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MOON BASE 2030

JULIUS-MAXIMILIANS-UNIVERSITÄT WÜRZBURG
CHAIR OF COMPUTER SCIENCE VIII
AEROSPACE INFORMATION TECHNOLOGY
PROF. DR.-ING. HAKAN KAYAL

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Vorwort zur Lehrveranstaltung

Im Zuge der Vorbereitungen und später mit der ersten erfolgreichen Mondlandung von N. Armstrog und B. Aldrin 1969 war man zuversichtlich, dass kurz danach die Besiedlung des Mondes anstehen würde. Es gab daher zahlreiche Studien zu dem Thema, wie die Besiedlung des Mondes am besten gelingen könnte. Wichtig war in diesem Zusammenhang konkret die Frage, wie das Szenario in den ersten 2-3 Jahren aussehen müsste. Die anfängliche Begeisterung dafür konnte nach der Beendigung des APOLLO Programms aber nicht mehr aufrechterhalten werden.

Langfristig ist dennoch von einer Kolonisierung des Erdmondes und anderen Planeten wie dem Mars auszugehen.

Es gibt dazu erste konkretere Ansätze in neuerer Zeit, ergänzt um das heutige Wissen über die Beschaffenheit des Mondes und der Planeten, wie z.B. die „Mars One“ Initiative zur Landung von Menschen auf dem Mars in 2023. Mit der erfolgreichen Landung eines Rovers auf dem Erdmond Ende 2013 setzt auch China seine Bemühungen zur Vorbereitung einer Mondbasis konsequent fort. Im Rahmen von ESA Studien wird der Einsatz von 3D-Druckern zum Bau von Gebäuden auf dem Mond untersucht.

Vor diesem Hintergrund wurde im Rahmen der Lehrveranstaltung „Entwurf von planetaren und orbitalen Basen“ ein Semesterprojekt durchgeführt. Das Ziel war der konzeptionelle Entwurf einer Mondbasis inklusive der Simulation von wichtigen Parametern aus den Bereichen wie Logistik, Lebenserhaltung, Ressourcengewinnung, Umweltbelastung, Energieversorgung, Kommunikation oder Oberflächentransport. Der in sehr intensiver Arbeit erstellte Entwurf der Mondbasis verdeutlichte allen 12 studentischen Teilnehmern den äußerst interdisziplinären Charakter von komplexen Systemen in der Raumfahrt. Zahlreiche besondere Aspekte und Detailfragen beim Entwurf einer Mondbasis, die bei anderen Raumfahrtsystemen wie z.B. Erdbeobachtungssatelliten keine Rolle spielen, mussten beachtet werden.

Der Entwurf wurde in Form des vorliegenden Endberichtes zusammengefasst und durch eine Abschlusspräsentation ergänzt. Ich danke allen Teilnehmern für Ihre motivierte, ausdauernde und interessante Arbeit und hoffe, dass sie in nicht all zu ferner Zukunft auf das Thema in ihrer beruflichen Laufbahn zurückkommen können.

Prof. Dr.-Ing. Hakan Kayal
13. Februar 2014



Preface

Years have passed, since the last human left our Earth's naturally satellite, the Moon. For many years, engineers have been dealing with the idea of return. However, NASA canceled their Constellation Program in 2010: The lunar revival is too expensive.

In 2013, a team of twelve Computer Science and Aerospace Engineering students studied a potential manned lunar base, scheduled to the year 2030 of human return. While Constellation was not the first, our study will not be the last. But, a long-term project like the manned base on Moon is driven by one single notion – while driven by many new approaches and managed by humanity. This report shall record our ideas, our assumptions and concepts, our results and experiences. Ideally, it is a small but further step to the Moon.

The project MOON BASE 2030took the winter term 2013 and a vast amount of our time. We investigated the lunar environment and looked for past, current, and future technologies; while some of the solutions presented in this study have been well-tried in aerospace missions, others have still experimental character on Earth, too. By and by, a couple of individuals became a team, and neither technical difficulties nor drawbacks have prevented us from presenting at all: *Our lunar base vision*.

I would like to thank Prof Hakan Kayal for the supervision of our project, for the instructions and guidance through the term, and for his experiences about planning and operating aerospace projects and missions. Notably, I wish to thank the University's Library of Würzburg and its team, who shortly acquired a couple of related literature. Finally, I thank my team, Christina, Dennis, Florian, Frederik, Helge and Helge, Kai, Martin, Max, Tobias, and Wendelin; you did a great job, despite challenges, trouble and circumstances. Thank you!

Torbjørn Cunis
February 13, 2014



Introduction

by Kai Werner

Motivation

The Moon is an ancient dream of humanity. But, after the APPOLLO missions have been finished more than fourty years ago, no human has ever been there again. Today, the Moon, and the Mars, are in the focus again and may be soon visited again. The general motivation for visiting the Moon will be more detailed in chapter 1.

In view of the above, Prof. Kayal of the Chair of Aerospace Information Technology offered a students project to design a complex space system going beyond simple components. The objective was to work out the concept of a manned base on the Moon, including motivation and objectives, using technology already available or assumed to be available during the next twenty years.

Research Group

This paper was written by twelve students of Space Science and Technology or Computer Science at the University of Würzburg within the lecture "Entwurf von planetaren und orbitalen Basen" as part of the respective Master's curriculum during the winter term 2013/2014. the lecture was estimated to require about 150 h per student. Therefore, the extent of the project was limited to about 1800 h of work.

The project was supervised by Prof. Dr.-Ing. Hakan Kayal, but the students were expected to work autonomously and Torbjørn Cunis was declared project manager. The project was divided into workpackages resembling the chapters of this paper and distributed on the students as noted in the respective chapters. Kai Werner was responsible for the schedule of the project and the documentation in this report. To accomodate for possible international publishing, English was chosen as the language for written reports and this report. This paper was written in LaTeXand is based on the Tufte-style [36].

This style features a particularly large margin and was chosen to place additional information and smaller tables or graphics in the margin without hampering the flow of reading the main text.

The project has been finished in two iterations of about six weeks each. The second iteration has been started over again, to fix fundamental errors which may have crept into the project in the first iteration and were discovered too late or were to much depended on by further work to fix easily in the first iteration. This report and a final presentation were finished in another three weeks.

Organization Of The Paper

This report is divided into three major parts;

Basics The motivation for constructing a lunar base is examined and the scientific goals that the Moon base should be able to work on are defined.

Based on the established goals the scientific equipment to be available in the base is determined.

The schedule for constructing and running the moon base itself is worked out based on a twenty-years estimated lifetime, preparation not included, as well as the necessary crew composition.

The Basics part is finished with the selection of an appropriate placement for the base.

Infrastructure The Infrastructure part deals with the requirements of establishing a base on the Moon and the challenges the hostile environment poses.

The part opens with the actual construction of the base, a structure of inflated modules covered by regolith.

To achieve a base to be mostly independent from Earth, a regenerative live support system must to be established in the base. It will provide O_2, water and food, as well as disposing waste.

The Moon provides many hazards to any structure which need to be scrutinized as well as developing appropriate counter strategies and the restraints they put on the other packages.

To construct and support a base which is to last for several years, a great amount of mass will have to be transported from the Earth to the Moon. Appropriate means and a schedule for these transports need to be determined.

The base will be powered predominantly by solar energy.

Communication between the base and Earth as well as between installations on the Moon will be secured by a ring of satellites and



communication devices installed in the base, rovers and outlying installations.

For a mostly independent base, resources available on the Moon will have to be utilised, especially water and O_2. Both will be mined from the ground by rovers and refined in the rover or the base itself.

Rovers will be used for several different tasks on the Moon, such as basic transportation needs, mining resources for the construction of the base or to support the live support system, helping in the construction of the base itself as well as the scientific exploration of the Moon.

Results The final part puts the project to the test by simulating the most important features and factors of influence.

Afterwards the results are examined in regards to the goals stated at the start of the paper and the results of the project for future research are outlined.



1
Mission Objectives

by Frederik König

This chapter covers the „WHY". Why should human kind return to the moon and build up a lunar base. There are many topics which are affected. Many of them were mention in [13] - The Case for an International Lunar Base, 1st Cosmic Study of the IAA, 1990. In this document, the objectives are categorized in the following subcategories: humanistic objective, political objectives, scientific objectives, utilitarian objective. They go much further than the objectives of our Lunar Base, but for comparison and for a deeper understanding of the scope and the significance the are part of this chapter. The world has changed a lot, since this document had been written. Despite of this, many of the reasons, why to go there, haven't changed. So the list of objectives from [13] is cited here:

Humanistic Objectives

1. assist in reducing tensions and conflicts on Earth, thus contributing to peace on Earth
2. provide opportunity for involvement of a broad spectrum of people in exciting frontier activities
3. enhance the evolution of the human culture
4. establish the first extraterrestrial human settlement as an initial step for expanding human activities in the solar system
5. provide a survival shelter for elements of the human race and its civilization in case of a global catastrophe

Political Objectives

1. demonstrate the potential growth beyond the limits on Earth
2. provide opportunity for international co-operation



3. provide the infrastructure and experience for global enterprises

4. provide a peaceful outlet for national, competitive high technology urges and a useful employment of existing industrial-military capabilities

5. enhance the national prestige of participating nations

Scientific Objectives

1. improve the understanding and control of our own planet

2. improve our knowledge of the Moon and its resources

3. improve our understanding of the solar system beyond the Earth-Moon system

4. improve our understanding of the universe beyond our own solar system

5. provide a science laboratory in a unique environment for experiments in physics, chemistry, biology, geology, physiology, and sociology which cannot be conducted on Earth

Utilitarian Objectives

1. provide a rewarding job opportunities and thus, stimulate the economy on Earth in general

2. stimulate the development of advanced industrial technology on Earth

3. produce marketable space products other than in the aerospace industry for extraterrestrial as well as for terrestrial use

4. contribute to the supply on Earth with renewable solar energy

5. provide an isolated depository to store high-level, long-lived nuclear and other wastes on the far side of the Moon (if legally possible)

6. provide safe and economical space transportation systems including a lunar spaceport and production facilities (mandatory for the exploration of other celestial bodies of the solar system)

7. provide thrust and focus for the continued development of space technology other than space transportation systems

Those objectives from [13] look into a far future. It is clear, that the first Lunar Base cannot achieve them all. It will be the first step, to open the gate to a future for mankind in space. A future in which endless expansion for humanity is possible and the limits of the natural resources on earth will become unimportant. Endless growth with limited resources is impossible, on earth, resources are limited. The reader may have observed the peoples striving for higher wealth, which can be measured with the Human Development Index (HDI) [5], following this observation; it becomes absolutely clear that humanity will need the resources from the solar system for continuing this development. A habitat for living is also an important resource.

