson, W.; Pranke, L.; Human Spaceflight, Mission Analysis and Design, The McGraw-Hill Companies Inc., Space Technology Series, 1996

Man-System Integration Standard, Vol. 1, NASA STD 3000, Rev.B (1995), NASA-Johnson Space Center, Houston, TX

NASA, Mars Landing Site Catalog, Reference Publication 1238, 1990

Raitt, D.; Gyger, P.; Woods, A.; Colonization of Space. Innovative Technologies from Science Fiction for Space Applications. BR-176, European Space Agency, June 2001. p. 22

University of Houston, SICSA Outreach, Experience, Analogs and Simulations to guide Planning for Prolonged Missions, Saskawa International Center for Space Architecture, vol.2, 1989

Zubrin, R.; Wagner, R.; The Case for Mars, The Free Press, Simon & Schuster Inc., 1996, Mars Society, Mars Society Flashline Arctic Research Station, http://arctic.marssociety.org/

5 Conclusion

During the entire development of the study, the author was faced with the following situation: the original design objective comprised interior configuration only, i.e. the configuration of predefined units in space. Starting from this approach, the author soon expanded her focus to an issue more closely compatible with architectural know-how: the arrangement of rooms in relation to each other and their physical shape. She also moved into systems configuration and systems engineering, allowing engineers specializing in these fields to profit from the differentiated approach taken by an architect and vice versa. Rather than following a linear process, the system was developed in a controlled yet free-moving, dynamic process that left room for various development steps to be combined and different options to be examined. On several occasions this gave rise to new approaches and implementation strategies, although the general scenario and the strategy set forth by the engineers' team lead did not always leave a lot of room for creativity. The author believes that architects can help speed up the process by making sure that different options and their detailed aspects are immediately visualized - for after all, this is the very point of architecture: taking a holistic approach and co-operating across different disciplines; never losing sight of either the whole picture or the individual details, and finally combining and integrating the various elements.

At the same time, the present project clearly demonstrates how spaces can be developed and designed with a special view to fulfilling the "soft" needs of their inhabitants or users, even in a field where the primary focus is always on the "hard", quantifiable requirements. Still there must be no doubt that soft factors deserve increased attention, especially when planning longer missions.

