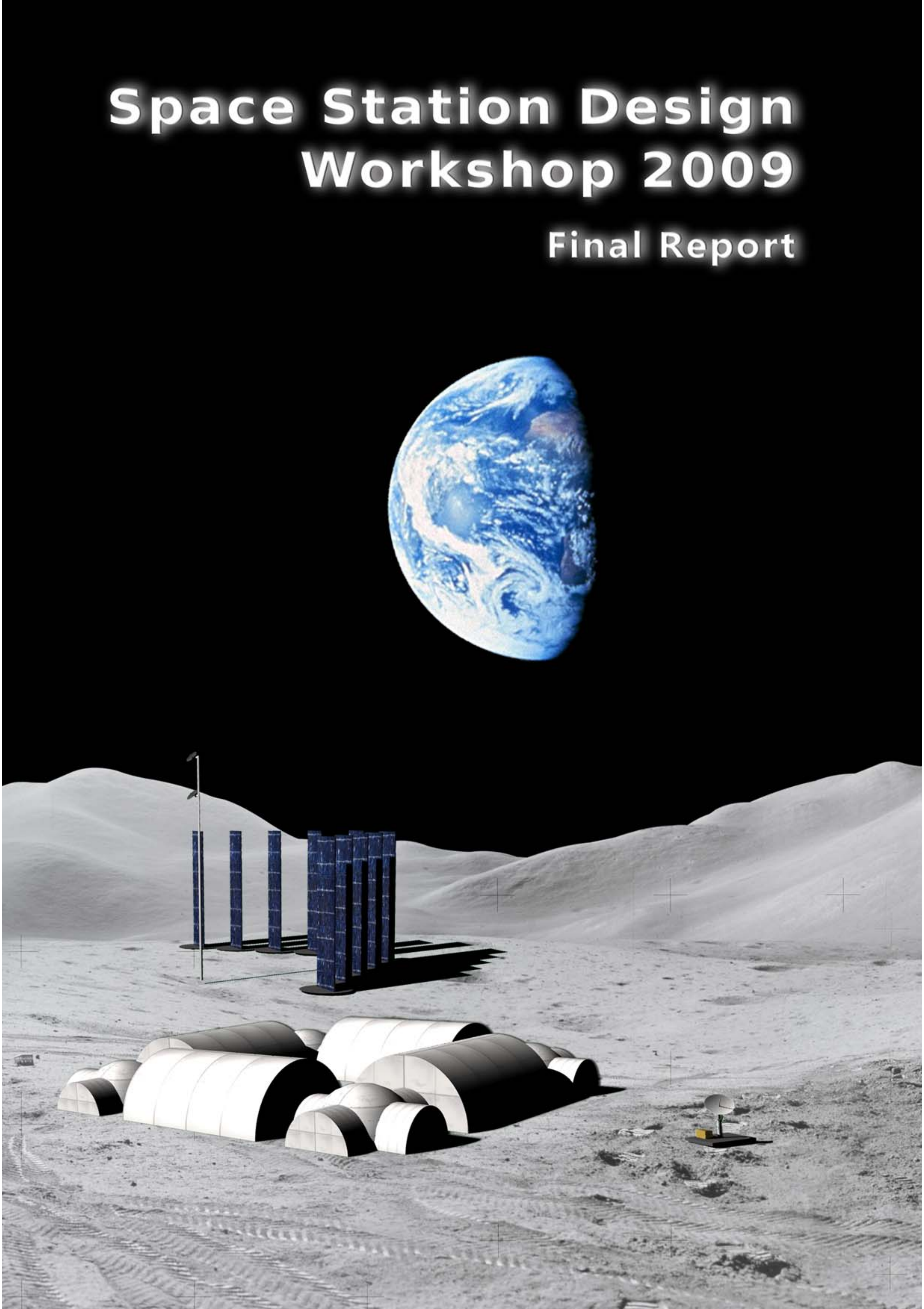
Space Station Design Workshop 2009

Final Report



Space Station Design Workshop 2009

Final Report

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Foreword

Human history has favoured both the spatial and cultural expansion. Fresh prospects yield new perspectives. Life springing from the sea to land was similarly favoured. We now stand on a beach, our small world, timidly dipping a toe into the sea of the universe. We stare into this ocean of night and imagine we are the new Columbus generation.

Strong sentiments have recently emerged that there must be a clear destination and purpose for human space flight. We propose a global guide to space built on human needs, scientific knowledge, technological challenge, and the sense of discovery and progress that only space exploration can provide. Others recognize that space applications can provide vital knowledge to deal with life endangering issues such as global warming, worldwide drought, and holes in the Ozone layer. A well-conceived international program of human space exploration, space science and space applications can advance discovery, understanding, and cooperation. It can lift our sights and fuel our dreams.

Thus it is time to develop a logical, systematic, and evolutionary architecture for human expansion into the solar system, with an approach leading ultimately to a human exploration of Mars and a permanent human presence in the solar system. Likewise it is time for international cooperation to use space to unlock new scientific knowledge and to use space technology to improve the human perspectives.

Within this framework, the Moon has been and continues to be an important waypoint close to our home haven. Future programmes involving astronauts and targeting the Moon require new technologies and new approaches compared with the Apollo program 40 years ago. In coping with technical, scientific and political objectives given by an international lunar outpost, well-trained system engineers are required who are familiar with modern tools and methodologies of system engineering and who have acquired sufficient hands-on experience at the universities or in their first years of professional preoccupation.

Lectures on space stations, subsystems and its utilisation have been given at the Institute of Space Systems at the University of Stuttgart since more than two decades. When it became clear in 1995 that many European countries would join the International Space Station project, the lectures were extended and supplemented by the so-called Space Station Design Workshop or "SSDW". Here students learn, as part of their regular studies, in a hands-on, interactive, team-centred environment to perform conceptual design studies of a complex human spaceflight system. They are supported by a concise methodology and by customised software tools enabling them to successfully tackle the challenging task. These methodologies and tools were developed, constantly improved and extended in recent years for near-Earth exploration missions in the frame of research projects mainly carried out by PhD students at the Institute of Space Systems.

Reflecting the interdisciplinary working environment, the SSDW involves students from many disciplines and partner universities, and consequently was conducted with English as the working language. In many instances, the SSDW was also held at the partner universities´ sites, e.g. in Toulouse, at the International Space University in Strasbourg, at the University of Sydney and at ESA´s Space Research and Technology Centre ESTEC in the Netherlands.

This time again at the University of Stuttgart, it was a pleasure for me to see the fresh design ideas, the enthusiasm emerging from working together with student teams and supported by equally motivated university staff. I wish to thank ESA for the support given again as in previous years, and the other sponsors, and all of the participants, including the students and the instructors for their contributions to making this Space Station Design Workshop 2009 such a valuable experience for all of us.

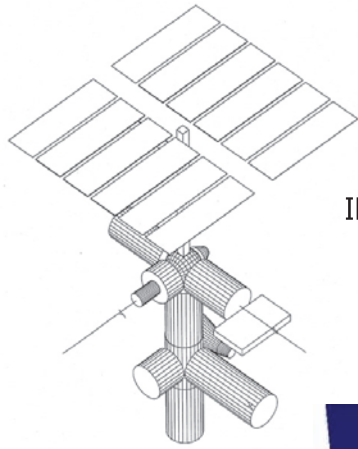
November 2009
Ernst Messerschmid

Introduction and History

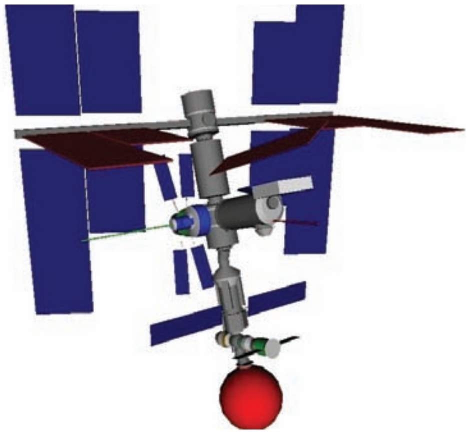
From LEO to the Moon and beyond

Developed over more than ten years at the Institute of Space Systems (IRS) of the University of Stuttgart, the conceptual design environment of the Space Station Design Workshop (SSDW) provides exceptional capabilities for space systems engineering and human space mission design. Originally adopted for space station design (hence the name SSDW), the technical expertise at IRS as well as the environment, its methodology and computer tools have considerably evolved in recent years for exploration missions beyond low Earth orbit (LEO) to destinations such as libration points, near Earth objects, Moon and Mars. It enables a small design team to run through a conceptual design process in a relatively fast time, usually one week, while addressing all aspects of concurrent and systems engineering of a complex human space exploration mission.

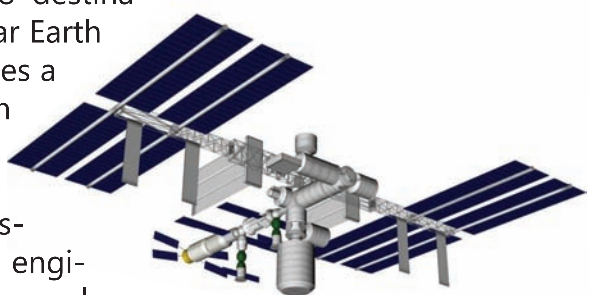
While the SSDW design environment allows professional assessment of new designs, existing infrastructures and study plans, it also provides an exceptional opportunity for hands-on student education in the form of yearly workshops. Conceptual design problems require well-trained systems engineers who are familiar with modern tools and methodologies and have gained sufficient hands-on experience at the universities or in their first years of professional preoccupation. In this context, international participants have been invited in these educational events to use and validate the SSDW design approach at exploration missions beyond Earth orbit since