Fig. 1.1 shows the increasing HDI of several countries over a period of thirty years, it can be expected, that this development will continue in the future.

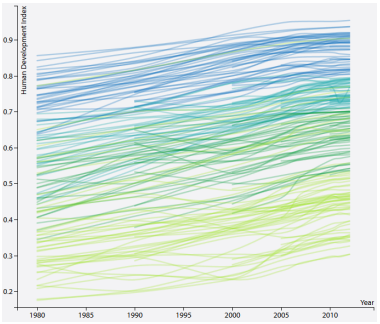


Figure 1.1: Human Development Index (HDI) progress from different countries over the years. Image source: [5]

The sophisticated reader may remember an example from history: the Roman Empire, which collapsed, after expansion was stopped. There were also other reasons, but humanity's population also grows, resources are limited and all people strive for higher economical wealth. Forecasts 1.2 , 1.3 about population development in combination with HDI show, that there exists the possibility of social and economic tensions which will be caused be the limitation on resources, which can lead to armed conflicts. The figures 1.2 and 1.3 show several prognoses on population development. The red lines show population development based on a constant rate, the others show prognoses with a lower birthrate. So, astronautics is a logic conclusion for keeping the system stable.

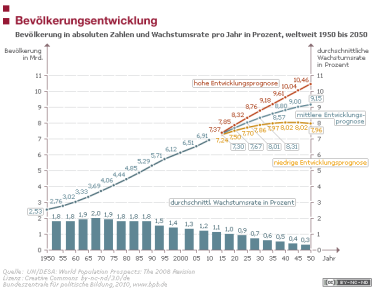


Figure 1.2: Population development estimation till 2050. Image source: [10]

Will a Lunar Base solve those and other problems? – No. But it is the first step for finding solutions. The objectives of the planning-scenario of this study do match with the ranked list of priority objectives from [13]:



Figure 1.3: Population development estimation till 2100. Image source: [11]

- Provide a science laboratory in a unique environment for experiments in physics, chemistry, biology, geology, physiology and sociology which cannot be conducted on Earth
- Establish the first extraterrestrial human settlement as an initial step for expanding human activities in the solar system
- Improve our knowledge of the Moon and its resources

But, it is also important, that we show that it is achievable with our existing technology – A proof of concept. We need to explore the technological basis if we want to go further in space in the future. And further means mars in the nearer future. Humans are curious, so

it is in the human nature to explore. By developing new technologies for a base on the moon, the benefits for humans on earth can't be predicted yet, but space technology has already improved our all lives. The reader may remember technologies like: GPS, communication-satellites and so on.

Why is a Lunar Base better than going straight to mars? – Despite the fact, that mars' gravity is more similar to gravity on earth, moon has with its gravity of $\frac{1}{6}$ g other important benefits. It is closer than mars to earth. So the flights are shorter and faster. Flight durations to mars depend on the current relative position between mars and earth, because of the different turnaround times for the sun.

Base Information from [4], approximating calculation: Average-distance Earth-Sun: 149 600 000 km, Mars-Sun: 227 000 000 km, Earth-Moon: 384 400 km, derived average-distance Earth-Mars: 78 000 000 km; speed of light in vacuum: 299 749 km/s. Communication-delay-one-way: Earth-Moon: 1.28 s, Earth-Mars: 260.22 s 4.3 min. So the round-trip-time is at least double the one-way-time.

Communication will be possible in almost real-time without a huge time delay as with mars. This will be good for the psychological state of mind of the crew. In case of emergency, rescue missions will be easier and faster achievable.

It is a huge difference between a psychological simulation conducted on earth for a mars mission like Mars-500 [7] and really being out there. So the moon is a better test-case to find out, if humans can live on an isolated outpost, farer away from the rest of humanity than isolated polar bases.

The Lunar Base will also have other side-effects, as mentioned above in the text. Cause of the astronomical costs of money and resources, many participants will be involved: United Nations, countries, space agencies, enterprises and more. It probably will be one of the largest international economic stimulus plans, ever seen. Some estimation speaks about 100 billion USD [8]:

... $104 billion for NASA's campaign leading to human missions to the moon, as laid out in the Vision for Space Exploration. This project involves the development of a new spacecraft system for lunar trips — and the projected expense has led NASA to scale back the scope of its $100 billion international space station project. ...

The NASA poster "WHY THE MOON?" [9], also goes into a similar direction with its populist goals:

- Human Civilization: Extend human presence to the moon to enable eventual settlement
- Scientific Knowledge: Pursue scientific activities that address our



fundamental questions about the history of Earth, the solar system and the universe – and about our place in them

- Exploration Preparation: Test technologies, systems, flight operations and exploration techniques to reduce the risks and increase the productivity of future missions to Mars and beyond
- Economic Expansion: Expand Earth's economic sphere and conduct lunar activities with benefits to life on the home planet
- Public Engagement: Use a vibrant space exploration program to engage the public, encourage students and help develop the high-tech workforce that will be required to address the challenges of tomorrow

After having a look on these aspects and the objectives from [13] and [9], the objectives for this study's Lunar Base are as followed:

- Building up a Lunar Base in multiple stages
- Possibilities for Experiments in many scientific disciplines
- Exploration of moon, earth, earth-moon
- A Lunar Base as self-sufficient as possible
- Testing of technology
- Proof of concept
  - Show that it is logistically possible to transport the required materials to the moon
  - Show that it is possible to build-up a lunar base
  - Show that it is logistically possible to supply a lunar base
  - Show that it is technologically possible to run a closed environment
  - Show that it is technologically possible to gather the required resources for a human habitat, running the base and to do scientific research
- Infrastructure for astronautics

For achieving those objectives, the Lunar Base has to be built-up in several phases. At first, preparation will be needed. After preparation, there will be a first small base including life-support, energy- and resource-harvesting to show, that the concept works. It can be supplied with resources from earth.



After this, this initial base will be extended. After extension, the base shall go operative, including research activities. At the latest, it has to be as autonomous as possible at this moment in time.

After having achieved this goal, people have an outpost on moon, which may be extended further depending on the needs of mankind, science and astronautics for opening the door to a future in space.

At the end of this text, the author wants to conclude with a bon mot: We are standing on the beach of the known, in front of us the wide ocean of the unknown. – It's time to swim.

2
Scientific Usage

by Florian Gillmann, Christina Hempfling, Frederik König, Helge Lauterbach and Dennis von der Wals

2.1 General Scientific Experiments

by Frederik König

This chapter covers the „WHAT". What should we do with a Lunar Base. As described in the previous article, a Lunar Base has to serve as a scientific platform to conduct various experiments from many scientific disciplines. Following the objective from [9]: Scientific Knowledge: Pursue scientific activities that address our fundamental questions about the history of Earth, the solar system and the universe – and about our place in them. In [13] is spoken about "both world experiments". Those experiments are of high value, because they will help to re-validate the existing models or help to correct them. Scientific disciplines which shall be satisfied with a Lunar Base are for example, with sample research-activities:

- physics: recheck the existing model for improvement of knowledge
- astronomy: telescopes which profit from the unique environmental conditions
- chemistry: discover, if it is possible, to process matter under lunar conditions
- biology: discover, how organisms adept to lunar conditions in long term studies
- geology: discover lunar resources, gaining a deeper understanding on geology itself
- medicine: long term study on humans living under $\frac{1}{6}$ g gravity and in an artificial environment

- sociology: discover which social-structure is the best for long-term missions

- psychology: discover how humans react under such extraordinary life-conditions in long-term

Of course, nobody can exactly predict, which experiments will be done in more than 15 years in the future on the moon. Even with the best known experts, such a prediction concerning the future is nearly impossible, depending of the level of accuracy.

One important question is: How to cover all those disciplines and more?

A from computer-science well known principle will be applied for serving the different scientific disciplines: the rack-principle. An adaptable standardized system to fulfill the current needs. Fortunately the same principle exists also for scientific experiments in space. Multi-purpose platforms for serving the current needs are International Standard Payload Racks (ISPR) [6]. Those ISPRs are currently serving on the International Space Station (ISS) as a platform for experiments and also as for logistics called „Multi-Purpose Logistics Module (MPLM) “.

ISPRs are well specified by Boeing [2]. Figure 2.1 shows the first ISPR being installed onboard the ISS. The European Columbus-Module [3] makes use of them in different manners:

Columbus was fitted with five internal payload racks at launch

- Biolab - supports experiments on micro-organisms, cells and tissue cultures, and even small plants and small insects

- The European Physiology Modules Facility - a set of experiments that will be used to investigate the effects of long-duration space-flight on the human body. Experiment results will also contribute to an increased understanding of age-related bone loss, balance disorders and other ailments back on Earth

- The Fluid Science Laboratory - accommodates experiments in the strange behavior of weightless liquids. Bringing far-reaching benefits on Earth: better ways to clean up oil spills, for example, and improved manufacture of metals

- The European Drawer Rack - a modular and flexible experiment carrier system for a large variety of scientific disciplines, providing basic accommodation and resources for experiment modules housed within standardized drawers and lockers

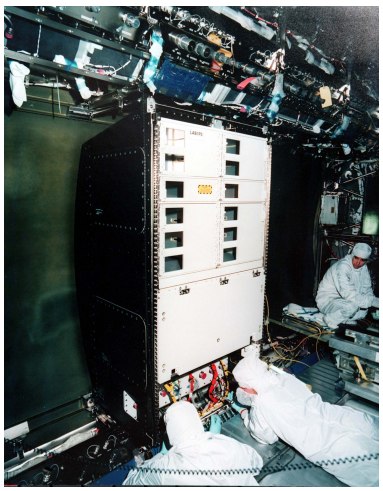


Figure 2.1: The first ISPR being installed on ISS. Image source: [12]

- The European Transport Carrier - accommodates items for transport and storage. In orbit it will serve as a workbench and storage facility

Those existing module-types can be reused.

Some facts about ISPRs and Columbus [37]: ISPR-Payload: 700 kg, Columbus has four solar panels with 20 kW, 13.5 kW for science and 16 racks, so about 840 W each.

The required energy-maximum is there for 0.84 kW for continuous operation in a duty-cycle. Depending on the conducted experiments, it may be less and some experiments will need less energy.

Let's have a look on information technology, which will be required for running the experiments. There will be the need, to process and store gathered data. Based on current available computer-technology, the following estimation is made. Of course, some experiments will need to process data in nearly real-time, so cloud-computing will not serve all the needs. So it is appropriate to give each rack a notebook for this type of operation if required, which also can serve as an access-terminal. Modern efficient notebooks have power consumption between 0.02 kW in idle and 0.06 kW under full load. To process other data, that will not need real-time speed; a small distributed server-cluster can be set up, which also fulfills the requirement of redundancy. Four servers with maximum power consumption with 0.75 kW under full load each will be sufficient. If current standard-industry technology is not assumed, special computer-boards, which only use direct current can be used; this will be more energy-efficient. Information technology which will come in future can be expected to require less power and simultaneously to be more powerful than estimated.