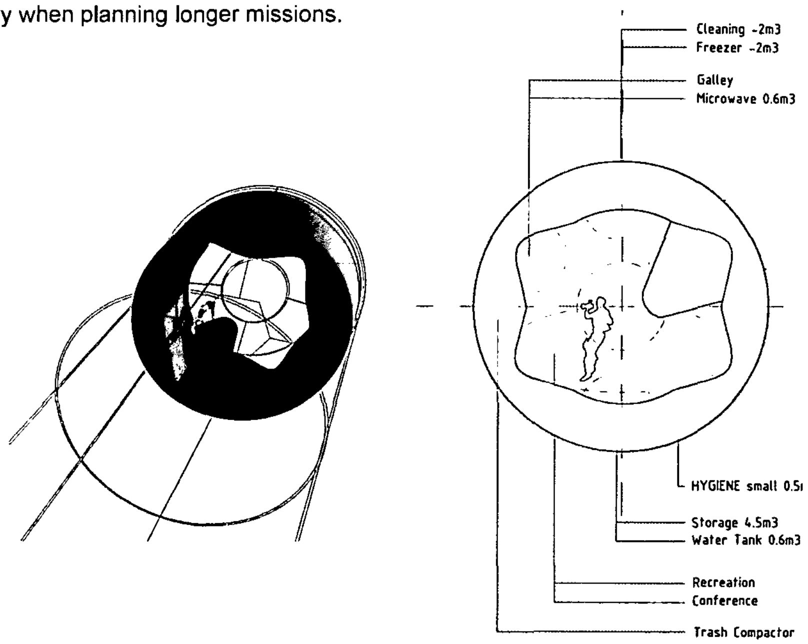

Fig. 5 - 1: Social area in the THM with modular curved configuration

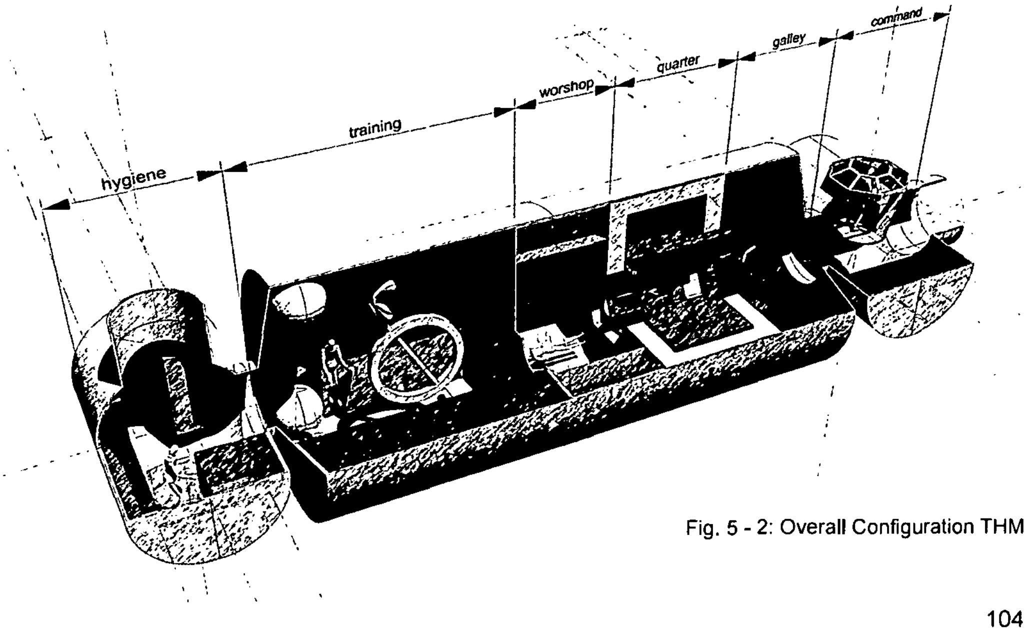

Fig. 5 - 2: Overall Configuration THM

The baseline designs were also an attempt at identifying and providing a conceptual context for specific architectural elements designed on the basis of spatial analysis and perception of space in zero and partial gravity, and thus linking up with current issues in architectural discourse. To attain an impression of spaciousness, all lines of horizon had to be curved rather than straight - Fig. 5 - 1 / 5 - 2; spaces were designed to be open and functionally flexible. When looking at the layout of the ISS the inhabitable space is a long stretched cube. Its defining lines are more than evident. The eye can follow the line right through to the section point with the next line. All lines end at section points, i.e. invariably end points. In the case of a curved line, the eye can follow a continuous line. As there are no end points of the lines the space in its perception appears larger than a cubic or box space.

"Der Raum im Endless House ist kontinuierlich.... Jeder der Raumkerne kann einzeln von der Ganzheit der Wohnung getrennt werden, kann abgeschlossen und wiedervereinigt werden, um verschiedenen Bedürfnissen zu genügen...." (Bogner;) In his text on the Endless House, Friedrich Kiesler asserts that the space of this house is continuous, and each of the space-defining cores (such as galley, hygiene facilities etc.) can be separated from and recombined with the rest of the house, depending on the needs of the inhabitants. He concludes that the Endless House is a very practical house provided that "practical" is not defined too narrowly, and that the poetry of life is acknowledged as an integral part of everyday life. Kiesler's approach and concept for his Endless House dealt with infinity in a holistic sense, which also includes shape and form.

Fig. 5 - 3: Friedrich Kiesler - Model for the Endless House

Therefore the curved modular parts in the conception for the THM are an interpretation of Kiesler's holistic logic, i.e. so curved lines and spaces incorporate a sense of infinity in their perception.

Quite essentially, the architect is also aware that a space habitat is permeated by technology and thus provides enough technical interfaces for virtual space extensions. Apart from facilitating communication with Earth, this virtual augmentation of reality could also support an individual environment created and controlled by the astronauts themselves, which would make the demanding but lonely and dull routine of life in space more complex and render daily life in the spaceship more interesting. Though this aspect of the study has not yet been sufficiently examined, it should become a major aspect in further planning projects of this kind.