IRS 1997 **LEO**

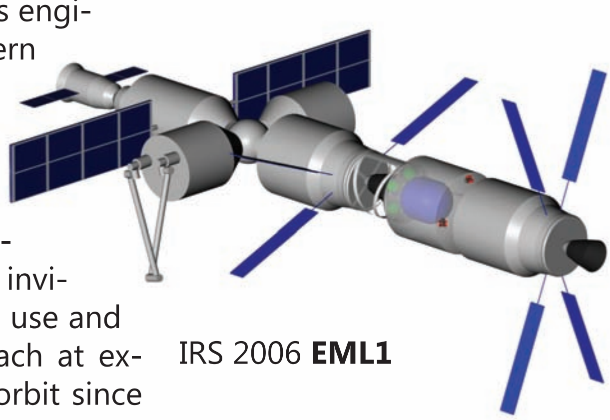


IRS 2001 **LEO**



ESTEC 2002 **LEO**

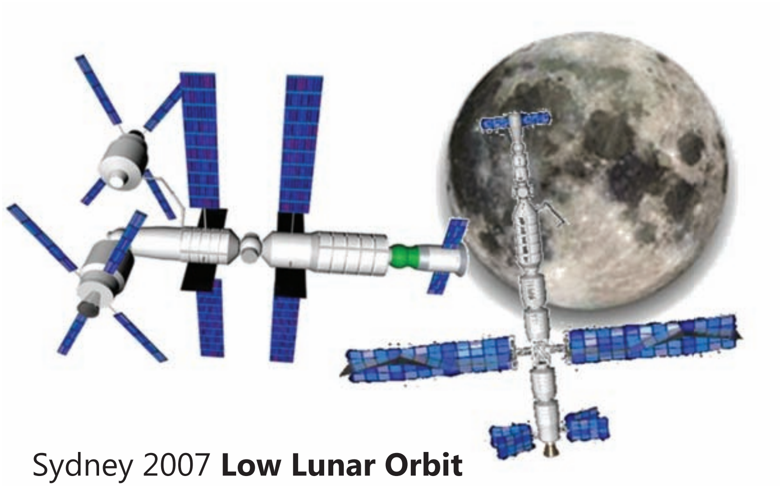
IRS 2005 **GEO**

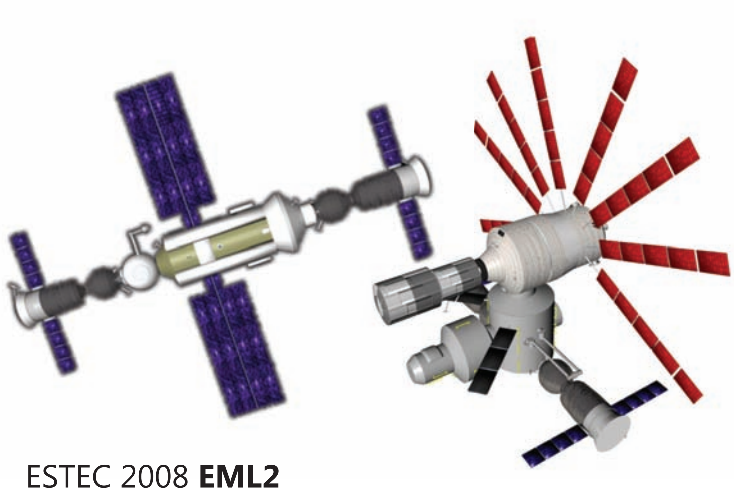


IRS 2006 **EML1**

2006, with the definition of potential transportation elements as well as lunar orbit infrastructures in support of Moon exploration. The SSDW 2009 opened a new chapter in the workshop history with the first analysis of planetary surface installations on the Moon. This step even further completes the capabilities of the design environment for orbital station, near-Earth and interplanetary transfer, and planetary surface missions.

This report shortly describes the SSDW methodology and tools for conceptual mission design, including the typical complexity of a human space project and the solutions to support, to stimulate and to accelerate the early design phase. While discussing the general concept of the design first, it provides detailed insight into the organisational efforts, the task and the resulting concept solutions of the SSDW 2009, analyzing two diverse lunar base installations and their respective environments.


Sydney 2007 **Low Lunar Orbit**


ESTEC 2008 **EML2**


IRS 2009 **Lunar Surface**

Conceptual Human Space Mission Design

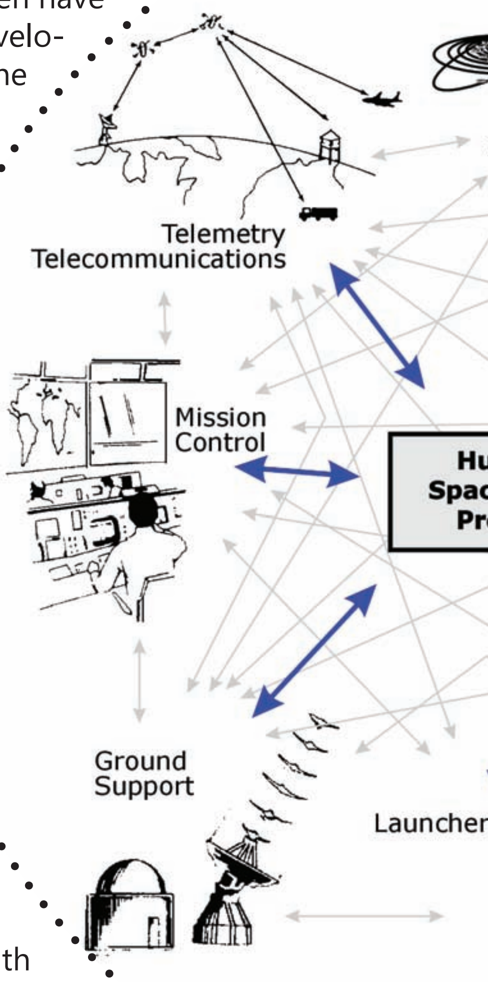
The Conceptual Design Problem

In the beginning of designing a space mission or system a mission statement lists the objectives of the customer. Politicians, economists or scientists have their specific expectations in mind to formulate these objectives. Therefore, from the engineering point of view, the given mission and system requirements are rather vague or "fuzzy" and have to be translated into primary and secondary objectives, defining technological requirements as well as political and economical constraints. The understanding and verification of the customer´s expectations and needs is crucial for project success. This early phase of a space project is referred to as the conceptual design phase.

All mission and system elements of a human spaceflight project are strongly interdependent. Changes to one element impose direct or indirect changes to largely every other element. All local interferences could yield significant consequences to the whole system. Therefore, within this early project phase of conceptual design of the overall mission and the systems, all the mission elements must be considered simultaneously down to a high subsystem requirement level. Conflicting requirements must be dispelled and fundamental mission and system parameters have to be concretised, optimised and fixed in a baseline concept following an iterative process.

The designers of complex space systems are faced with the following set of challenges:

Adverse relationship between available information and consequences of conceptual design decisions
By defining system elements during the conceptual design stage, central decisions about mission performance, system architecture, technical risk, development effort, cost, and organisational structure are made. However, sufficient information on which to base these decisions is usually not available. Subsequent design phases provide more information, but design decisions that are made then have to stay within the envelope defined during the conceptual phase and are thus limited in their mitigative potential.

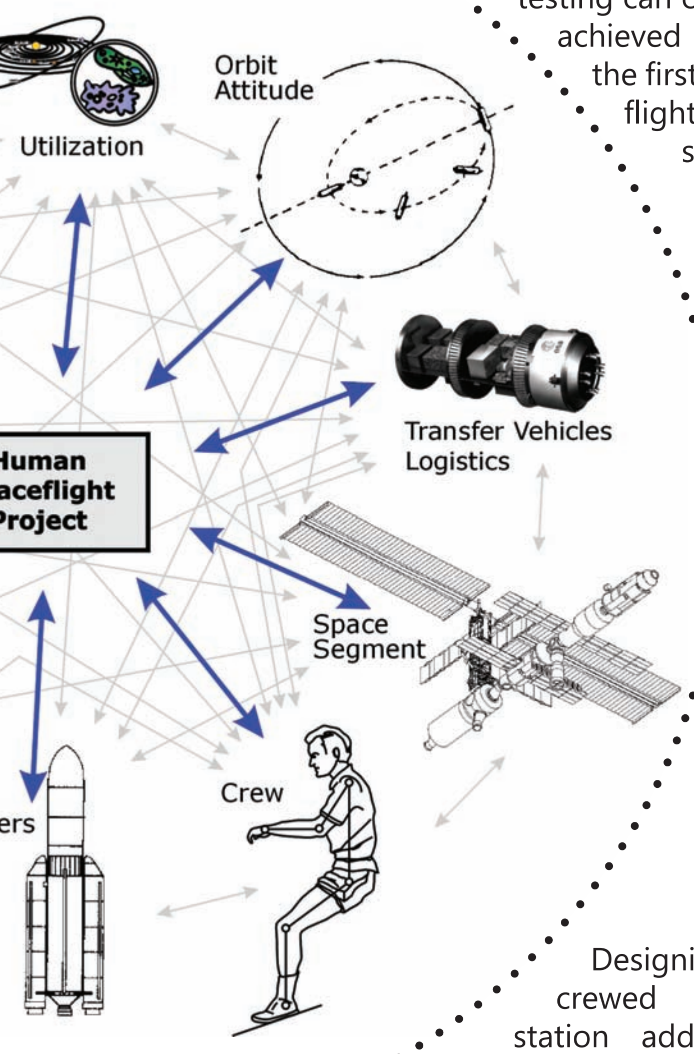


Fuzzy problem formulation
Objectives and boundary conditions are initially vague. The mission must be developed in detail together with the space system.

Strong interdependencies among system elements
The complexity of designing a space system stems from the network of links among its elements. These preclude the separate, sequential definition of individual elements.

Extreme boundary conditions

Compared to other systems of comparable technological complexity, space systems are subject to much tighter technological boundary conditions: they have to operate in the harsh space environment (temperature, vacuum, radiation, microgravity, debris) as well as withstand high g-loads during launch. They must be designed for minimum weight, and must be maintainable under difficult access conditions. Complete testing can only be achieved during the first space flight of the system.



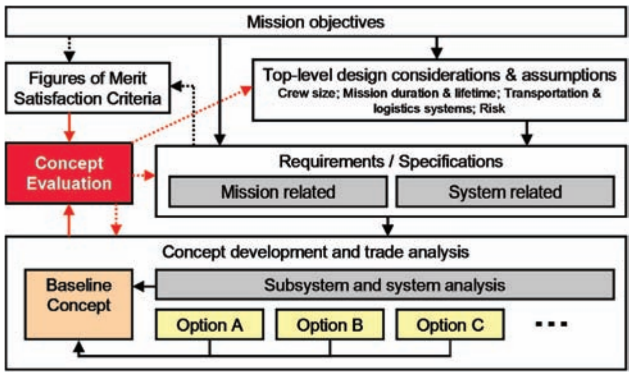
Crew

Designing a crewed space station adds the complications of life support requirements, increases demands on safety and reliability, crew integration, as well as the degree of public scrutiny in a highly politicised environment.