So much about standardized experiments, but not all scientific research can be done inside racks. Geological exploration for example needs to be mobile. Seismic measuring stations need to be placed; rocks and soil have to be analyzed to find out more about the moon. Mobility is estimated to be within a 100 km radius at the beginning. Another discipline which has special needs is astronomy. Moon has no atmosphere and is therefore ideal for large optical telescopes such as liquid mirror telescopes (LMT). An astronomic observatory will be required at an adequate position. Also other types of telescopes like infrared and radio can be placed, if the proof-of-concept has succeeded and the technology works.

Another discipline which has special needs is astronomy. Moon has no atmosphere and is therefore ideal for large optical telescopes such as liquid mirror telescopes (LMT). An astronomic observatory

will be required at an adequate position. Also other types of telescopes like infrared and radio can be placed, if the proof-of-concept has succeeded and the technology works.

2.2 *Astronomy*

by Christina Hempfling

Establishing a permanent moon base provides opportunities for astronomical observations. Some earthbound telescopes face atmospheric disturbances (e.g. clouds, moonlight, humidity) which affect the data taken. Since the Moon has no atmosphere, problems like these do not exist there. For our moonbase, a so called (Lunar) Liquid Mirror Telescope ((L)LMT) will be used which observes the universe in the infrared range. On Earth, such infrared telescopes are used to study the early universe but due to high atmospheric and thermal background, highly red shifted objects can not be followed up. Placing such a telescope on the Moon would increase the sensitivity and compared to already existing LMTs on Earth, objects a 100 times fainter can be detected [109].

As the name already implies, LMTs use a liquid to create a primary mirror. Primary mirrors must achieve and maintain very tight optical tolerances which is often bound to high costs for the complex systems to achieve this. The advantage of liquid mirrors lies in the natural equilibrium of a fluid under gravitational and inertial forces. They are easier to fabricate and much lighter.

For an LMT a liquid is applied to a parabolically shaped construction which is rotated with the help of a motor. Due to constant spinning the liquid is evenly distributed which creates a smooth surface that can be used as a mirror. In order to detect the highly redshifted objects, a primary mirror diameter of 20 m to 100 m is necessary. For our moonabase, a primary mirror of 20 m and a secondary mirror of 5 m will be used (see Figure 2.2). With these dimensions, the area of the primary mirror is about 314 m^2, the total mass of the telescope is 3 t and its field of view has a size of 15′.
On Earth, these LMTs use a mercury liquid to generate the mirror [109]. On the Moon, it can not be used since the reflecting surface must be much colder than the freezing point of mercury or it will produce a background thermal radiation much brighter than the very dark natural sky background [18]. So the challenge for a LLMT is to find a liquid that can be made reflective and has the following characteristics:

- it remains liquid down to temperatures between 70 K and 100 K since the Moon's surface temperatures lie in that range

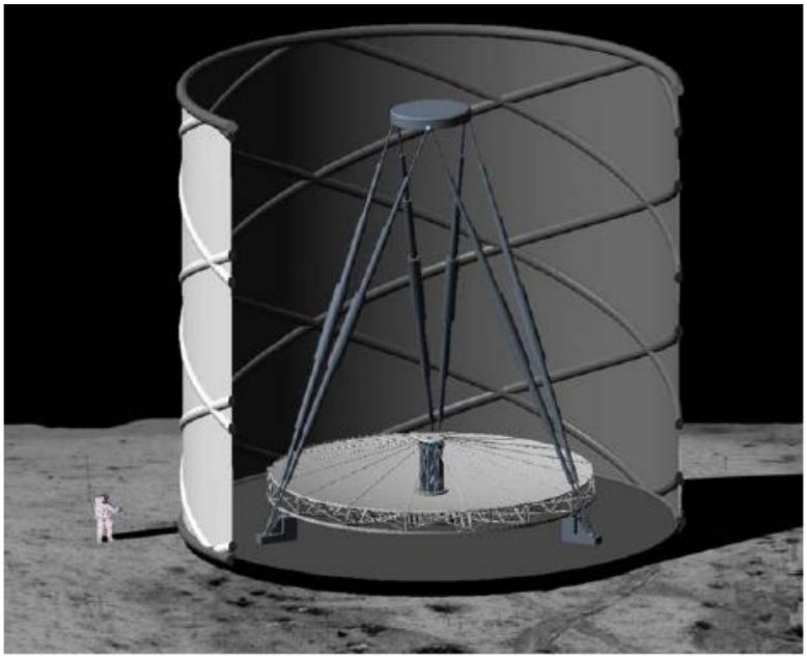


Figure 2.2: Artist's impression of the Liquid Mirror Telescope. The first mirror has a diameter of 20 m, the secondary 5 m. In order to shield the telescope from radiation, an inflatable solar radiation shield surrounds the telescope. Credits: Tom Connors, University of Arizona [18]

- the liquid must have the low vapor pressure required to prevent evaporation in the lunar vacuum
- the liquid must be (made) reflective

Currently, research is done to find a suitable liquid and various ideas exist. One promising approach uses a low-reflectivity liquid with a thin metallic coating to make it reflective. In 2006, a big step towards establishing an LLMT was made when [18] proved this theory by successfully coating polypropylene glycol with vacuum deposited tin and silver.

2.3 *Seismology*

by Dennis van der Wals

The lunar ground show still seismic activity in form of Moonquakes (see 7.3) and Transient Lunar Phenomena (see 7.6.1), even the inner core seems to be cold. Those effects need further research to get more information about the state and origin of the moon and the solar system. It is also useful to ensure the security of the base. Plans for such a network are already made, containing 8 to 10 seismographic instruments placed over the moon (see figure 2.3).

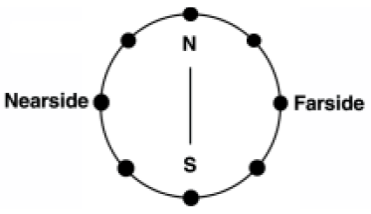


Figure 2.3: Lunar seismic network stations on the moon. [77]

Every instrument should be developed to be just dropped to the ground and work with an energy consumption of 5 W to 7 W,

powered by a radioisotope thermoelectric generator. The planed communication network for the future moonbase can be used to collect the data and transfer them to earth. The amount of data should not exceed 8 $\frac{\text{Mbit}}{\text{h}}$ and sending of these data should be triggered by the communication satellite at its flyby. Adding some instruments for researching the radiation environment and especially the *CME-Events* would also be useful for enhancing the forecast time and so the exploration distances for the astronauts (see **??**).

2.4 *Reconnaissance*

by Florian Gillmann and Helge Lauterbach

Before the first crew will arrive on Moon, some explorations next to the designated moon base coordinates can already be done by autonomous rovers or via telecommands from earth, during the so called Preparation phase (see Sections 12.1 and 3.1). These explorations should conduct mapping for the cartography and a topographical survey, to further increase the in-depth knowledge about the terrain, and to find possible dangerous or hazardous conditions mentioned by the environmental hazards work package. This data can also help possible crew members to get familiar with the environment, before they will be sent to the moon in a later phase. Once new crew arrived, they have to repeat this sort of near base exploration in person, partly in their EVA suits or with a suitable rover, described in the surface transportation work package, to refresh their memories and fully understand the location.

From the Supplied base phase (see Section 3.2) on, the crew is allowed to make explorations of a distance up to 20 km around the base and for a duration up to 48 h. In this exploration type, typically, two crew members use a pressurized rover, but alternatively, also unpressurized, smaller and faster rovers can be used as soon as they are brought onto Moon. In this case the crew is only protected against radiation and shielded by their EVA suits, which limit the whole excursion duration to six hours.

They will continue the mapping tasks and also collect different samples of soil, regolith and rocks for further processing and analysis. The analysis will be done in different experimentation racks inside the base with aims like:

- understanding the history of the Moon
- understanding the nature and history of solar emissions, galactic cosmic rays and dust from interstellar medium, to invent better prediction



- element and composition analysis to find useful material for in situ resource utilization

For later phases (see Sections 3.3 and 3.4), the exploration distance is raised to 100 km and the duration can be up to 14 days. This exploration type will be performed every two to three months with four people housing in two pressurized rovers and continues previous aims. To be able to do this, the crew will also have to take along a so called portable utility pallet (PUP) as described in the surface transportation work package(see Section 12.5).

Studies on magnetic or gravitation anomalies or electro-magnetic structure of the crust would be another possible scientific aim for these extended explorations(see [91], [63]).

3
Mission Scenario

by Torbjørn Cunis

In this chapter, we present and describe the mission's timing to build up our lunar base; we call the phases by time and indicate the significant milestones of our mission. The mission is separated in five consecutive phases, which perform several and partly different purposes due the build-up. In opposite to the fifth phase in the long run and beyond the scope of study, the first four phases shall be examined in detail in this study. The phases are:

1. Preparation phase (p);
2. Supplied base phase (s);
3. Base extension phase (x);
4. Operational base phase (o);
5. Colonization phase.

3.1 Preparation Phase

This first phase directs towards an autonomous reconnaissance, preparation and construction in the run-up to a manned lunar base mission. In the early sub phases, the base's designated location as well as the surrounding area shall be examined from orbit first, on-ground later. In particular, detailed information about the surface's nature and the occurrence of water is required. Then, rovers are going to gather water to stock up for use by the first crew; further rovers shall construct most base parts autonomously. The sub phases in detail and their goals are:

p1. Reconnaissance I. Probes in (low) lunar orbit study base's later location and the Moon in general concerning geological and geophysical aspects. The satellite network for future communication



(Moon–Moon as well as Moon–Earth; see Chap. 10) is established. Furthermore, a Moon-spanning network of seismologic sensor stations shall be set up to obtain Moon's physics (see Sec. 2.3).

p2. Reconnaissance II. The base's later location and its near peripherals is explored using unmanned rover to seek, in particular, further data about the nature of surface and its chemical composition, quality and quantity of present water, and so forth, beyond today's state of knowledge.

p3. Water winning. A special rover, MISWE (see Sec. 11.1), starts collecting water and builds up stocks for use in the Supplied base phase.

p4. Mine & Build. Autonomous robots and rovers, respectively, constructs most base parts, so that first crew will procure the base after a delay as short as possible only (cf. 1st Supplied base sub phase).

The Preparation sub phases 1–3 are scheduled to last one year each before Supplied base phase. The last sub phase, Mine & Build, however, takes at least five years due to the chosen build-up technique as well as strategy (cf. Sec. 5.6).