Without any doubt, a human mission to Mars is one of the biggest challenges to humankind. It provides a chance for humans to explore spaces yet unknown in peaceful co-operation, a joint mission that has the potential of enriching human life and increasing our knowledge of how things relate to each other – not just with a view to scientific progress as such (searching for life on other planets), but also in terms of economic benefit (using extraterrestrial resources and "living off the land") and cultural development (mankind with its various forms of society and cultural organization settles down on another planet and thus changes society).

A mission as complex will become technically feasible with the next major surge in technological development, but the question remains whether humans will have the necessary physical and psychological abilities to actually go on this expedition unless we advance in this field as well. In brief, the human factors, sociology and psychology, as well as the integrative, creative and innovative potential of architecture and design must be part of mission planning and implementation from the beginning to the very end.

Outlook

Living in space

Living in space is best captured by those who have been there. This different kind of life, and the possibility to behave, perceive and live in entirely different ways, not only stimulates the urge to explore, it also touches the innermost parts of our soul. Although, technically, we have proven our capability of spending extended periods of time away from Earth, our mother ship, we have shown that, beyond adaptation to the environmental conditions, we can further gain by extending our own perception of the world. The first man on the moon, and the photo of planet Earth, as seen from the moon, lead not only to the foundation of Greenpeace, but through the technologies developed, it also left an indelible mark on our culture. Life in zero gravity and partial gravity, such as on the moon or on Mars, is quite different from life on Earth. The environment determines the rooms making up the habitat, but also human behavior and the relationship each crew member develops with their environment and with the crew itself. The brevity of most missions limits our experience of the human factor in the space environment. Due to the sparse accounts from these missions, we can only anticipate some basic rules for habitat design.

Zero gravity

"The first hours in space are no idyll. You have the physical sensation of all your blood running to your head, which feels very heavy. When your eyes are closed it seems you are tumbling backwards. Either you are always floating up from somewhere or you are turning backward somersaults. There is an unusual lightness in your body, and your trained muscles seemed to have no purpose. Your inner ear - the organ responsible for providing you with a sense of position - becomes like a compass whose pointer has suddenly lost the Earth's poles. To begin with you felt to always want to hang onto something. Your first hold on, letting go with trepidation, and then you find there is nowhere to fall and that you simply hang in the same place."
Georgi Beregovoy, USSR (1)

"You're okay. You're okay. You're not going to fall. The bottom is way far away. And now a second, even more intense feeling washes over him: He's not just plunging off a cliff. The entire cliff is crumbling away."It wasn't just me falling, but everything was falling, which gave (me) even a more unsettling feeling," Linenger told his debriefer."So, it was like you had to overcome 40 years of whatever of life experiences that (you) don't let go when everything falls. It was a very strong, almost overwhelming sensation that you just had to control. But I could see where it could have put me over the edge. The disorientation is paralyzing. There is no up, no down, no side.There is only three dimensional space. It is an entirely different sensation from space walking on the shuttle, where astronauts are surrounded on three sides by a cargo bay. And it feels nothing – nothing – like the Star City pool. Linenger is an ant on the side of an falling apple, hurtling through space at 18 thousand miles an hour, acutely aware what will happen if his Russian made tethers break...." (2)

"It takes a while for the new crew to adapt in weightlessness", Linenger notices."Ewald is always bumping into people in midair. But the one having the most problems is Lazutkin. He has already started vomiting. Space sickness hits about half the people who reach MIR. Lazutkin, in fact, will endure severe headaches and periodic vomiting for much of his first two weeks aboard the station." (3)

"It is amusing how any position, such as upside down or at any angle, is possible in a spacecraft. For instance I like attaching my legs to the ceiling, while Vitali Sevastyanov 'sat'strapped in the couch. Our heads turned out to be on the same level but twisted 180 degrees. We found it convenient and we had dinner together and talked and joked with each other that way. Of course, from a distance it seems very strange." (4)
Andriyan Nikolayev, USSR

Partial gravity

"When I came back after 12 days on the flight to the moon,I could appreciate little things like being able to sit in a chair and feel the pressure against by backside, to be able to walk in a normal fashion, to be able to eat with a spoon, to be able to lie down in a bed and stay in that position, to be able to smell things, to appreciate the sense of Earth, to really hear sounds. We had been in an environment where we took our sound with us, because space has no sound; it's a vacuum. That was certainly very true on the moon. The world of no sound, of no smell, no sense." (5)
James Irwin, USA