Methodology

The interdisciplinary SSDW methodology for conceptual design of human space systems and missions has been developed at the Institute of Space Systems. Initially dedicated to space station design, the systems and concurrent engineering approach has been extended to mission design beyond LEO, including destinations such as near-Earth libration points, Moon, near-Earth asteroids and Mars.

It combines guidelines in the technical areas of engineering, physics and system architecture development with the art of systems engineering, pointing to the soft skills such as project design flow, team management, resolving conflicting objectives and opinions, customer presentation, and exploiting individual expertise and experience.



Simple and clearly defined steps introduce the teams to the design process and provide guideance:

1. Review of mission statement and identification of objectives, requirements and constraints.
2. Development of alternative system concepts and selection of a baseline.
3. Characterization of system elements and preparation of system and subsystem budgets.
4. Evaluation and documentation of results.

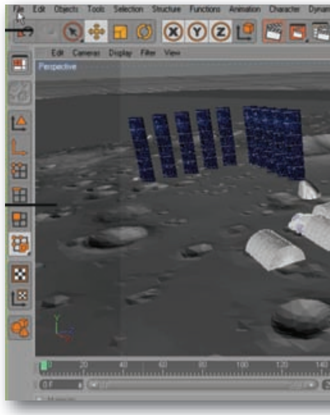
Top-level guidance is supported by specific system and subsystem instruction, recommendations, background information and software tools to facilitate design maturation and iterations. Extensive heuristics on human integration, crew composition, operational aspects and related issues (Human Factors) emphasize the human-specific issues in the design problem and contribute to the optimization with respect to habitability and crew performance.

Design teams usually consist of people of mixed gender, different cultural backgrounds and various disciplines, mirroring the heterogeneous environment of space business. While the workshop is highly goal-oriented from the perspective of the participants, it is also highly process-oriented, where team building, identifying individual expertise and coordination of the process flow become equally important.

Design Tools

Although many initial considerations and approximations can be done by hand and the value of brainstorming concept ideas should not be underestimated, the early conceptual phase already benefits greatly from dedicated, but easy-to-use software tools. They enable rapid turnaround assessment, facilitate repetitive numerical analysis, and support simulation and visualization of different options. The SSDW software package comprises a genuine set of custom-developed, highly adapted and continuously enhanced tools as well as commercially available general purpose software.

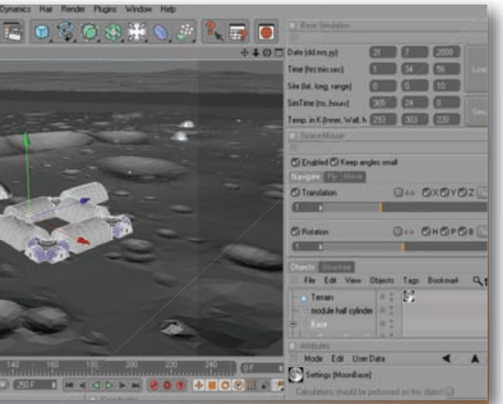
Cinema 4D and MOONBASE

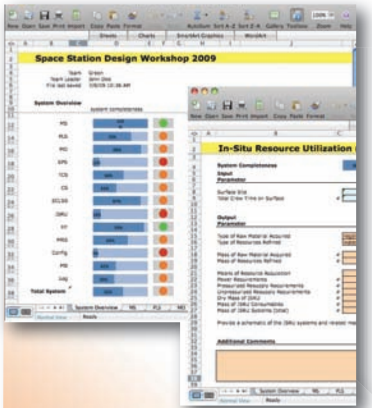


A recently created C++ add-on to Cinema 4D, the MOONBASE tool enables topographic 3D representation of the lunar surface and base modules as well as functional modeling and simulation. The tool currently uses latest released topography maps of the Japanese lunar orbiter SELENE (KAGUYA) Laser Altimeter and was used to calculate relevant environmental properties of the selected surface sites including the percentage of illuminated time, the longest continuous sun and darkness periods, the number of sunrises and sunsets (cycles), the percentage of Earth visibility, and the longest cutoff period from Earth contact as an input to the initial base design. At a later step, the tool then enables the full integration and functional modeling of the surface elements in order to assess top-level budgets regarding power and thermal energy management as well as communication links.

ELISSA

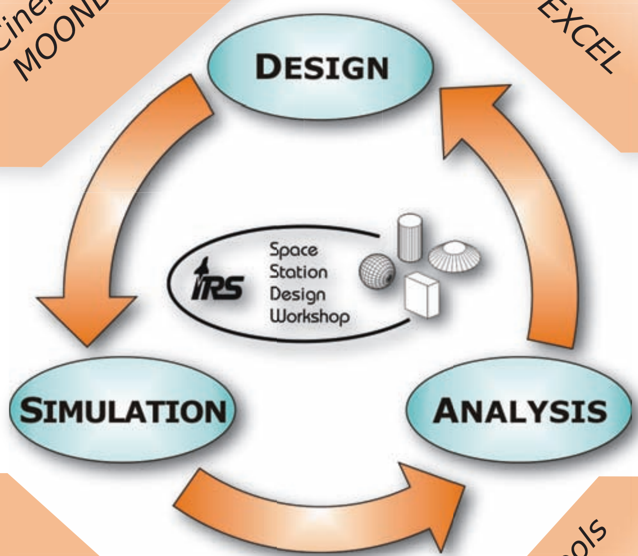
The Environment for LIfe Support systems Simulation and Analysis, implemented in the laboratory software LabVIEW, provides convenient graphical modeling of interlinked subsystems and interactive simulation of dynamic problems.
Predefined component libraries provide simulation features for life support systems as well as for the power supply and attitude/orbit control subsystems. Using drag-and-drop techniques, the user models the subsystem to be analysed before starting simulation runs.
Simulation results comprise mass, thermal and power budgets.

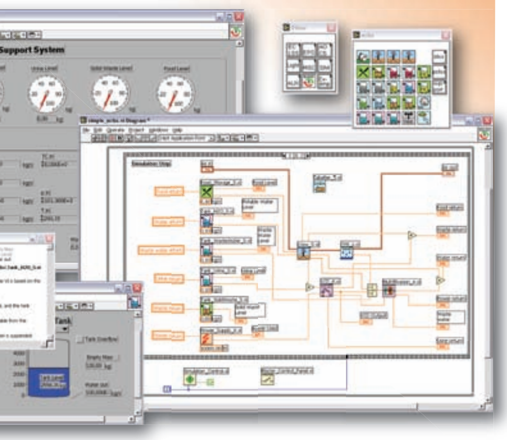




Mission Parameter Database (MPDB)

The Mission Parameter Database is an approach to facilitating the complex conceptual design process as well as the system analysis. As a top-level systems engineering tool it integrates subsystems and their interdependencies, accounting for all critical subsystem parameters required for the preliminary design phase. Furthermore, it controls the process flow and collects the overall concept budgets. Its modeling capabilities include subsystem parameters, interdependencies, and synergisms as well as design progress and maturity.





Support Tools

Commercially available software suites such as Microsoft Office (Word, Excel, Powerpoint) are extensively used for concept analysis and documentation, while Cinema 4D provides advanced visualization options. Reference material for the design process is provided through selected literature, but additional information is widely available through the use of internet resources.

SSDW 2009 at Stuttgart

Drawing from the experiences of past workshops abroad, the SSDW 2009 was held once again at the local premises of the IRS in Stuttgart, Germany. 31 students and young professionals from 11 nationalities and with diverse backgrounds in engineering, architecture and psychology were selected from a large applicant pool and invited to the University of Stuttgart from 26 to 31 July 2009 for a truly international, multidisciplinary challenge. The participants formed two competing design teams, tagged "RED" and "BLUE" , and faced an intense one-week program.

Organisation

Through the support of various sponsors and partners as well as experienced local staff, the SSDW 2009 was well-prepared in terms of infrastructure, time planning and technical contents. Without knowing the original task that was awaiting them during the week in Stuttgart, the participants were introduced to human space mission design aspects already two months prior to the workshop. Dependant on their backgrounds and preference, they received pre-workshop assignments including reference literature and deliverables in order to engage them and to level out expertise within the design teams.

Once in Stuttgart, local accommodation and transportation had been arranged for the international participants to enable a flawless execution of the intense workshop program. The infrastructure included a dedicated lecture hall and staff room as well as two well-equipped team rooms. Each of the latter featured a full set of networked computers with pre-installed software, beamer, interactive whiteboard, flipcharts and selected reference material. Furthermore, every participant received a folder with all relevant organizational information as well as dedicated guidelines, instructions and recommendations. These so-called "Recipes" include information about process milestones and associated deadlines, but also cover various aspects of space systems development.