Crew	0
Satellite Network	yes
Rover	0
MISWE	0

Table 3.1: Key figures p1

Crew	0
Satellite Network	yes
Rover (Athlete, Chariot, minor)	2, 2, 0
MISWE	0

Table 3.2: Key figures p2

Crew	0
Satellite Network	yes
Rover (Athlete, Chariot, minor)	2, 2, 0
MISWE	1

Table 3.3: Key figures p3

Crew	0
Satellite Network	yes
Rover (Athlete, Chariot, minor)	2, 2, 0
MISWE	1

Table 3.4: Key figures p4

3.2 *Supplied Base*

Previously constructed, the proto-base is procured and the energy, communication, and life supply systems are put into operation by the first crew (four astronauts). Later, the astronauts shall start gardening and performing first lunar research projects. Since there has never been any lunar base, this phase's primary goal is to test and experience as well. This first manned phase is divided into the short but sensitive First settlement sub phase and the original Supplied base sub phase:

s1. First settlement sub phase (f). First and critical for mission's effort, crew must establish base's primary systems: energy, communication, and life supply systems are booted up so that the astronauts are able to finally procure the proto-base.

s2. Supplied base sub phase. Supplied with oxygen, nitrogen, and food from Earth, the water gathered previously, and first lunar food production using greenhouse, our initial base has to prove itself. In addition, first lunar experiments and manned reconnaissance expand human's knowledge about Earth's natural satellite.

The result of the First settlement sub phase is crucial for mission's success, as the life supply systems in particular as well as the additional systems guarantee crew's survival at the Moon. Therefore, and

Crew	4
Rover (Athlete, Chariot, minor)	2, 4, 0
MISWE	2
earth-dependent	yes
Experiments, reconaissance	yes
telescope	no
Supply flights/year	2
Crew flights/year	2

Table 3.5: Key figures s

since there has never been any lunar base mission before, a secure and fast return of the crew back to earth must be possible during this sub phase and the subsequent.

The Supplied base phase shall take another five years and starts in the year 2030 at all.

Crew	4
Rover (Athlete, Chariot, minor)	2, 4, 2
MISWE	2
earth-dependent	yes
Experiments, reconaissance	yes
telescope	no
Supply flights/year	2
Crew flights/year	2

Table 3.6: Key figures x1

3.3 Base Extension Phase

In the next phase lasting five years again, the lunar base is extended to house the full Operational base phase's crew (twelve humans). In addition, the prepared base shall be independent in respect to food, oxygen and water [1]. From here to the next phases, crew shall partly contain general scientists, too, instead of prior specialized crew formations. The Base extension phase is partitioned into two similar sub phases (x1, x2), due which the next base parts and their system elements are constructed and established.

[1] Through the lunar chemical composition as known today, a lunar base must be supplied with nitrogen in any phase and to any time.

Crew	8
Rover (Athlete, Chariot, minor)	2, 4, 2
MISWE	4
earth-dependent	yes
Experiments, reconaissance	yes
telescope	no
Supply flights/year	1
Crew flights/year	2

Table 3.7: Key figures x2

3.4 Operational Base Phase

This last studied phase shall validate the stable and autonomously operation of the lunar base until the year 2050; the base is as extended as done in the phase before. Crew pursues a quite "normal" lunar daily work, containing research projects, food, oxygen and water production, maintenance work etc.. Furthermore, a telescope (see Sec. 2.2) is added to the existing research projects.

Crew	12
Rover (Athlete, Chariot, minor)	2, 4, 2
MISWE	5
earth-dependent	no
Experiments, reconaissance	yes
telescope	yes
Supply flights/year	1
Crew flights/year	3

Table 3.8: Key figures o

3.5 Colonization

A successfully validated lunar base may lead to a future, permanent colonization of the Moon; a steady human lunar colony would enable scientists and engineers to institute endurable studys on Moon, extending human knowledge about the Earth, the Moon, the Solar system, the Universe and anything else.

3.6 Base Evacuation Scenario

Within the safety concept described in Chap. 7, it is absolute necessary to ensure a evacuation in case of any events – either unforeseen or not. However, the details of the evacuation scenarios change during the phases:

In the *Supplied base phase*, due to our absence of any experiences about lunar bases, the crew must be brought back to earth at any time

and within 48 h. Therefore, the lander regularly carrying crew there and back will be handed to manage fast evacuation.

During the *Base extension sub phases*, the first quartet of astronauts will be brought back directly and within 48 h using the lander mentioned. The second four astronauts, in the second sub phase, shall be supported by the pressurized rover (cf. Sec. 12.3) for at least two weeks, until a rescue mission will have been started from Earth and picked up them.

Finally, in the *Operational base phase*, up to six astronauts will be brought back within 48 h using the lander, while the other six outlive in rover and base, respectively, before the rescue mission is finished.

3.7 Crew Formation & Daily Routine

Crew Formation Design As usual, first lunar mission's crews will be formed by well-trained astronauts, i.e. by generalists who are able to solve a variety of miscellaneous challenges. In course of the (later) phases, when both crew and lunar base are growing in order to mission's functions and tasks, the mission design requires special professionals like engineers, biologists, and medicines, as well as non space-familiar scientists.

During late Supplied base phase, some of the astronauts are replaced by each an engineer and biologists. From second Extension phase then, further specialists including medical staff, and first scientists reach the Moon.

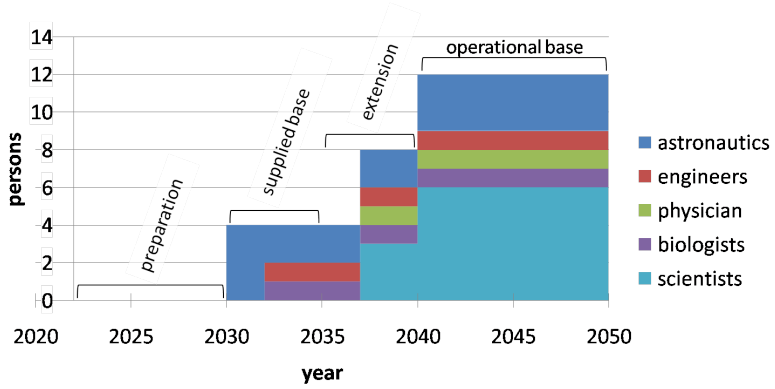


Figure 3.1: Proposed crew formation evolution by time and phase.

In the first phases, Supplied base and Base extension 1, each crew shall stay on Moon about half a year, as it is usual for ISS crews, too. During the next phases, the durations increases up to 8 months

in Base extension 2 and a year each in the Operational Base phase. However, as in the later phases crew parts shall be replaced only, and since the LunarLift covers four astronauts per flight, the manned flights to Moon and back also rise.

Crew's Daily Routine On Moon, crew has to cope with several tasks, from the set-up and maintenance of the base and its components over daily supply up to up-coming scientific experiments. These tasks are both inside and outside the shelter base, so that field work is limited by radiation protection rules (see Sec. 7.7). Furthermore, of course, each crew member has own needs besides mission tasks, e.g. sleep, eat, and private spare-time.

To plan crew's daily routine, we take a civil earth day (24 h) as a basis, whereupon 8 h are reserved for sleep and 4 h to spare time. In order to fulfill radiation protection rules, we limit out-base work (except in-rover tours) to 0.5 h per day on average; in case of 4 crew member in the first phases, this is equal to a 7-person-hour field work twice a week. In order to the tasks, challenges, and capabilities changing during the phases, the rover excursion are scheduled to last 0.5 h–2.5 h per day, e.g. to maintenance outside components or explore base surroundings.

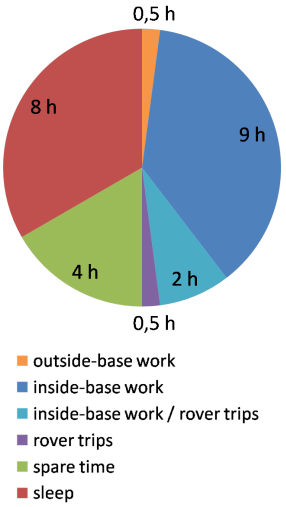


Figure 3.2: Proportion of crew's daily tasks.