"You see the sun come around every so often as you rotate the spacecraft. Then you see the moon coming around, so through the windows of the spacecraft you get this constant parade of darkness and stars on one side, and then the Earth swings through, and then the sun swings through and then the moon swings through and then back to the star-filled skies again. It's eerie. You suddenly start to recognize you're in deep space,

that planets are just that, they're planets, and you're not connected to anything anymore. You're floating through this deep black void." (6)
Edgar Mitchel, USA

Interpreting The Footprints of Long-Duration Missions

It will clearly make a difference to the future long-duration mission whether we have developed a basic understanding of the human factors involved, and of their implications. This will include sensitizing the astronauts/cosmonauts since they are the actual clients of space architects, i.e. the final users of the space station or surface habitat to be built.

Now, the built environment stands for the physical and spatial transformation of a situation between two individuals in action. As previously mentioned (ref. Preface) a space habitat is a space permeated by technology, which is inhabited by its users and would therefore clearly constitute an interface between humans and their environment. If humans are to live in extreme conditions during long-duration space flight, the form and infrastructure of their space will need to be formulated with absolute precision so that technology can truly interact with human beings, and vice versa.

In space flight, however, most concepts are strongly focused on engineering issues and tend to be planned in great detail where machines are concerned. Space architects, on the other hand, hardly get involved beyond the initial concept stage.

The layout of the International Space Station (ISS) is reminiscent of a machine. Although designed by a NASA architect, the ISS has not become a habitat for humans: the architect has missed out on the socio-psychological human factor and the dynamics of space it implies. Like on previous occasions, engineers and one architect/engineer succeeded in enclosing a machine but failed to devise a habitat for astronauts/ cosmonauts on long-duration missions. The ISS has not been considered in architectural detail, or in its role as a man-machine interface. The long-duration campers have to work among a confusion of tubes, wires, ropes and storage containers that cannot be stowed away. Moreover, any clear overview of the systems and space on board has been absent since the operation's initial phase.

Fig. Outlook - 1: ISS - Configuration 2004, courtesy NASA

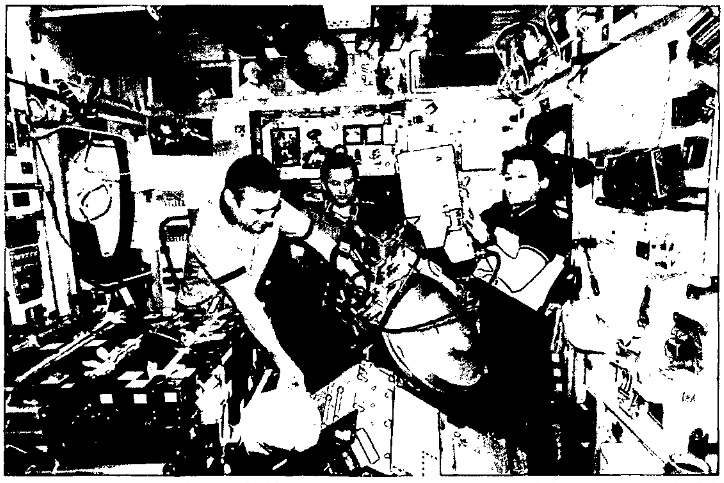

Fig. Outlook - 2: ISS - Russian Command Module, courtesy NASA

The aim is to conceive a new approach to *[space]architecture*. Space, and hence also architecture, is vital for human life. Space engineers argue that it is difficult enough to build a habitat that functions in technological terms. "One step after another" is a motto frequently quoted - but then again, who would want a Mercedes that takes you from A to B but only consists of a chassis and a box for a cabin? And, after all, should a space habitat not at least match a Mercedes?

In this new genre *[space]architecture*, every habitat is expected to reflect an understanding of the processes in space. In its existence as a space machine, the space habitat, implies a flexible rather than a rigid structure. The point is to develop an outlook on architecture that focuses on processes rather than just on rigid walls. Therefore buildings, as we see them, are intermediary results rather than statements. Accordingly, contemporary architecture is increasingly understood as the product of a process - an adaptable expression of a living society - that is also the goal for *[space]architecture*.