After the welcome and introduction, the first three days included half-day lectures addressing critical aspects of human space mission design, while the participants already engaged in workshop sessions during the afternoons. This hands-on design team work

Time	Sunday, 26.07.	Monday, 27.07.	Tuesday, 28.07.	Wednesday, 29.07.	Thursday, 30.07.	Friday, 31.07.	Time
Topic	Welcome Introduction	Subsystems Lectures and Requirements Engineering	Requirements and Systems Engineering	Systems and Subsystems Engineering	Subsystems Engineering, Documentation	Evaluation, Final Presentation	
08:30		**Mission Statement**	Q&A Session	**IRS Guided Tour**	Q&A Session	Final Report Delivery	08:30
09:00		**Surface Environment**	**Life Support & ISRU**	**of Facilities**	**Workshop Session IV**	**Intro to Evaluation**	**09:00**
09:30		*J. Schlutz (IRS)*	*B. Ganzer (IRS)*	*J. Noll (IRS)*	Subsystems	**Design Results**	09:30
10:00		**Surface Construction**	**Energy Management**	**Workshop Session III**	Engineering	**Evaluation**	**10:00**
10:30		*Ruess/Braun (HE2)*	*S. Belz (IRS)*	Systems and			10:30
11:00		**Transportation Arch.**	**Workshop Session II**	Subsystems Eng.			**11:00**
11:30		*F. Renk/J. Noll (IRS)*	Initial Systems				11:30
12:00		Team Introduction	Engineering				**12:00**
12:30		& Organisation				Lunch Break	12:30
13:00	Welcome Reception	Lunch Break	Lunch Break	Lunch Break	Lunch Break		**13:00**
13:30	**Welcome & Intro**						13:30
14:00	*Mess./Zimmer (IRS)*	**Workshop Session I**	**Workshop Session II**	**Workshop Session III**	**Workshop Session IV**	**Public Presentations**	**14:00**
14:30	**Human Exploration**	Requirements	Initial Systems	Systems and	Subsystems	**and Graduation**	14:30
15:00	*Mess./Schlutz (IRS)*	Engineering	Engineering	Subsystems Eng.	Engineering		**15:00**
15:30	Coffee Break						15:30
16:00	**Systems Engineering**					**Final Reception**	**16:00**
16:30	*J. Noll (IRS)*		**System Concepts**		**Preliminary Design**		16:30
17:00	**Human Factors**		**Reviews (SCR)**		**Review (PDR)**		**17:00**
17:30	*I. Schlacht (TUB)*		Workshop Session II				17:30
18:00		**Preliminary Req.**					**18:00**
18:30		**Review (PRR)**	**Planetarium**		Workshop Session IV		18:30
19:00	**Welcome Dinner**	Workshop Session I	**Stuttgart**				**19:00**
19:30		**Social Evening**	**Social Evening**			**Social Evening**	19:30
20:00							**20:00**

Lectures / Reviews (Lecture Hall)	Groupwork (Team Design Rooms)	Other

is started early in the timeline and grows in importance throughout the workshop, where full days are dedicated to systems and subsystems engineering, modeling, simulation, and concept refinement.
Even though densely packed with project work, the SSDW also encouraged socializing between the participants and featured cultural activities on most evenings.

Mission Statement

The SSDW 2009 task assumed growing interest, technology development, and coordination for lunar exploration at international level. As such, continued operation of ISS for preparation and technology maturation and the manned activities of the US, Russia and China would be complemented by European and Japanese assets for transportation of cargo and potentially crew at a later stage.

The mission statement is well inline with current discussions at international level and thus provides relevance to exploration activities. Technically, the objective of the conceptual study is to define an evolutionary lunar base concept in an international lunar exploration scenario.

Mission Statement of SSDW 2009:

“Outline a comprehensive study of an international lunar outpost concept, with the potential to be installed within one decade, to provide sustained surface exploration capabilities and growth potential towards a permanent lunar base.
The outpost shall allow for extensive manned and robotic surface exploration in its first phase, enabling new insights into the Earth-Moon system and its development as well as technology demonstration and maturation for future human surface activities on Moon and Mars. It shall stimulate commercial partnerships as early in the program as possible, while specifically focusing on extending exploitation capabilities and commercial partnerships in its further development and continued operation after 2030.”

In particular, the outpost shall:

- provide initial habitation capabilities for extended surface stays no later than 2025
- accommodate a crew of at least 4 astronauts for missions to the lunar surface of up to 180 days at assembly complete
- provide safe haven capabilities for a crew of 4 astronauts for up to 14 days
- provide growth potential towards a sustainable permanent lunar base including commercial partners after 2030
- offer the possibility to conduct research on human aspects as well as on technology for long-term surface operations on Moon and Mars
- outline a significant contribution and visibility of Europe in the international program

The two design teams considered various options within the specified frame of the mission statement, both at systems and subsystems level.
Two distinctly different approaches were chosen for detailed assessment, characterized primarily through the site selection in the equatorial region (Team RED) and the South Pole (Team BLUE).

Team BLUE Design Results

Concept BLUE

Team BLUE conceptualized and assessed a concept in the South Pole area in the vicinity of Shackleton crater rim. Promising solar illumination for more than 95% of the time, the infrastructure can profit from the benign environmental conditions as well as from the interesting surface features in the proximity of the base, while adequate means for continuous Earth communication are more challenging.

The abundance of energy as well as considerations on extensive utilization, human interaction, and Mars forward planning led to the selection of a nominal crew of six astronauts at the polar site.

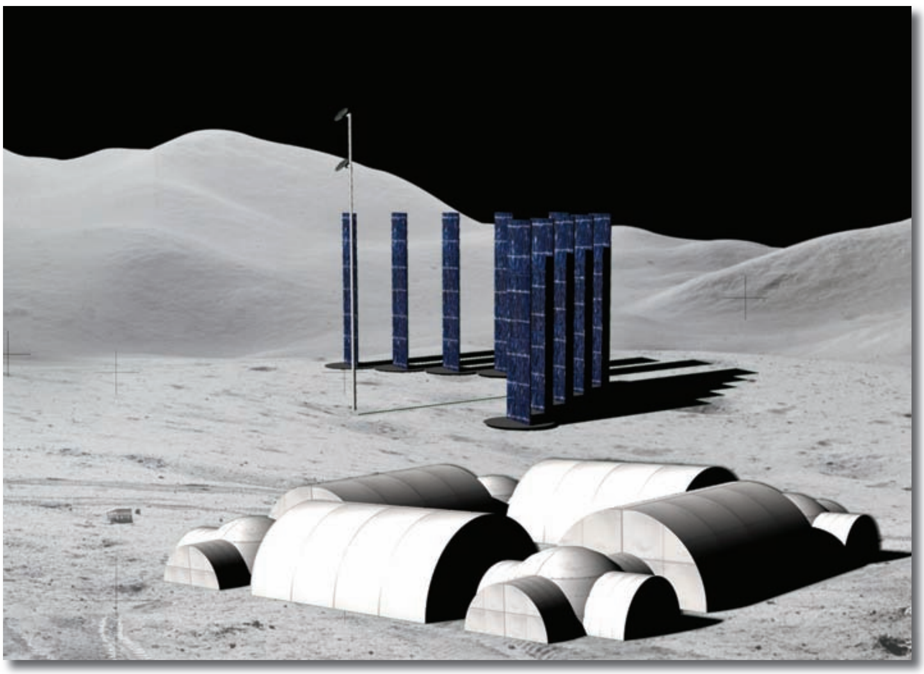
The base core consists of four pressurized modules with associated connecting nodes and airlocks in a racetrack configuration. The initial habitat is a rigid full cylinder module that will be partially buried in the lunar ground and covered by a regolith layer of up to 2 m to ensure long-term radiation and micrometeorite protection. Including an attached airlock/node assembly, this initial module allows for habitation of a crew of two astronauts very early in the program. The other three pressurized elements are half-domed cylindrical modules with a diameter of 7.4 m and a length of 9.5 m. Together with the node elements they complete the full core base configuration and provide further habitation and common areas for four astronauts, a laboratory, and storage space.

Assembly and utilization phases of the base are supported by three redundant mobile elements, namely six-legged heavy lift vehicles for unloading and cargo transportation, unpressurized mobile crew platforms, and small robotic rovers for inspection and servicing tasks.

Transportation

In order to enable continuous crew rotation for the crew of six, the development of a two-crew access to the lunar surface in addition to the US Altair lander (four crew) has been assumed. Plans for similar systems are currently discussed at conceptual design level in Russia, Europe and Japan, thus maturation of the technology until the early 2020s is potentially possible.

Similar to competing concept RED, Team BLUE assumed a share of European and US launchers to enable crew and cargo transportation of different masses and volumes. The launch manifest includes a total of 33 flights for a timeframe of about eight years, including 13 heavy cargo deliveries, 6 medium cargo landers and 14 manned missions for continued crew rotation.



Environmental Control and Life Support System

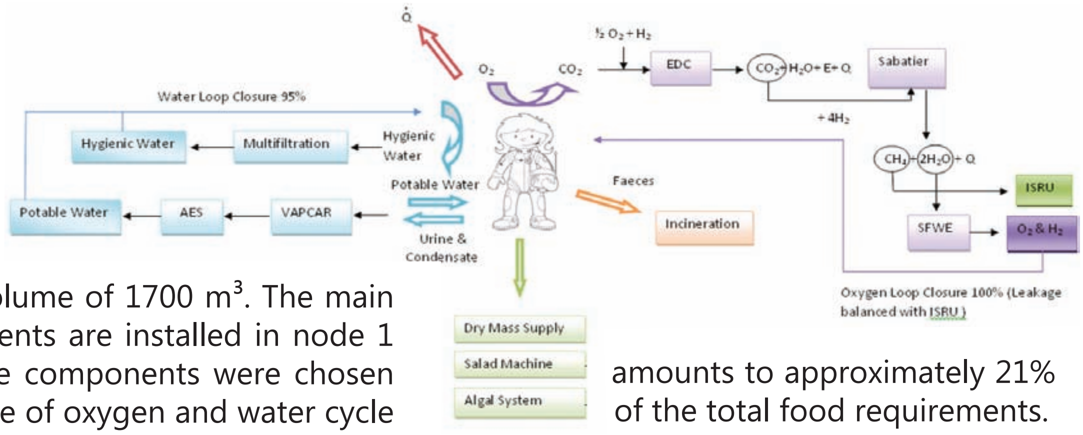
The life support system in final configuration was designed to support a crew of six astronauts inhabiting a pressurized volume of 1700 m^3. The main system components are installed in node 1 and node 2. The components were chosen for a high degree of oxygen and water cycle closure. Some innovative technologies, such as EDC or VAPCAR are included in the system for their high efficiency. The total wet mass of the system amounts to 9.9 t. At peak times the system requires 5 kW of electrical power and produces 8 kW of waste heat. The resupply needs for a logistic interval of 180 days comprise 1.6 t. The main needs are food, nitrogen, and hydrogen.

Carbon dioxide is filtered form the cabin air using electrochemical depolarized concentrators (EDC). Oxygen is recovered form the carbon dioxide employing a combination of Sabatier reactor and water electrolysis. Oxygen loss because of leakage and human metabolism (1.7 kg/d) is balanced by ISRU. The trace contaminant control system (TCCS) removes toxic trace compounds from the air. Condensing heat exchangers (CHX) control air humidity and temperature.