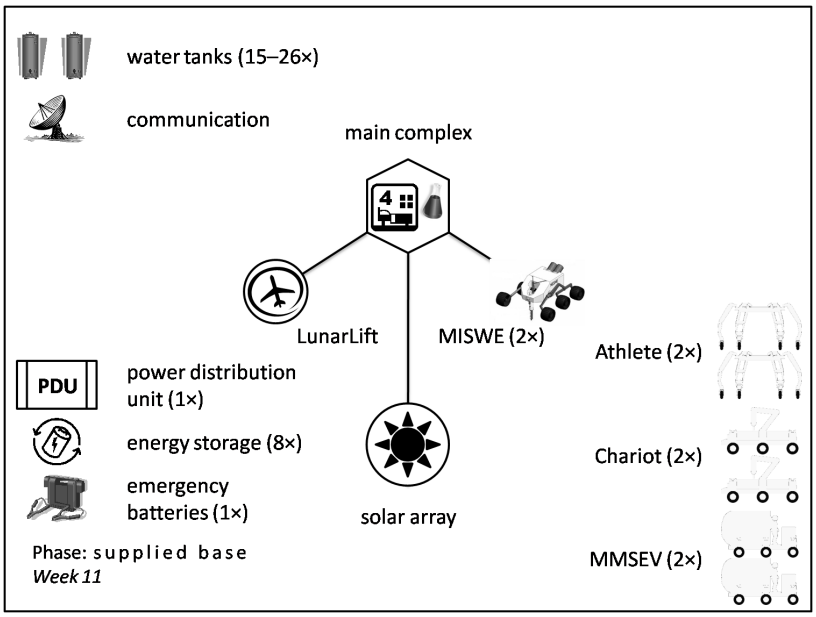


Figure 3.3: Nutshell Supplied Base

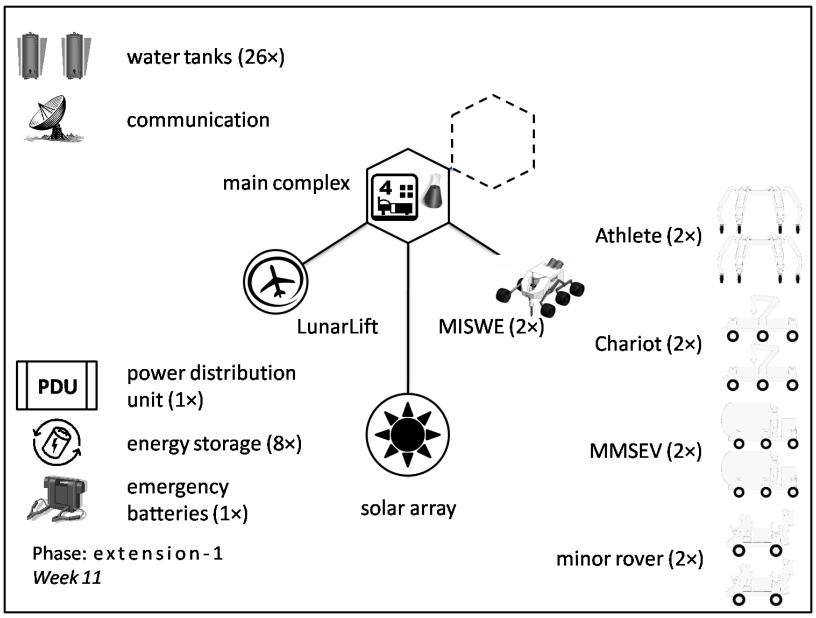


Figure 3.4: Nutshell Base Extension x1

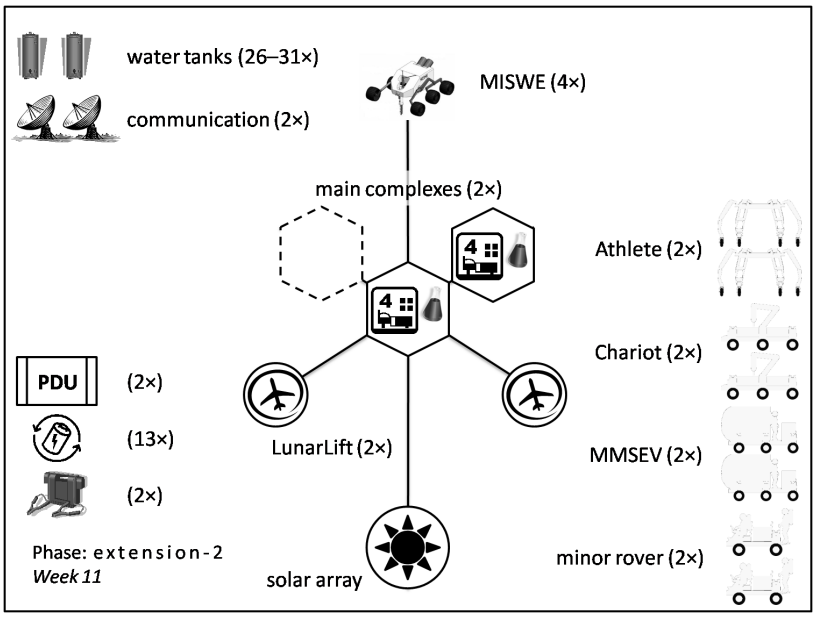


Figure 3.5: Nutshell Base Extension x2

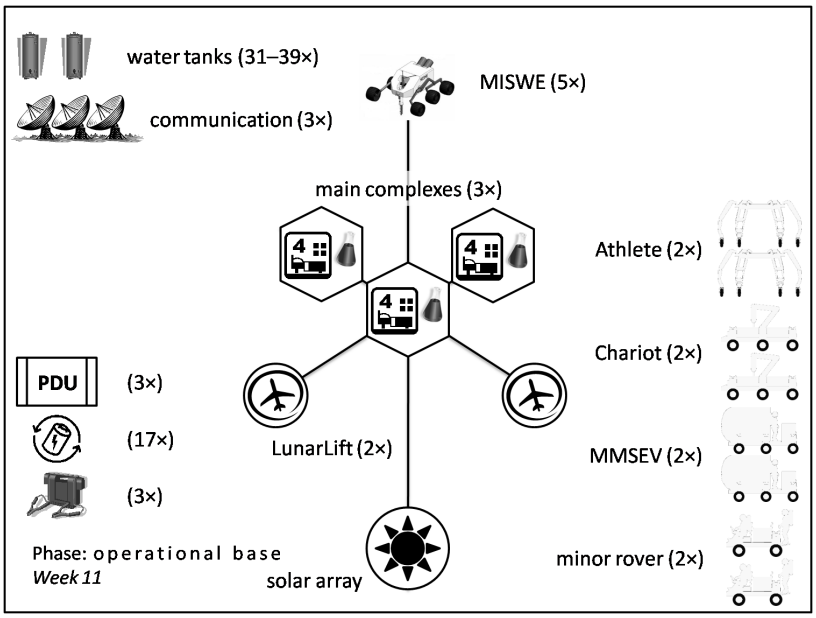


Figure 3.6: Nutshell Operational Base

4
Placing The Base

by Torbjørn Cunis and Tobias Wenzel

4.1 The Close to North Pole Peary Crater

by Tobias Wenzel

In general, for a stationary lunar base site there are four possibilities of locations to choose as stated in [45].

1. Polar Site North or South
2. Equator Near Side
3. Equator Far Side
4. Lunar Limb Earth Terminator

Each of them has its own advantages and disadvantages. The main driver of our decision are resources like water and solar energy. For further differentiated background the source is given above.

Latest discoveries [97] [26] [70] detect water ice inside some craters on lunar poles. In this craters there was no sunlight for several millions of years. At the lunar north pole there is assumed to be a significant amount water ice stored in comparison with the south pole. In a self-supplied approach of a lunar base this water ice resource should be extracted.

Another important fact is that at poles there are regions of almost continuous sunlight. So power generation by adjustable solar arrays will be a crucial source of energy.

This interest leads us to the lunar north pole, more exactly to the craters "'Peary"' and "'Whripple"'. These are pretty close with a distance of about 20 km to the lunar north pole. There is research into building a lunar base near the "'Peary"' crater by NASA, too [67].

4.2 *Within Peary Crater or Onto the Edge?*

by Torbjørn Cunis

Chosen the Peary Crater as lunar base's area, two alternating placing strategies and places, respectively, were discussed: First, to place the base within the crater, or secondly onto the crater's edge. Both alternatives fulfill the general requirements for lunar base's position, namely, for example, being close to water occurrences (see Section 11.1) as well as solar arrays (see Section 9.2); flat surface in a radius of 1 km due to base build up and suitable landing site no farther than 5 km. Furthermore, the base must not be placed closer to the crater's edge than 3 km due to the risk of slides (see Section 7.3) and the way to the components should not be steeper than 40° in order to meet the rovers' needs. Ideally, the base location is as sunny as possible, since light has favourable affect on the human psyche and can drive solar powered build-up robots.

Place	Latitude	Longitude
Within Peary Crater	89.299° N	68.869° E
Onto crater's edge	89.483° N	109.384° E

Table 4.1: Coordinates of the alternative places.

Priority	Requirement	Within	Edge
most	close to water occurrences	Yes	Yes
	not closer to crater's edge than 3 km	Yes	Yes
	way to components not steeper than 40°	Yes [1]	Yes
	close to solar panels [2]	farther	nearer
	flat surface (max. difference of altitude: 1 m) in a radius of 1 km	Yes	Yes
	(possible) landing site not farther than 5 km	Yes	Yes
less	sunny base site	Rarer	More often

Table 4.2: Requirements for base places by decreasing priority.

As one can see, the placement onto the crater's edge is nearer to solar panels positions and guarantees sun light more frequently without violating any other requirement. Therefore, this alternative will be favored.

[1] Since solar panels will be placed onto the crater's edge anyway, rovers have to climb edge.

[2] Each 10 km distance to one solar panel requires 8 t of copper wire from solar panel to base.

5
Base Construction

by Max van gen Hassend

5.1 Working and living complexes

The moon itself is a dangerous environment and building and supplying a permanent settlement for humans on it is definitely a difficult step for mankind but also an important one. We have a whole section about dangers from the environment which could occur and how to be prepared against them (see Chapter 7). But core to these concepts is that we have a well designed base to protect the astronauts against the environmental hazards. Protection is important, but our base needs to be more than a simple shelter. It has to house plenty of technical and non technical subsystems which are required to ensure safety and comfort on the moon. Most technical subsystems are covered in their respective parts. This chapter will be divided in two subchapters. One subchapter for the structure of the base. This part will discuss how the base is constructed and why it is built the way it is built. Part of this subchapter will also be thermal control, although this is only covered on a reduce scale. The other subchapter will be about the construction of the base.

5.2 Structure of the base

This section is going to start with the requirements at the structure of the base. The base needs some sort of protection against solar radiation, especially against the increased radiation from temporary solar storms (see Section 7.2).Moreover protection against small particles and mini meteorites. Obviously for an manned outpost it needs to be able to be filled with atmosphere for the astronauts to breathe and not leak it. Additionally, considering the approach of increasing the number of astronauts who are living in the base over time, the base



itself has to be easily extendable. An elevated spot for our antennas is also nice to have.

Which techniques do we have to construct such a base. Basically there are three kinds of structures. There are rigid structures for example aluminum, then there are inflatable structures and then there are regolith structures. Rigid structures are very heavy and need to be transported from earth, therefore its very expensive to use them a lot. On the other hand they are needed for stabilizing the base or for some complex structures like airlocks. Inflatable structures are very light and thin and can be inflated with gas to form their required shape. They are easy to transport due to their low volume and mass and are first choice for rooms within the base. On the other hand they can't form any complex structures because they need to be inflated and therefore need to be almost convex. Then the third type of structure at our disposal are regolith structures. Regolith structures are created via the technique of 3d printing. There are two major ways of how 3d printing works. One possibility is to use sintering and the other possibility is to create printing ink by adding a binder to the regolith. For the sintering process the regolith is heated up to 1200 °C to 1500 °C and pressurized in a way that the regolith doesn't melt but gets compressed [105]. Their respective drawbacks are that the heating for the sintering costs a lot of energy and the binder needs to be transported from earth. Regolith structures are being used for protection against small particles and radiation. With all these tools at hand it was now required to come up with a concept that minimizes the cost of the project and holds the constraints.

The base is going to be constructed with a combination of rigid, inflatable and regolith structures, using each according to their strengths. We make sure that the ground is level and there is no dust on it. This will be done with our rovers and is further described in that section

The structure of the base will be discussed first and later on the way the base is built will be discussed (see Section 5.6).

Research about the environmental hazards provided the following two numbers about the required thickness of the regolith structures. In case of an coronal mass eruption (see Section 7.2) radiation is coming from every angle and in order to reduce the radiation level to earth level the base needs to be covered with a regolith layer with a size of 3.5 meter and density of 700 $\frac{\mathrm{g}}{\mathrm{cm}^2}$. But be careful this is not a density per cubic meter, its per square meter. If you calculate the density per square meter you get:

$$700\,\tfrac{\mathrm{g}}{\mathrm{cm}^2} \cdot \tfrac{1}{3.5\,\mathrm{m}} = 200\,\tfrac{\mathrm{g}}{\mathrm{cm}^3} = 2\,\tfrac{\mathrm{t}}{\mathrm{m}^3} = 2\,\tfrac{\mathrm{g}}{\mathrm{cm}^3}$$

Reviewing those numbers it became clear that if we want full

protection in the entire base against those solar events, which is appreciated for numerous reasons, then the surface of the base needs to be minimized. Reasons for total protection might be ongoing experiments, which can't be paused, and require human intervention or psychological reasons: people might be unable to sleep, because they need to be able to get up any time in order to go to the save room. Additionally the construction of a save room would not be easy. A save room still needs the total protection which costs plenty of space. Then it has to shelter a group of 4 people for about a week. There needs to be food, bathroom facilities, some places to sleep. There is no way that this would have no psychological implications. From a press point of view it would be terrible as well. One might even argue that conditions like this would violate the proof of concept, because live on moon might not be worth it if the conditions are that bad.