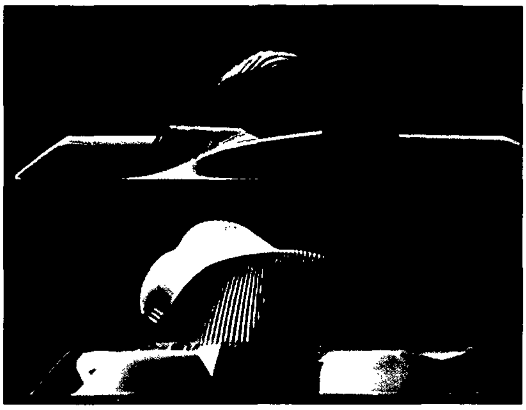

Fig. Outlook - 3: Greg Lynn FORM embryological house
© tm, 1998 mock-up

„The relationships of structure to force and gravity are by definition multiple and interrelated, yet architects (and engineers) tend to reduce these issues to what is still held as a central truth: that buildings stand up vertically. The primary perception of structure has always been that it should be vertical. A re-conceptualization of ground and verticality in the light of complex vectors and movements, might not change the need for level floors, but it would open up possibilities for structure and support that take into account orientations other than simply vertical." (7) In some aspects, orbiting space habitats correspond to Greg Lynn's theoretical approach: they have no more foundations, and their structure is no longer determined by the human sense of balance, which - given its function - might also be referred to as the sense of gravity. Verticality loses its unambiguous nature; basically, all directions are equally valid. On a research trip to Mars, there would be phases of zero gravity and partial gravity, and as a result the habitat would not only be determined by verticality.

To be able to interpret the reactions of and interactions among the crew, it is important not only to take into account the environment within and outside the habitat, but also the character and cultural background of the crew and the conditions of space occupation. In view of the complexity of these structures on an international mission, it is difficult to formulate a clear statement for architecture. Any such statement would have to be based on experimentation and experience.

Several prototypes would need to be built, reflecting the actual situation and extreme living conditions, not only for the purpose of designing life support machinery, but also with regard to isolated life in a simulation habitat. This is the only way to assess the validity of the architectural concepts and theories devised. In this way we will contribute to overall mission sustainability.

References - Outlook

(1) Kelley, K.; Homeplanet, Addison-Wesley publishing Company inc.
(2) Burrough, B.; Dragonfly, HarperCollins Publishers, 1998, page 224
(3) Burrough, B.; Dragonfly, HarperCollins Publishers, 1998, page 116
(4) see (1)
(5) see (1)
(6) see (1)
(7) Lynn, G.; Animate Form, Editor: Therese Kelly, Princeton Architectural Press, 1999, p.14

Fig. Outlook - 4: Mars spaceship 1+, Transformation project, HB2, TU Vienna, 2004

Abbreviations

AOCS	Attitude and Orbital Control System
AL	Advanced Life Support
CDF	Concurrent Design Facility
CM	Crew Member
CQ	Crew Quarter
ERC	Earth Return Capsule
ESA	European Space Agency
ESTEC	European Space and Technology Center
EVA	Extra Vehicular Activity
GCR	Galactic Cosmic Rays
HMM	Human Mission to Mars
ISS	International Space Station
LS	Life Support
LSS	Life Support System
MAV	Mars Ascent Vehicle
MEV	Mars Excursion Vehicle
NASA	National Aeronautics and Space Administration
RSA	Russian Space Agency
SHM	Surface Habitat Mars
THM	Transfer Habitat Module
TV	Transfer Vehicle

Curriculum vitae

Barbara Imhof, *1969 in Vienna

Professional Activities

1998 - Sept. 2006	University of Technology, Vienna, Austria, Department for Building Technology and Design, Prof. Helmut Richter Assistant professor http://wwwhb2.tuwien.ac.at
2004 - current	LIQUIFER Systems Group, Austrian based cross-disciplinary team, working for the European Space Agency and other European space companies
2003 - current	LIQUIFER, office for space architecture, (partners: Susmita Mohanty, Waltraut Hoheneder) Vienna, Austria http://www.liquifer.at
1997 - 2003	ESCAPE*spHERE, office for architecture with partners Sandrine von Klot and Birgit Trenkwalder
1997	Project architect for BIOPLEX, human rated test facility, simulation basis for a Mars habitat, JOHNSON SPACE CENTER, NASA, Houston