The water management treats potable and hygiene water separately using a decentralized concept. Hygiene water is cleaned by multifiltration (MF) only. Potable water is regained from urine and condensate by vapour phase catalytic ammonia removal (VAPCAR). The system is able to recover up to 95% of the water. Solid waste is disintegrated by incineration (SWIS – solid waste incineration system).

Although food is provided mainly by resupply from earth, two bioregenerative facilities, a salad machine and a photobioreactor, were included in the system for technology demonstration. Both components are illuminated by natural light employing a solar collector. The in-situ production of food amounts to approximately 21% of the total food requirements.

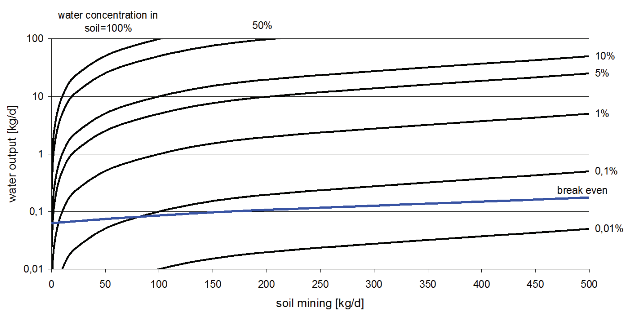
Most critical component of the system is the carbon dioxide removal. In case of a total failure of all EDC the carbon dioxide level in the cabin rises and exceeds one Vol% within four days.



In-situ Ressource Utilization

Oxygen contained in the regolith is gained by a carbothermal reduction system. It is able to extract 4 kg/d of oxygen. The ISRU system possesses a total mass of 415 kg and consumes 1.35 kW of electrical power. It processes 27.6 kg/d of regolith and consumes 0.27 kg/d of methane provided by the ECLSS. Further 0.08 kg/d of hydrogen are required for the process.

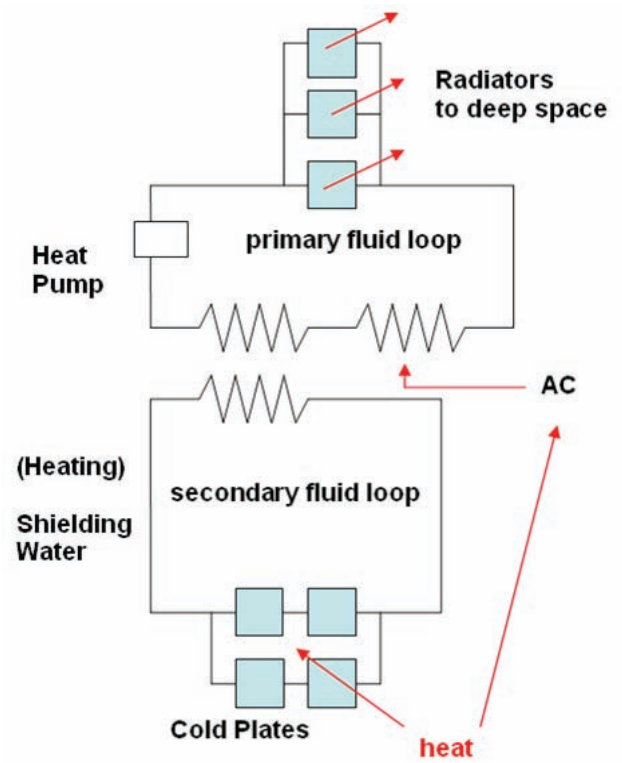
In case water ice is found in the depth of Shackleton crater, oxygen could be also obtained from melting and electrolysing water. The benefit of water mining depends on the concentration in the ground. Calculations show that concentrations as low as 0.1% can be profitable.



Energy Management

The site selection at the lunar South Pole area promises solar illumination for more than 95% of the time. Electrical power und thermal control systems can profit from the constant environmental conditions.
The modular electrical power generation is based on a photovoltaic system and enables growth of the solar cell area during development of the base infrastructure. Each single GaAs panel provides about 100 m^2 of area (5 m wide, 20 m high) and 14.93 kW_{el} of power output. Power demand of about 50 kW_{el} for initial habitation capabilities are met by four panels while the power demand for the final base configuration grows up to about 80 kW_{el} ensured by a total of ten array elements in an L-shaped arrangement. Due to this arrangement minimum power of 89.58 kW_{el} and peak power of 149.3 kW_{el} is generated depending on sun position and mutual shadowing effects.
The mass of the complete photovoltaic system is about 3.26 t. For the longest lunar night of three Earth days a regenerative solid oxide fuel cell system of about 2400 kg is installed. Hydrogen and oxygen are stored in cryogenic tanks to minimize leakage rates. The tanks are placed in shaded areas (140 K) in order to minimize cooling effort.

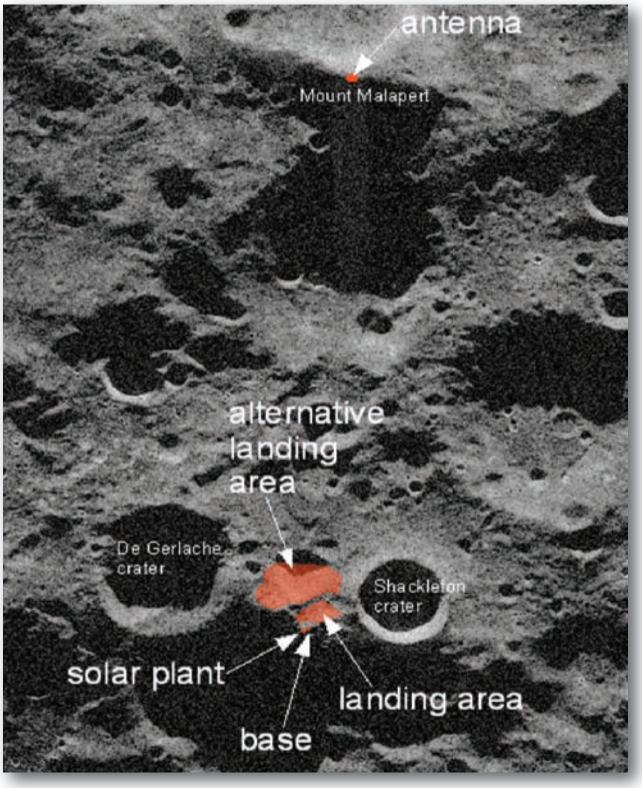
Obtaining oxygen or water from ISRU or methane from the ECLSS are synergetic options. A small independent power system based on Cassini type radioisotope batteries (mass 0.1 t, power 0.596 $kW_{el,EOL}$) is installed for LED landing site lighting.



Thermal control of the base is achieved by passive (insulation) and active techniques (fluid loops and radiators). Modules are covered by a regolith layer 1.5 m on the top and 2 m at the sides. Nodes are insulated outside with a silver mylar foil and inside with 0.1 m thick thermal protection wool layer. Windows of 15 cm thickness allow no IR-transparency. The active system consists of two pumped fluid loops (each redundant) and five horizontal, flat condensing radiators (54 m^2, 810 kg each) providing a total heat rejection capability at assembly complete of 152 kW_{th}. The radiators must be regularly cleared from lunar dust.
Inside air temperature is controlled by water temperature in cold plates at the walls (max. heating capability of 6 kW_{th}) inside the base and air conditioning (max. heating capability of 12 kW_{th}). The total mass of the thermal control system is estimated at 8.73 t.

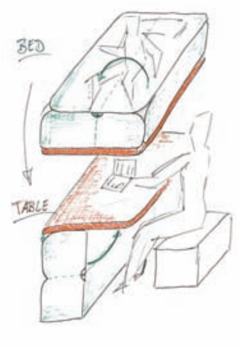
Communication System

A critical aspect for concept BLUE was the continuous communication link to Earth, where the selected site regularly faces cut off periods of up to 11 days. Orbital relay satellites were avoided due to the intense efforts of establishing and maintaining a constellation for continuous coverage and the added pointing requirements for ground based systems. However, an innovative solution is implemented, in which a relay station is installed on the peak of Malapert Mountain, overlooking the South Pole area at about 150 km distance from the selected base location.



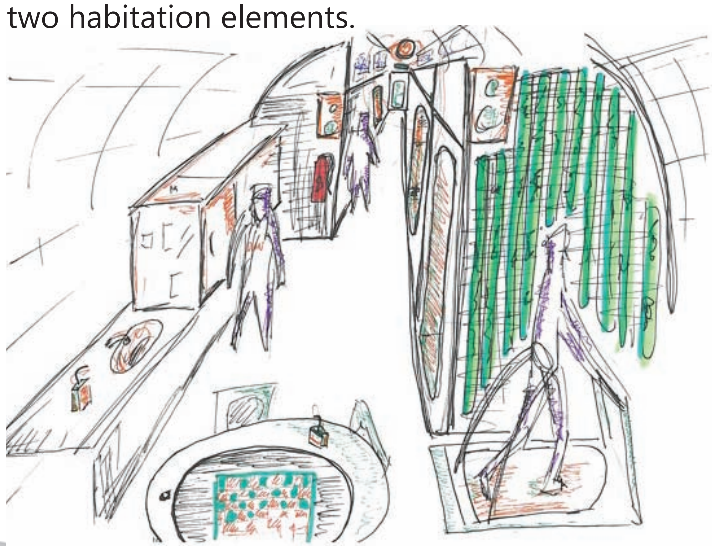
Simulations show a high Earth visibility of more than 99% for the optimized peak location. In order to account for landing accuracy and deployment of the relay system as well as to avoid obstruction of the antennas by local features, the two parabolic antennas (S-, Ka-band) are installed on a 30 m mast. With the site being directly visible from the surface base, optical laser communication terminals are used for high bandwidth transmissions of up to 200 Mbps. Backup S- and Ka-band antennas are also provided at the lunar base site for direct Earth communication during the initial installation phase and when Earth visibility is available. The ground segment on Earth consists of TDRSS ground stations for Ka-band communications and ESA-ESTRACK ground stations for S-band communication.

Human Factors



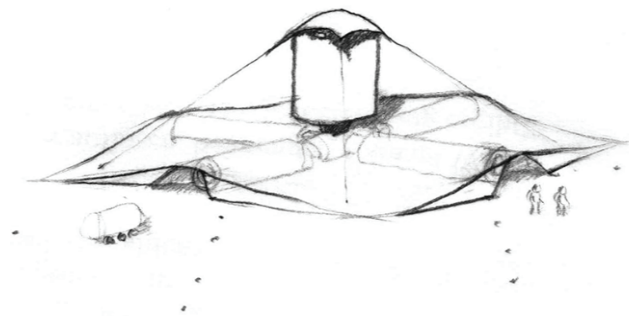
Human Factors become notably important when considering crew surface stays of 180 days and more. Thus, human experience and human-centred design has to be combined with latest technology developments.