Maximum achievable minimization of surface with respect to volume can be achieved by using a half sphere. The dimensioning of was first done with an estimation and then further developed into detail with the help of an artist's tool called blender. Due to the fact that the first dimensioning was quiet off, the final result will be shown here first and then the space requirements will be discussed. But first there's another number that is quiet important. Its the height of the rooms of the base. It was decided that every room should have a height of 2.5 m. Due to the fact that the astronauts should have no regulations in height it can be assumed that there is an astronaut who is at least close to 2 m. Additionally some space for lamps and other obstacles probably wires and some comfort space is required. If that is taken into consideration a height of 2.5 m is just fine.

Considering the shape of a sphere the height should be roughly a multiple of 2.5 mplus a bit because you still want to use the top floor. Therefore it was decided to use a radius of 8 mfor the sphere and then put everything required in. And fortunately it worked out quiet well. Note that this base is only for four persons which will be living there in the settlement phase. Each time four new people arrive the same module will be constructed with slight modifications. More about the differences later on. But note also that the first module is really the crucial part in will be mostly discussed here.

The radius allows us now to calculate the total volume of a module and use this to estimate the required gas to fill all the inflatable modules.

$$V = \frac{4}{3}\pi \cdot (8\,\mathrm{m})^3 \cdot \frac{1}{2} = 1072\,\mathrm{m}^3$$

In fact not the total volume of the half sphere will be filled with gas, only the space within the inflatable modules. The reasoning behind

that is that although the sintered regolith would be able to hold oxygen within it, it is not a good idea to put oxygen there because this would create an internal pressure on the regolith which would reduce its lifespan [28]. Therefore the volume of required gas is about $1000\,\mathrm{m}^3$.

The inner radius of 8 m of a module allows us to further calculate the required mass of the regolith in order to be sintered. We use the following formula. Basically the volume of a half sphere with radius 11.5 m minus the volume of a half sphere of 8 m radius.

$$V = \tfrac{4}{3}\pi \cdot (11\,\mathrm{m})^3 \cdot \tfrac{1}{2} - 1072\,\mathrm{m}^3 = 2113\,\mathrm{m}^3$$
$$m = 2113\,\mathrm{m}^3 \cdot 2\,\tfrac{\mathrm{t}}{\mathrm{m}^3} = 4226\,\mathrm{t}$$

This number is important for the workload of the rovers because they need to bring material to the base and is later on important to estimate the construction time of the module and the energy consumption in the Athlete chapter (see Section 12.5).

The regolith structures of the base have been covered so far. There are still the inflatable and rigid ones remaining but in order to explain their masses and volumes we need to take a look at the actual structure.

1st Floor We start with the first level.

The picture is taken with an orthographic view from the top. Due to our concept of expansion we want to connect our modules that way that Astronauts can walk from one module to another without the need of actually leaving the base. The problem is if a module has only two entrances you can't just merge one of them for two modules to create connection because then in total you will still have only two entrances. This is bad security wise because with more and more modules the base would get the shape of a queue and if there is an accident in one of the nodes in the middle the base would be separated. Therefore a minimum of three entrances per module is required. This concept positions the three entrances each with an angle of 120° to the other two entrances. This allows each module later on to be connected with the other two modules via one node.

Each of those nodes is a cylinder with a diameter of 2.5 m and a height of 2.5 m as well. Each node contains an airlock which allows the transportation of items in and out of the module. Each module has a special upgraded node which is connected to a regolith garage for the rovers which serves as a protection against the lunar dust and allows to clean and repair the rovers. The garage starts 1.3 m below the surface of the area due to the fact that the rovers are 1.3 m higher than the node which allows the rovers to dock at the base

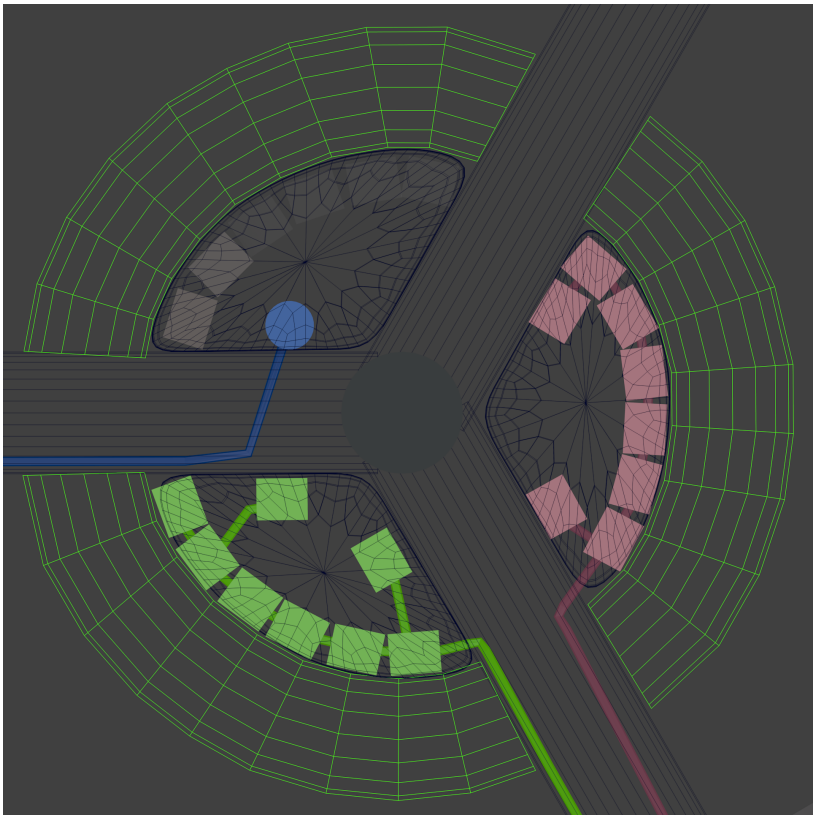


Figure 5.1: 1st Floor

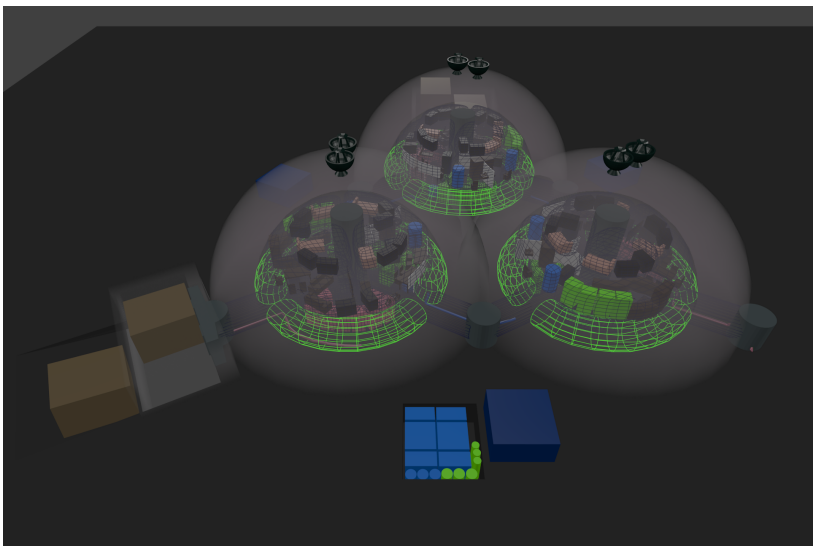


Figure 5.2: General Shape of the base

and this allows the astronauts to go into the base without the need of a spacesuit. This also keeps the contamination low. This process is described more deeply in the rovers section (see Chapter 12). In order to estimate the mass of such a node we assume it consists of aluminum with a width of 5 cm.

$$A = 2\pi \cdot 1.25 \cdot 2.5 + 2\pi \cdot 1.25^2 = 29.5\,\mathrm{m}^2$$
$$V = 29.5\,\mathrm{m}^2 \cdot 0.05\,\mathrm{m} = 1.47\,\mathrm{m}^3$$
$$m = 1.47\,\mathrm{m}^3 \cdot 2.7 = 4\,\mathrm{t}$$

This does not mean that the thickness of the aluminum needs to be 5 cm everywhere. Its more about getting some idea about the mass.

The first level of the module is the subsystems level. There is live support, energy and resource production. The blue cylinder consists of two water tanks used by the resource production. Each of the rectangular structures are in fact racks (see 2) which are being used by their respective subsystems. The eight light green ones belong to live support (see Chapter 6). The eight pink ones belong to energy (see Chapter 9). The dark gray ones belong to research (see Section 2.1) and the brown ones are repairing and 3d-printing racks. Those two kind of have the same job because if replacements are required they can be 3d printed with the other rack. But the 3d-printing rack has some other uses as well. Especially simple components can be printed on moon with just the materials and therefore for future missions the requirements for transport to moon are only its mass and there is moreover no need for a soft landing which increases the energy efficiency of the transport.

The most difficult task of this floor was basically the placement of the gardens. The gardens are the light green wired structures. The problem with them was that they used some vertical farming technology which allowed them grow plenty of plants in a small space but requires a cylinder shape. This problem was solved that way that the gardens were folded around the base. That way space could be used without wasting anything. In total there was the requirement for the gardens that for each person a cylinder with length of 7 m and diameter of 2.5 m was required. This made in total a required garden space of $28\,\mathrm{m}^3$.

The space which is now covered with gardens is the scope of a circle with radius $\frac{(8\,\mathrm{m}-2.5\,\mathrm{m})}{2} = 6.75\,\mathrm{m}$. This makes a total length of 35 m after subtracting the three losses for the paths:

$$l = 2\pi \cdot 6.75\,\mathrm{m} - 3 \cdot 2.5\,\mathrm{m} = 35\,\mathrm{m}$$

The additional space for the gardens can be used for surveillance, additional food or food of higher quality. There is no way that the

space could've been used more effective without folding the gardens.



Figure 5.3: 2nd Floor

2nd floor On the second floor there is the living and working area of the astronauts. There are 4 rooms. A bathroom, a kitchen, a living room and a command center. The bathroom is separated into two separate rooms. Each room with a toilet, a basin, a shower, a water tank with a heater and storage room, which can be used for towels, cleaning, medicine, toothpaste.