Education

1996 - 1997	Master of Space Studies (MSS, International Space University), Strasbourg, France
1993 - 1996	University degree in architecture at the Academy of Applied Arts, Vienna, studio Wolf D. Prix (Coop Himmelblau)
1994	4 months exchange scholarship at Southern Californian Institute of Architecture (SCI-ARC), Los Angeles
1992 / 93	Bartlett School of Architecture, University College, London
1987 - 1992	Architecture studies at the University of Technology in Vienna, first degree - undergraduate

Memberships

since 2005	Membership IG-Architektur, Architects Austria
since 2003	Membership of the American Institute of Aeronautics and Astronautics (AIAA), www.spacearchitect.org
since 1998	Member of the Dutch architects' chamber, reg.no. 1.990701.021

Biography

Barbara Imhof has been a free-lance architect since 1997, and has been working with Susmita Mohanty in the LIQUIFER team since 2003. In 2004 Waltraut Hoheneder joined the team. The team concentrates on the interface between architecture and space architecture. In their work LIQUIFER focuses on architectural concepts and their implementation in terrestrial and extraterrestrial environments. In this context, space is not regarded as a static phenomenon, but rather as the product of a dynamic network of users, surrounding spaces, and technology. Studies for habitats in zero gravity, on the Moon or on Mars are combined in the projects implemented by LIQUIFER, such as the adaptation of the Austrian Space Agency in Vienna (project "Spacegate"). The same is true for projects for „down to Earth" projects. In 2004 LIQUIFER SYSTEMS GROUP was formed as an interdisciplinary task force to work on ESA study programmes. In 2005 the LIQUIFER SYSTEMS GROUP was awarded the FIPES Study of an Integrated Simulator.

In 2003 ESA tasked Imhof with conducting a study under the comprehensive Aurora program, the only European program for human missions to Moon and Mars. Specifically, the study concentrated on the first human mission to Mars, which is scheduled for 2030 and may be expected to last about 900 days. Central topics included the architectural design of the crew habitat module, the Mars transfer module, as well as a habitable module for the Martian surface. Originally their task was limited to interior configuration, i.e. the interior design of pre-defined space units, but Imhof soon expanded her work to include a field more closely compatible with architectural know-how: the organization of the individual units in relation to each other, and their original shape. This work was to form the basis for the present dissertation (2006).

From 1997 to 2003 Barbara Imhof worked together with Sandrine von Klot and Birgit Trenkwalder under the team name ESCAPE*spHERE. This cooperation produced projects like "Back Projection" (2001) for Ars Electronica or "Smart Environment" (2002), an exhibition concept on digital design processes.

Having studied at the Vienna University of Technology, Bartlett School of Architecture in London, and Sci-Arc in Los Angeles, Imhof graduated from the Vienna Academy of Applied Arts (studio of Prof. Wolf. D. Prix). In 1997 she acquired her degree as Master of Space Studies at International Space University and worked as BIOPLEX project architect for NASA at Johnson Space Center. In this context, she developed habitats for human missions to Mars.

From 1998 to September 2006, Barbara Imhof had a teaching assignment with Prof. Helmut Richter at the Vienna University of Technology, Department for Building Technology and Design. This includes developing and implementing architectural projects on her own initiative together with student teams, each project focusing on a specific scientific topic.

In 2004 Imhof published the research volume "Transcripts of an Architectural Journey - Musings towards a New Genre in [Space]Architecture". The book focuses on a broad-based discussion of [space]architecture, placing the topic into a wider cultural context so as to link up with other forms of space design and encourage an exchange of concepts between planning paradigms on earth and in (outer) space. The research report contains a chronological categorization of [space]architecture, in which the first era of early space utopias is referred to as "Voyage d'esprit", while the second phase characterized by the predominance of engineering architecture is called the "Man-in-a-can" era; the third era, already emerging but mainly lying in the future, is termed "Trans-gravity". The latter is based on architectural and design concepts on Earth to be applied to [space]architecture. The research project primarily focused on investigating the third genre. The research team included Susmita Mohanty, Hannes Stiefel (stiefelkramer architects), Constance Adams (NASA architect) and Sandra Häuplik.