The racetrack configuration of the lunar base reflects historical human dwellings and creates a feeling of safety against a potential harmful environment, supporting psychological well-being. Local materials are used to protect the base from radiation, with regolith covering reaching up to about 2 m. In the interior, dynamic multi-purpose furniture, ambient lighting and quarter`s walls folding systems, allow each person to be an active creator of his/her own place and space, providing the possibility to arrange the modules in almost countless combinations. This configuration also provides an effective guard against boredom and depression due to monotony. The six crew quarters provide 11 m^2 (27 m^3) each and are distributed in the two habitation elements.



Team RED Design Results

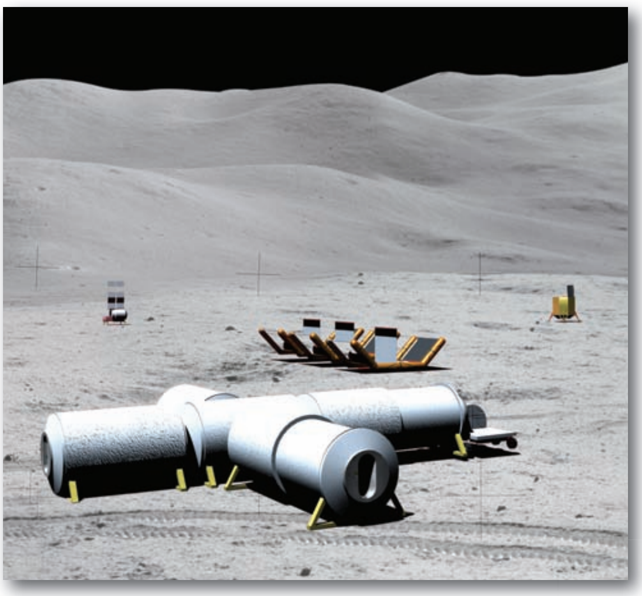
Concept RED



Team RED decided on a lunar surface installation at the near side eastern limb, north of Mare Fecunditatis, due the accessibility and anytime return capability for transportation as well as constant and direct Earth communication and visibility. The proximity to the limb and the far side might also allow for exploration of far side locations once extended mobility capabilities are installed. Dictated by the site selection, a major challenge of the design is the energy management during long and repetitive darkness periods in extended surface operations.

The lunar base of team RED provides habitation and utilization for a crew of four astronauts in four pressurized modules. At assembly complete the base concept comprises:

- one service module as central connecting node
- an initial habitat for early crew accommodation
- an extendable habitat for long-term habitation,
- a laboratory element
- an extendable storage and supply module



The primary structure is a monocoque composite pressure shell, to which a 60 cm regolith cover is applied robotically for radiation and micrometeorite protection. At a later stage of the infrastructure development, the team also outlined the addition of an inflatable pressurized module to increase utilization and habitation volume of the base.

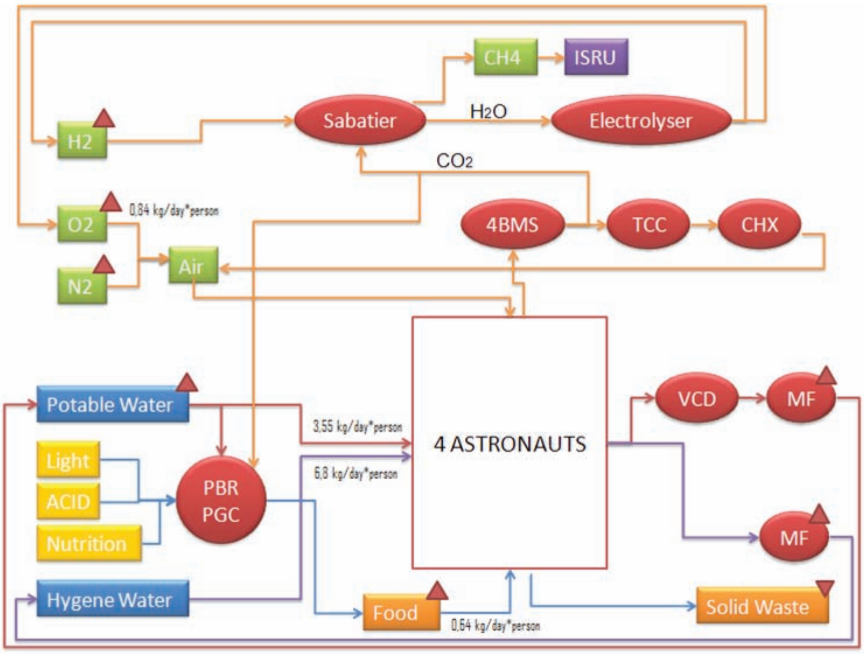
Mobility and utilization aspects are enhanced by a set of robotic assets such as a large rover platform with pressurized cabin, small scouting robots as well as cargo carrying EVA assistant platforms.

Transportation

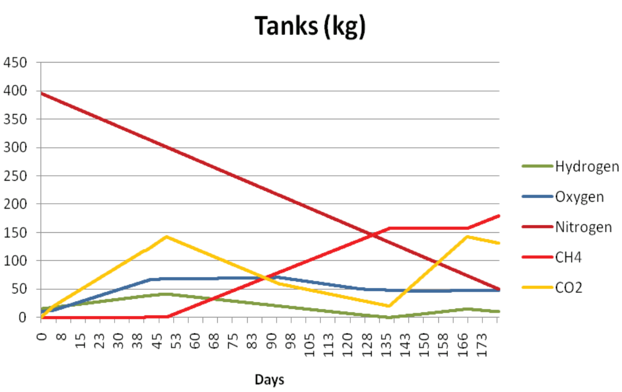
Build-up of the lunar surface base is initiated in 2022 with site preparation and initial robotic mobility delivery, while first surface modules arrive in 2023. It uses a combination of the envisioned US launch systems Ares I (crew) and Ares V (crew lander, heavy cargo) and the European Ariane 5 for medium and light cargo delivery to the lunar surface. Through a total of 11 cargo flights (6 heavy, 3 medium, 2 light), the base reaches assembly complete and permanent habitation capability in 2025, at an installed surface mass of about 119.5 t.

Environmental Control and Life Support System

The main life support system was designed to support a crew of four astronauts inhabiting three modules with a pressurized volume of 240 m^3. The system is installed in the service module as well as in the laboratory module and allows for a high degree of oxygen and water cycle closure. In general very robust and well approved technologies are used. The dry mass of the system amounts to 6.6 t. It requires 3 kW of electrical power and produces 4 kW of waste heat. The entire life support system (including rover ECLSS) requires 1.7 t of resupply every 180 days. Resupply needs are mainly food, nitrogen and water.
Carbon dioxide is filtered from the cabin air using four-bed molecular sieves (4BMS). Oxygen is recovered from the carbon dioxide employing a combination of Sabatier reactor and water electrolysis. The trace contaminant control system (TCCS) removes toxic trace compounds from the air. Condensing heat exchangers (CHX) control air humidity and temperature.
The water management treats potable and hygiene water separately using a decentralized concept. Hygiene water is cleaned by multifiltration (MF) only while potable water is obtained by vapour compression distillation (VCD) and multifiltration of urine and transpired water. The system is able to recover about 90% of the water.
Food is provided mainly by resupply from earth. For technology demonstration two bioregenerative facilities, a salad machine and a photobioreactor, were included in the system. Both components are illuminated by natural light during day time and are switched off at night time. A solar collector concentrates the light onto optic fibres conducting the light into the components.
The pressurized rover is provided with an open loop life support system able to support two astronauts for ten days. Oxygen and potable water is supplied from tanks and carbon dioxide is removed by LiOH cartridges.



Waste water in the rover is stored and added to the water treatment after returning to the base.
For safety reasons all critical technologies of the life support are installed as two separate components. The most critical components are the molecular sieves; if they fail it takes 1.8 days for the carbon dioxide level to rise above one Vol%.
In case of a total system failure, contingency is provided in the save haven modules by oxygen candles, LiOH cartridges and potable water tanks allowing a crew of four to survive 14 days. If the LiOH cartridges are expired or fail the carbon dioxide level reaches one Vol% after approximately seven hours.



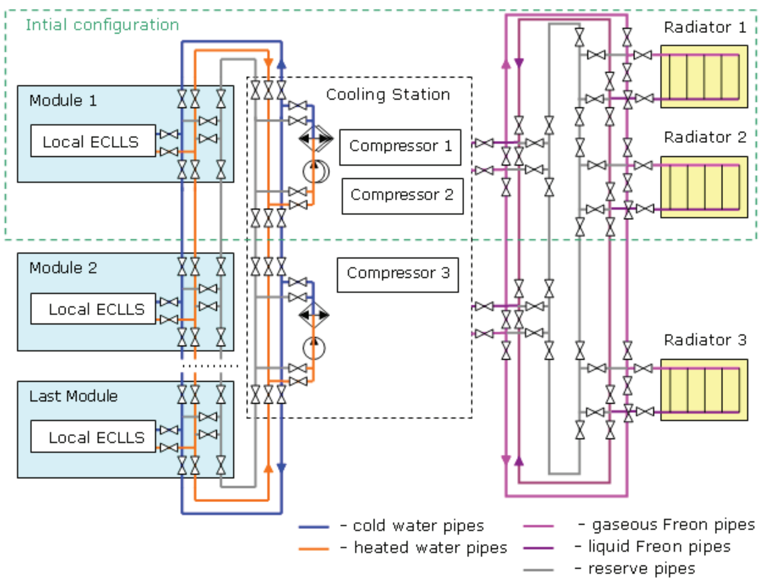
In-situ Ressource Utilization

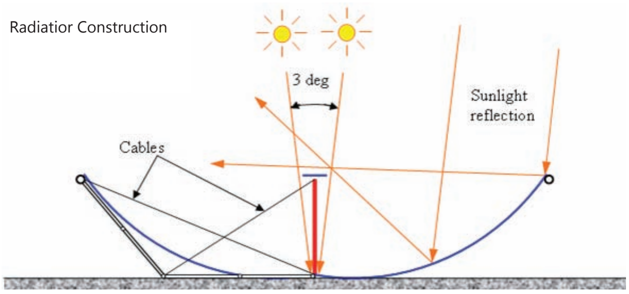
A technology demonstrator for in-situ resource utilization is operated at the base. The carbothermal reduction system is able to extract 1.67 kg of oxygen per day from the lunar regolith. The oxygen is used to compensate atmosphere and metabolic losses in the ECLSS. The ISRU demonstrator has a total mass of 372 kg and consumes 0.8 kW of electrical power. It processes 11.6 kg/d of regolith, which is transported to the plant by rovers. The carbothermal reduction process requires methane (0.11 kg/d) and hydrogen (33 g/d); both is provided by the ECLSS. Considering the savings in oxygen resupply the total mass of the ISRU system is amortized after 180 days of operation.