The kitchen has 4 Racks of storage for food. One for each person. These are the green ones. Next to them are two cookers. Both redundant. Then there are two fridges and basically a kitchenette with storage options for tableware and space which helps cooking. Then there is the living room with a table and four chairs which can be used for dining. Additionally there is a big flat-screen which can be used to watch films and TV with two couches where the astronauts can enjoy their free time. Enjoyment in general is really important not only because the astronauts are on a long term mission, which is up to now incomparable with any other mission in the history of

spaceflight, but additionally its simply important to be relaxed if you want to do a great job.

The forth room on this floor is the command center. In the command center there are two big screens for communication with the earth and surveillance of all important subsystems. Conferences with earth will be held there. The green rack in the command center is responsible for the communication with the satellites, which means tracking, directing the antennas, interpreting the signals, calculating the Doppler shift and so on (see Chapter 10). If there is currently no conference and the astronauts want to improve their fitness there is an treadmill and a training bicycle and other fitness stuff in the storage next to it.

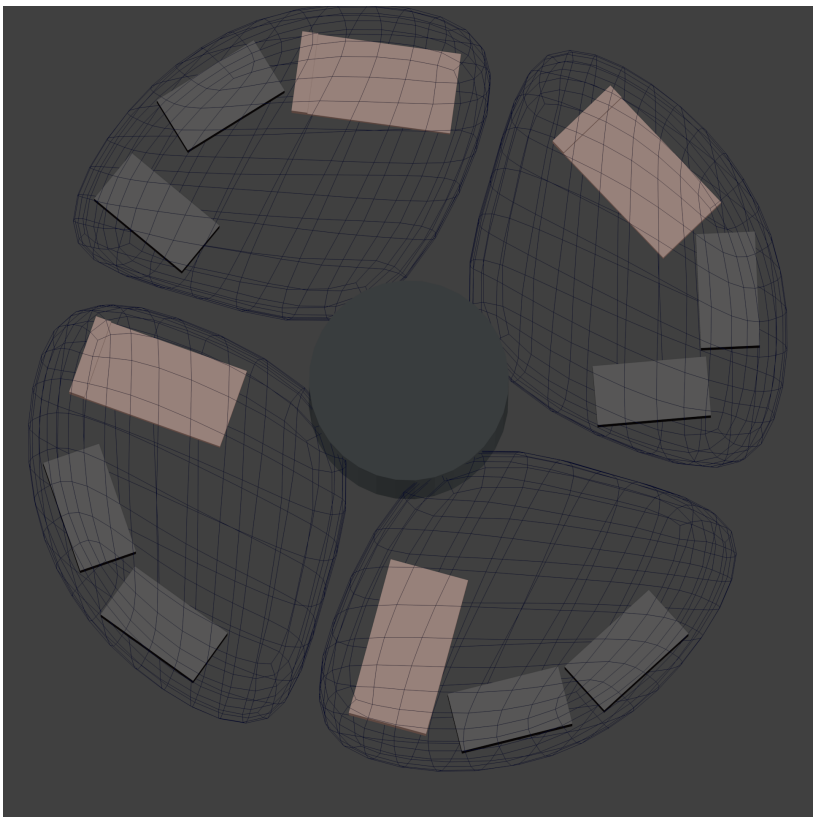


Figure 5.4: 3rd Floor

3rd floor The third floor consists of the four rooms of the crew. Each room is identical. The brown object is a bed and the gray objects both are storage. This storage can be used for personal stuff, for example clothes, pictures or books (more likely a kindle with some ebooks). Having a separate rooms for each astronaut is very important. It reduces the psychological stress of having to sleep with another person and allows the astronauts more private time, which makes them more relaxed and so on. Another important point is that the rooms are constructed that way that they don't connect with each other so that there is hopefully no noise. This is specifically mentioned because in a project about a deep space habitation simulator, test subjects specifically complained about the noise [58].

The total energy consumption of the second and third floor together will be around 2 kW average and maximum 20 kW if everything is running. Most crucial to that number is the cooker with a maximum power consumption of 10 kW. Apart from that we have an elevator with at most 3 kW a washing machine with 2 kW, computers and monitors with total of 2 kW. There will be a fridge with 0.3 kW. The rest comes from illumination and other small gadgets like water boilers, ipads, hairdryers, shavers and other personal stuff which is rarely used.

20 kW is a huge number compared to the 2 kW but its explainable, because all energy intensive tasks are about heating and this is done after a short time and the 20 kW are only the power which is really required if every device is turned on. In order to really use that energy there must be a coincidence that one person is just cooking and doing so it is using every hot plate to its maximum capacity. Meanwhile there must be a person which is using the elevator. Then the washing machine is just starting to heat the laundry up. To make a long story short it would be surprising if there are long time intervals where the energy consumption is over 5 kW. The average power consumption of 2 kW comes mostly from the computers and monitors as they will be switched on a lot. Note as well that the 2 kW of power consumption for the computers and monitors was their maximum power required if they are doing some difficult calculations. Most of the time they will use less energy. This will be about 1.1 kW. The cooker will take average of 200 W. The fridge will take its 300 W mentioned above because he has to be always online. Illumination will take 200 W as well. The rest same smaller gadgets mentioned above.

5.3 General shape

Having multiple floors is beneficial as shown before if you have the aim of minimizing the amount of regolith required to construct the base. But still the floors need to be connected and therefore an elevator is required. Fortunately on the moon the gravity is only $\frac{1}{6}$ g, so using an elevator is comparably energy efficient. The elevator is going to be placed in the cylinder in the middle of the base. Obviously as part of the astronauts safety there will be a spot for a ladder as well. The required power of the elevator is estimated to be 3 kW if its running. Basically this estimation has been made by dividing the power required for an elevator on earth by 6 [52]. The mass of this core component was estimated by using the same formula as for the outer nodes, just with a different height. Note that the tower has only a height of 7.5 m, not 8 m. This is the case because the 3rd floor ends at 7.5 m.

$$A = 2 * \pi * 1.25 \cdot 7.5 + 2\pi \cdot 1.25^2 = 68.7\,\mathrm{m}^2$$
$$V = 68.7\,\mathrm{m}^2 \cdot 0.05\,\mathrm{m} = 3.44\,\mathrm{m}^3$$
$$m = 3.44\,\mathrm{m}^3 \cdot 2.7 = 9.3\,\mathrm{t}$$

Its not meant that the cylinder has a wall of 5 cm all over the place, its more of an average value to work with. This value already includes the mass required for all its airlocks. For more precise calculations architectural knowledge is required.

5.4 Inflatable Modules

The difficult question in this topic is to make calculations how thick the inflatable modules should be. There is a comparable project where a big lunar base is constructed and they say the size of the inflatable modules needs to be in the range of a few tenths of millimeters but later on they pick a size of 1 mm for the whole module [38]. The problem is that this is kind of not satisfying, because its not that clear how to compare the project with this one and its difficult to imagine walking on a few tenths of millimeters. Research showed that car bodies have usually a size of 1 mm to 2 mm. Since there is obviously reduced gravity on the moon those numbers are getting more realistic. But for safety the dimensioning of the size of the inflatable modules will be 3 mm for 1st floor, 2 mm for 2nd and 1 mm for 3rd floor. The mass for the inflatable units will be calculated now. The inflatable units will be made of Kevlar with a density of 1.45 $\frac{\mathrm{t}}{\mathrm{m}^3}$.

1st Floor (see Figure 5.1) We estimate the ground per room is $16\,\mathrm{m}^2$ and the range is 15 m. This was estimated by with help of the blender model. We estimate the corridors are 10 m long. A_{inf} stands for the surface of the inflatable rooms, A_{garden} for the garden's surface and $A_{corridor}$ for the corridor's surface.

$$A = A_{inf} + A_{garden} + A_{corridor} = 3x(2 \cdot 16\,\mathrm{m}^2 + 2.5\,\mathrm{m} \cdot 15\,\mathrm{m}) + 35\,\mathrm{m} \cdot 2\pi \cdot 1.25\,\mathrm{m} + 3 \cdot 10\,\mathrm{m} \cdot 2\pi \cdot 1.25\,\mathrm{m} = 719\,\mathrm{m}^2$$

2nd Floor (see Figure 5.3) Four rooms with each $30\,\mathrm{m}^2$ ground and 20 m range.

$$A = 4x(30\,\mathrm{m}^2 * 2 + 20\,\mathrm{m} * 2.5\,\mathrm{m}) = 440\,\mathrm{m}^2$$

3rd Floor (see Figure 5.4) Third floor: Four rooms with each $10\,\mathrm{m}^2$ ground and 15 m range with average height of 2 m, because of reduced height due to the half sphere.

$$A = 4 * (10\,\mathrm{m}^2 * 2 + 15\,\mathrm{m} * 2\,\mathrm{m}) = 200\,\mathrm{m}^2$$
$$V = 719\,\mathrm{m}^2 * 0.003\,\mathrm{m} + 440\,\mathrm{m}^2 * 0.002 + 200\,\mathrm{m}^2 * 0.001\,\mathrm{m} = 3.237\,\mathrm{m}^3$$
$$m = 3237\,\mathrm{m}^3 * 1.45\,\tfrac{\mathrm{t}}{\mathrm{m}^3} = 4.7\,\mathrm{t}$$

5.5 Thermal

As mentioned before Thermal concepts are only going to be covered within a reduced scale. This means that we are only considering Thermal energy flows from the base to the outside of the base and the other way around. There are three ways to transport heat. Radiation, conduction and convection. Convection plays no role since the moon has basically no atmosphere. Conduction is reduced a lot since lunar regolith has only a conductivity of $0.004\,\frac{\mathrm{W}}{\mathrm{m\,K}}$ [94] and there is quiete a huge wall of regolith. If we ignore the vacuum between the inflatable modules and the regolith we can show with the following calculations that conduction is not an issue at all. First of all we calculate the surface of the half sphere. Then use the formula for conduction and determine the lost power. We assume its night on moon. Therefore the temperature outside is about $-173\,^\circ\mathrm{C}$ [98]. This creates a temperature difference of about 200 K.

$$A = \frac{(4*\pi*8^2)}{2} = 402\,\mathrm{m}^2$$
$$P = \frac{0.004\,\frac{\mathrm{W}}{\mathrm{m\,K}}}{3.5\,\mathrm{m}*402\,\mathrm{m}^2*200\,\mathrm{K}} = 92\,\mathrm{W}$$

Assuming that one human creates heat emission of 100 W [46] there is really no concern about the loss of energy because of conduction.