Energy Management

The site selection near the lunar equator is highly challenging for energy management design due to alternating 14 Earth days of sun light and 14 Earth days of night. Team RED chooses for a nuclear fission reactor based on the NASA developed SP-100 reactor as a baseline, generating continuous power of about 100 kW_{el} in order to meet the average power demand of 70 kW_{el} by crew and instrumentation. Trading off against a large photovoltaic system with power storage by regenerative fuel cells the nuclear system with a regenerative fuel cell back up is three times more lightweight. The reactor is installed at 2 km distance from the base at the opposite side of the landing site. Including cable connections, power control devices, additional shielding, and radiators the nuclear system has a mass of about 12.34 t. Li-Ion batteries dischargeable within one hour at 2 kW_{el} are integrated in the service module for short time peak power demands. The mass for the battery stack is 30 kg. Backup systems for continuous power in emergency cases are also included in the habitats. To meet the power demand of 2 kW_{el} during 14 days, a regenerative solid oxide fuel cell system is used at a mass of about 0.34 t including tank, hydrogen, and oxygen mass. Until nuclear power is available, a small photovoltaic system is setup within the first uncrewed flights for recharging the batteries of rovers. The solar array area is 16 m² providing 4 kW_{el} during sun light.

For thermal control of the base passive (insulation) and active techniques (fluid loops and radiators) are used. The pressurized modules are covered by a 0.6 m thick regolith to minimize high heat fluxes between in- and outside. Airlocks and docking points are coated with multi-layer insulation. A double redundant system with internal fluid loops of water from the ECLSS, three external fluid loops of freon, three compressors, and two units of vertical condensing radiators (coated with white paint ZnO) with shades (coated with silvered mylar foil) ensures a heat rejection capability of up to 102 kW_{th}. One radiator is 6 m long and 5 m high.
Heating requirements of 2 kW_{th} have been calculated for lunar night survival. The total mass of the thermal control system is estimated at 7.86 t.





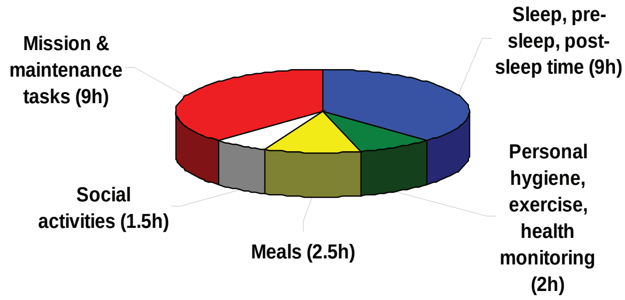
Communication System

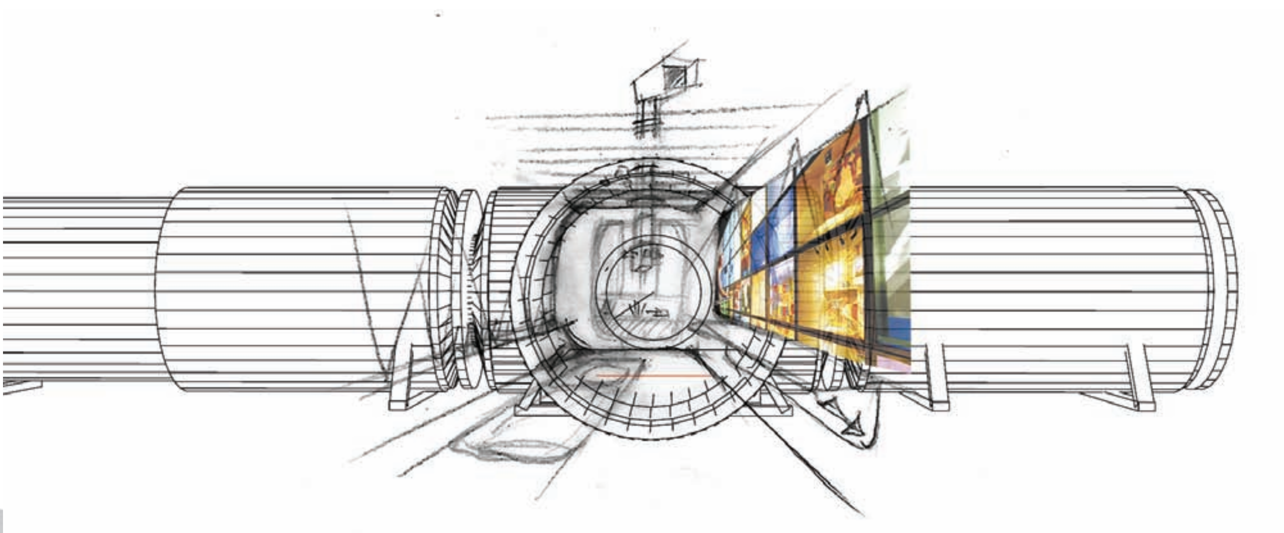
The lunar base location provides 100% link coverage to Earth. The communication system of the base uses S- and Ka-band for Moon-Earth transmissions. Redundant parabolic antennas allow for 50 Mbps (Ka) and 19.2 kbps (S) data rates at a low mass of about 50 kg each. Relay satellites could be installed in the Earth-Moon libration points to support inter-element communication links for extended mobility activities, while primary contact to Earth is provided by a direct link using TDRSS relay satellites and ground stations.

Human Factors

Human Factors Engineering is essential in the design of long duration surface infrastructures, where an ideal habitat system should support human´s experiences allowing the active gain of further knowledge. While the allocation of windows was disregarded for safety and cost reasons, many creative ideas and the use of modern technology has been introduced to avoid the psychological and functional problems of confined space and outward visibility.

The walls between crew quarters and walkways are made of "liquid crystal intelligent glass" to simulate windows. In crew quarters, the use of periscopes supports an individual place of exploration and spiritual and meditative dimension. Light colours and intensity can automatically change for day/night simulation or animation. Floors are flexible to allow for increased comfort of movement and relaxation. The "Camera Obscura" provides a really innovative idea, where little holes in the wall of a dark module sealed with lenses will create the inverted projection of the external environment.
The crew quarters are distributed in two highly personalized habitation modules, also featuring personal communication centers based on augmented reality foldable touch screens.
The composition of the four crew is assumed to comprise a commander (pilot & management), an engineer (pilot & servicing tasks) and two scientists (research), where gender mix is possible for psychological balance. The crew timeline for working days is distributed as shown below. One free day per crew and week is envisioned in accordance with the activity schedule. Crew operations will be more extensive during lunar day.





Design Evaluation

Evaluation Process

Throughout the design phase the team members gain considerable insight and experience in their respective fields of expertise and the available technologies, constraints and complexities. Thus, they are directly involved in the evaluation of the competing design concepts. The original teams are disbanded and the participants are assigned to one of seven evaluation committees depending on their role in the design phase, where they discuss and reflect their solutions and approaches taken.

The aspects assigned to the evaluation committees are:
1. Utilization and Programmatics
2. Overall Configuration
3: Mission Design
4. EPS/TCS Subsystem Issues
5. ISRU and Robotics Subsystem Issues
6. Human Aspects
7. Operations and Servicing

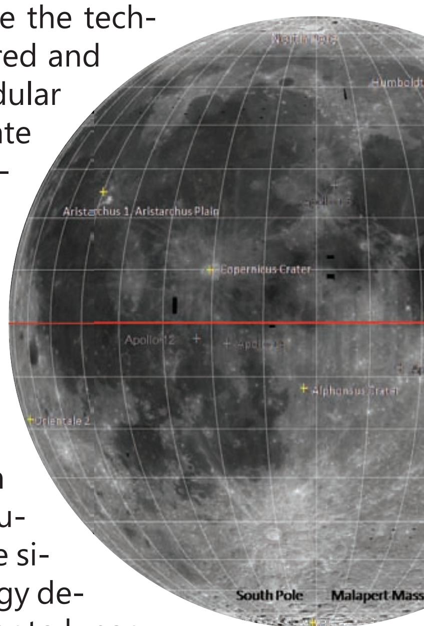
This section presents only some selected findings of the evaluation phase.

Mission Design

The major aspect of mission design is the aspect of site selection and the resulting hardware concept. With the adverse lunar surface sites chosen by the teams they provided a good assessment of the particular difficulties of each lunar region. While Team RED chose a robust design concerning energy management, Team BLUE´s approach seemed more optimized to the specific surface characteristics.
In terms of the transportation and logistics scenario, Team RED better incorporated international participation and considered all technical and programmatic constraints. However, the assembly strategy of Team BLUE advantageously allowed for early crew presence and continuous expansion of the surface infrastructure.

EPS/TCS Subsystems Issues

The technologies and implementation of the energy management subsystems are very different in both teams, mainly due to environmental characteristics of each surface location.
Team BLUE uses photovoltaic arrays as the main power source, where the technologies are highly matured and readily available. The modular approach in the ten separate arrays provides redundancy to single element failure and allows for further expansion. However, the long term effects of dust degradation and missing dissimilar redundancy are negative points in the concept. The EPS of Team RED primarily uses the nuclear fission reactor, where significantly more technology development is required prior to lunar deployment. However, the concept includes dissimilar redundancy with different systems for generation and storage for limited periods of time. Both systems are optimized for their respective locations. The EPS of Team BLUE scored slightly higher due to its simplicity and robustness.

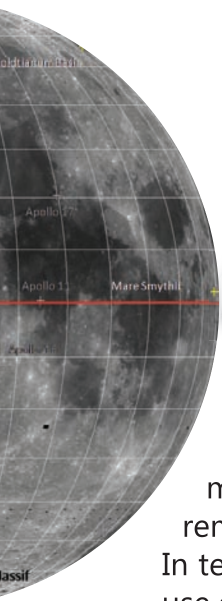


The approach to thermal control is more similar for both teams, where redundant fluid loops, heaters and multiple condensing radiators ensure safe operation at all times. Team BLUE explores synergies with the

ECLSS, while Team RED decided on an independent system with shaded radiators for higher efficiency. Overall, both teams' TCS solutions were evaluated equally suitable for the tasks.

ISRU and Robotics Subsystems Issues

Both teams explored the utilization of in-situ resources, particularly oxygen, for life support and potentially water. The ISRU concepts use the same technology and scale.



While Team BLUE nominally included the ISRU products for life support closure, Team RED decided on a demonstrator system prior to its integration. The difference of soil composition and thus output products for the two locations can not be determined from currently available data and remained unevaluated.

In terms of robotics, the teams assessed the use of various mobility platforms within their surface operations. Team RED outlined the utilization of a modular rover platform that is enhanced by a pressurized cabin for longer duration crew excursions, significantly increasing exploration range. However, they lack the versatility of the legged heavy mobility platform of Team BLUE for both cargo handling and transportation.

Overall, both teams equally well identified and explored the potential of ISRU and mobility systems in their concepts.

Human Aspects

The Human Aspects committee evaluated the approaches to life support, radiation protection and Human Factors engineering in the team concepts.

Both ECLSS look almost similar compared to each other. Team BLUE achieves full closure of the air cycle through ISRU, while Team RED accepts relatively high losses of up to 80%. Also the selected technologies allow for a water cycle closure of about 95% (BLUE) compared to 90% (RED) at the cost of higher power consumption. Synergisms to ISRU are considered in both systems, but RED has better integrated redundancy. Overall; Team BLUE´s ECLSS concept scored slightly higher due to the advanced closure and reduced resupply logistics requirements.

The radiation protection for both bases primarily uses lunar regolith with differing thicknesses. However, current knowledge of the accurate radiation levels on the lunar surface makes it hard to evaluate the quantitative impacts. The calculated protection means are considered appropriate for the concepts based on the assumed radiation hazards, where Team BLUE used more conservative values and thus incorporate added robustness to this uncertainty.

The Human Factors considerations can hardly be captured quantitatively, and different approaches have been implemented in both teams. Aspects such as crew composition, operational timelines, interior design, zoning, and recreational activities were assessed, where Team BLUE received slightly higher score from the participants.

Location	Coordinates [deg]	Sun [%]	Longest day [Earth days]	Longest night [Earth days]	Sunrises [-]	Earth visibility [%]	Earth cut-off [Earth days]
Equat. Limb (RED)	0.8N, 60E	50.1	15	15	123	100	0
Shackleton (BLUE)	89.5S, 135W	97.2	290	3	85	66.6	11

Operations and Servicing

This committee captured the solutions for operations, communications, EVA and surface mobility as incorporated by the team designs.

Particularly the communication approaches are very different. Team RED has a continuous direct link to Earth, but incorporated lower data rates. Due to their polar location, Team BLUE requires a relay station for Earth communication for up to 11 days. However, the innovative installation of a communications antenna system on Malapert Mountain, overlooking the south pole region, solves this problem. The integration of optical communication terminals on the station and the relay potentially increase available data rates significantly.

EVA activities are prominent in the surface exploration for both teams, but Team RED has longer excursion ranges with their pressurized rovers. Their suit lock for crew ingress and egress accelerates EVA preparation and respects both planetary protection as well as dust protection aspects. However, the airlock solution of Team BLUE is more robust against mechanical failures and allows for easy equipment and cargo transfer into the pressurized volume.

Summary Table

General Aspects	**Team RED (LunoX)**	**Team BLUE (LOReTTA)**
Location	0.8N, 60E (Equatorial)	89.5S, 135W (South Polar)
Crew size	4	6
Number of pressurized base elements	5 (central service, 2 habitats, laboratory, storage)	8 (2 habitats, laboratory, storage, 4 nodes)
Installed surface mass	~ 119.5 t	> 200 t
Number of flights	11 for assembly 2 crew, 2 cargo per year for operations	19 cargo, 14 crew flights during 8 year assembly & operations
Estimated program cost	45.6 B€	65.2 B€
Subsystems		
ECLSS	Hybrid (closures: 90% water, 80% air, 20% food)	Hybrid (closures: 95% water, 100% air with ISRU, 21% food)
ECLSS Logistics	1.7 t per crew mission	1.6 t per crew mission
EPS	Nuclear fission: 100 kW Backup systems. PV, RFC, Li-Ion	PV arrays: 74.7 to 149.3 kW RFC: 200 kWh
TCS	Double redundant fluid loops with compressors, heaters, 3 shaded vertical condensing radiators	Redundant pumped fluid loops, heaters, 5 flat condensing radiators
Radiation/micrometeorite protection	0.6 m regolith cover	1.5-2 m regolith cover
Communication System	S-/Ka-band direct to Earth, 50 Mbps	S-/Ka-band, relay antenna on Malapert Mt., up to 200 Mbps

Conclusions

The SSDW 2009 at the Institute of Space Systems in Stuttgart was a very successful, intensive, and interdisciplinary event with 31 highly motivated participants from all over the world who were confronted with future human exploration strategies. While the previous workshops handled exploration scenarios for stations in space, for the first time the participants of this year´s workshop were tasked with the complex problem of conceptual design of a crewed base on the lunar surface.

Both teams were supported by a concise, yet flexible methodology, by customized, intuitive, rapid-turn around software tools, and by experienced scientific staff. The elaborated lunar base concepts show a sophisticated work in all major aspects of conceptual design and meet the objectives and requirements issued in the Mission Statement. The difference in site selections and system approaches allow an interesting comparison of the solutions in further intensification of continuously evolving SSDW methodology while importance of lunar environment modeling and simulation for the early design process has been confirmed.

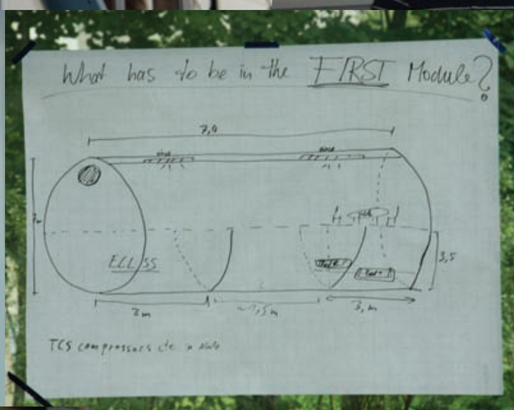
The SSDW 2009 tested and verified again its developing methodology and tools. Future workshops will benefit from its findings, seeing also further expansion of the tool capabilities to speed up the design process through integration of analysis and simulation tools with various levels of detail. More exploration mission scenarios towards Moon, Mars, and other interplanetary destinations within our solar system will provide a great range of Mission Statements for upcoming workshops, creating a design environment and educating capable system engineers for our future in space.

We want to thank all guests, supporters, and participants for their commitment and contributions that made this SSDW such a success and valuable experience for all of us.

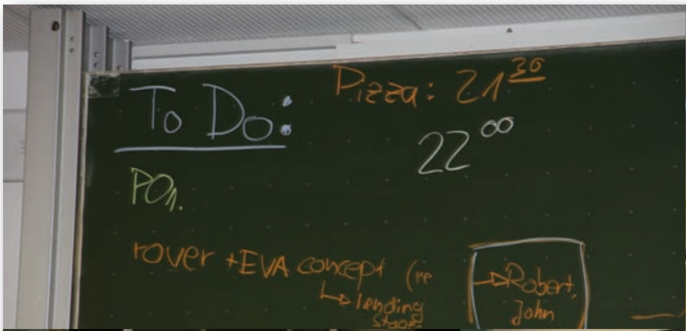
Workshop Impressions

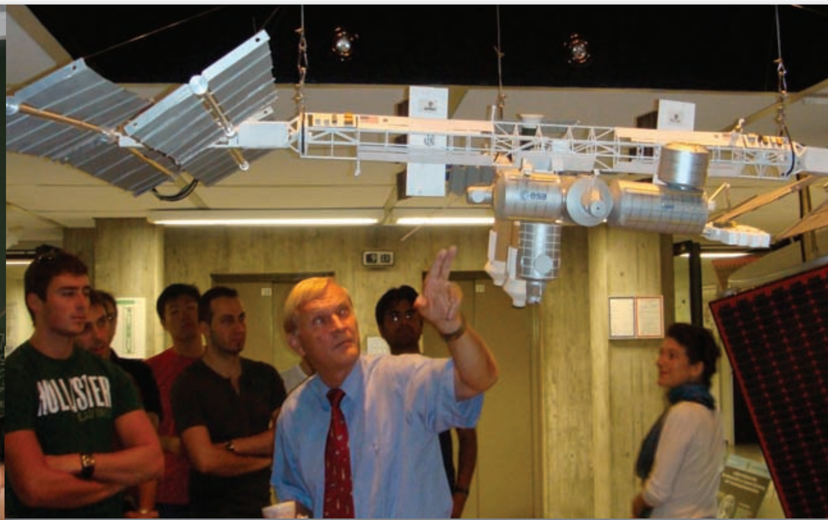
“It was great, a good mix of learning and social events. I had a good time and learned a lot.”

"Overall, it really was an awesome experience. … I personally wish that there were more events like this, but I think SSDW really is an outstanding example of hands-on education, fun and get-together."



"I think the SSDW is a great opportunity for students to gain new knowledge and have some practical experience! ... There was a lot of stress, but it's compensated when you see the final results and what you get after putting a lot of effort in the work."





"The workshop was a great experience;
it could have last for more than one week!"

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SSDW 2009 at the University of Stuttgart, Germany

31 students ...

... 11 countries ...

... 5 days ...

... 2 teams ...

... 1 mission

Conceptual development of a manned lunar base in an interdisciplinary education event!