Therefore the only way of emitting energy to space is the use of radiation. But first take a look at the energy which is used within the base. We have the following energy requirements. There are 2 kW from the stuff the astronauts need for their living. 4.2 kW from the gardens and 5 kW from life support. Additionally each astronauts produces 0.1 kW heat emission himself which makes up to a total of 0.4 kW. This adds up in total to an amount of energy spent of 11.6 kW. But in fact the real heat emission isn't that high. The gardens use most of their energy for light which is consumed by the plants in order to do photosynthesis. Moreover the chemical reactions being used from live support are endothermic processes which consume energy as well. It can be assumed that these chemical reactions work with energy efficiency of at least 50 %. For more details visit the life support section. This surely drops the average energy that needs to be emitted below 10 kWand therefore it will be alright if the radiators will be able to emit 10 kW of energy. We assume further that the degree of emissivity of the radiator is 0.8, which can be achieved by black paint. We further assume that we have a louver which can be closed to prevent the radiation. Using the Boltzmann formula we get the desired heat loss through radiation with a radiator area of 30 m^2 and a temperature of 20 °C or 293.15 K.

$$P = \frac{(293.15\,\mathrm{K})^4 \cdot 30\,\mathrm{m}^2 \cdot 0.8 \cdot 5.67 \cdot 10^{-}8}{\mathrm{m}^2\,\mathrm{K}^4} = 10.05\,\mathrm{kW}$$

As mentioned before this only covers how the energy is getting out of the base, but not how its transported within the base. There might be the need for additional energy transport within the base, but this would be too detailed for this kind of work. But there is probably no need for an additional component, since we can already assume that we need some kind of decent air circulation for the live support and convection is very potent in transporting heat. It is still to be seen how the reduced gravity would impact the concepts of a complicated Thermal System.

With the required area the total mass of the radiator can be calculated now. The radiator consists of aluminum and its width is 5 cm.

$$V = 0.05\,\mathrm{m} \cdot 30\,\mathrm{m}^2 = 1.5\,\mathrm{m}^3$$
$$M = 1.5\,\mathrm{m}^3 \cdot 2.7\,\frac{\mathrm{t}}{\mathrm{m}^3} = 4.05\,\mathrm{t}$$

5.6 Deployment

It is clear that the base needs to be constructed while no humans are there and once they come the base should be ready. This can be done with the help of automated and half-automated robots. The construction of the base starts with the aluminum tower from the middle of the base. Once this tower stands the inflatable modules are getting inflated. First the first floor then the second floor and so on. Then the sintering will start.

But in order to protect the 3rd floor from damage and from contact with the sintered regolith there will be another inflatable module which has up to no volume but covers the whole surface of the already inflated volumes. We assume the size of half a millimeter. We approximate the surface by taking the surface of the half sphere twice.

$$A = \tfrac{4}{2} \cdot \pi \cdot (8\,\mathrm{m})^2 \cdot 2 = 804\,\mathrm{m}^2$$
$$V = 804\,\mathrm{m}^2 \cdot 0.0005\,\mathrm{m} = 0.4\,\mathrm{m}^3$$
$$m = 0.4\,\mathrm{m}^3 \cdot 1.45\,\tfrac{\mathrm{t}}{\mathrm{m}^3} = 0.58\,\mathrm{t}$$

Athlete The Athlete robot is the robot which is going to do the printing job. It has the shape of a spider, it can be up to 6.4 m high and it has a max reach of 15.5 m. Therefore it is capable of reaching each point of the structure from below [69].

3d printing As mentioned before there are 2 ways of 3d printing. One way is to use sintering and the other way is to use some ink. Unfortunately research didn't offer any numbers of how many inc is actually needed to 3d print the whole structure. But even if the mass of the ink would only be 1 % of the mass of the regolith this would make up to a total of $4226\,\mathrm{t} \cdot 0.1 \cdot 3 = 127\,\mathrm{t}$ for the total base. Therefore this concept is not useful for the huge masses of regolith this project is dealing with. Therefore we will go with the sintering. The Temperature required to melt regolith is about 1200 °C to 1500 °C. Since sintering heats only sightly below the melting point we assume a temperature difference of 1200 K. Some energy could possibly be saved if the printing takes place during the lunar day but this goes to far into detail and this will be ignored in this study. The regolith consists mostly of silicium and aluminum. Their respective heat capacities are about $0.9\,\frac{\mathrm{J}}{\mathrm{g\,K}}$ for aluminum and $0.75\,\frac{\mathrm{J}}{\mathrm{g\,K}}$ for silicium. Although there is more silicium than aluminum we assume as combined heat capacity of regolith $0.85\,\frac{\mathrm{J}}{\mathrm{g\,K}}$.

We use conventional heating. Heating with conventional means

has many disadvantages compared to microwaves, for example the speed. But microwave technology is not worth it if there is already energy shortage, which limits the speed anyway.

$$W = 0.85\,\tfrac{\mathrm{MJ}}{\mathrm{t\,K}} \cdot 4226\,\mathrm{t} \cdot 1200\,\mathrm{K} = 4\,310\,520\,\mathrm{MW\,s} = 1200\,\mathrm{MW\,h}$$

There are five years allocated to construct the first base. In order to do all the sintering and assuming there are 5 years with 300 days each year the required power can be calculated.

$$P = 1\,200\,000\,\mathrm{kW\,h}/36\,000\,\mathrm{h} = 33\,\mathrm{kW}$$

33 kW would be required to construct a base with 4226 t of sintered regolith as shielding. This would drop the radiation inside the base to a number that is equal to earth level. But there is no way an energy system can be constructed which could provide that amount of energy without the help of humans. And since its not needed to lower the radiation level to earth level a compromise has to be made for the first module of the base. Later on the other modules will be constructed with the aforementioned standard.

1st Module Compromise We want a total of 2 m of regolith for shielding. From the 2 m of regolith 0.5 m are going to be sintered and the rest is just filled up with normal regolith. This is doable because sintered regolith is harder than steel (ref: sieheemailvonhelge) and in combination with the reduced gravity of only $\frac{1}{6}$ g it can easily carry the rest of the regolith. $1072\,\mathrm{m}^3$ is the volume we already calculated for the half sphere with 8 m radius.

$$V = \frac{4}{3} \cdot \pi \cdot (8.5\,\mathrm{m})^3 \cdot \frac{1}{2} - 1072\,\mathrm{m}^3 = 214\,\mathrm{m}^3$$

$$m = 214\,\mathrm{m}^3 \cdot 2\,\frac{\mathrm{t}}{\mathrm{m}^3} = 428\,\mathrm{t}$$

We only need to sinter a total mass of 428 t compared to the 4226 t earlier.

$$W = 0.85\,\frac{\mathrm{MJ}}{\mathrm{t\,K}} \cdot 428\,\mathrm{t} \cdot 1200\,\mathrm{K} = 121\,\mathrm{MW\,h}$$

This takes 121 MW h. There is five years time to produce that amount of energy.

$$P = 121\,\mathrm{MW\,h}/(365 * 24 * 5\,\mathrm{h}) = 2.8\,\mathrm{kW}$$

Therefore we need 2.8 kW energy on average. Since we can only calculate with solar arrays which work 50 % of the time we need twice as much power

$$P_{solar} = 2.8\,\mathrm{kW} \cdot 2 = 5.5\,\mathrm{kW}$$

With a solar density of 410 $\frac{W}{m^2}$ the total required area can be calculated.

$$5.5\,kW \cdot 0.41\,\frac{kW}{m^2} = 13.4\,m^2 \text{ solar array}$$

The energy is going to be transported with rovers to the athlete printer. This part covers the tradeoff between the workload for the rovers and required mass for batteries. In a first approach batteries of a size of 2.5 t were taken due to the fact that the rovers can transport a maximum of 2.5 t. The energy density is 0.2 $\frac{MW\,h}{t}$. The battery size can be calculated now.

$$2.5\,t \cdot 0.2\,\frac{MW\,h}{t} = 0.5\,MW\,h$$

Therefore we need a total of 121 MW h/0.5 MW h = 242 charged batteries. This means that in a scenario we need the rovers to drive 239 times to the mobile solar pannels to recharge the battery.

Driving with the rover to the solar arrays and back takes 3 h. The rovers need to be 1 h early to ensure that every bit of solar energy is used. This means a total time of $4\,h \cdot 239 = 956\,h$. Considering 5 years time this makes up to a total workload of $956\,h/\,(24 * 365 * 5) = 2.2\,\%$. This works only if we have three batteries. One battery with the Athlete, one with the solar array and one battery which is being transported. Considering the low workload for the rovers its possible to dimension the batteries of a size of 1 t. This would on the other hand mean that the workload on the rovers is 2.5 times as much: $2.2\,\% \cdot 2.5 = 5.5\,\%$. There could still be some mass saved by reducing the weight of the batteries but halving the mass would double the workload for the rovers, so there is not really much to gain.

Heat Problem As mentioned before there will be an additional inflatable module to protect the base from the regolith during the construction process. There is only a small problem. If the regolith is directly sintered above the base this will create temperatures of 1200 °C while the temperature where Kevlar, the material of the inflatable modules dissolves is at 500 °C. Although in the spirit of additive manufacturing, the layering of the regolith is in the tenths of millimeters there would not be much of a total heat. This problem can be solved by creating a small layer of 3d printed regolith using the technique of the binder. Assuming 1 mm size the mass of the binder can be calculated. This is still larger than two to three layer of sintered regolith. Therefore the temperature after heat balance should be below 500 °C. We use 800 m^2 here for the surface of the base which was calculated earlier.

$$V = 0.001\,\mathrm{m} \cdot 800\,\mathrm{m}^2 = 0.8\,\mathrm{m}^3$$
$$m = 0.8\,\mathrm{m}^3 \cdot 2\,\frac{\mathrm{t}}{\mathrm{m}^3} = 1.6\,\mathrm{t}$$
$$m_{ink} = 1.6\,\mathrm{t} \cdot 0.01 = 16\,\mathrm{kg}$$

Even if the 1 % number is wrong 16 kg or a bit more won't make a difference cargo wise and can be considered as part of the 3d printing athlete rover.

Outlook Once the first module is constructed the furniture and the technical devices can be put in. After that the construction of the other 2 modules can start. The other two modules are going to be pretty much like the first one considering the social and private areas but in the working area the composition of the racks is going to be differential. Some subsystems are going to need less space due to the fact that less redundancy is required. The base is easily extendable due to the three exits of each module and the concept of merging the corner nodes. For a small base with small energy production it was required to minimize the required energy to actually build up the base. In the future and with more energy buildings might be constructed differently. The reduced gravity of $\frac{1}{6}$ g allows us to do so.

6
Life Support

by Wendelin Fischer and Helge Mohn

6.1 Conventional Life Support Systems

by Helge Mohn

To start with the topic life support it is important to understand the purpose of this collection of systems. What is life support? A brainstorming helps to understand the assigned function to the overall system. The goal is to develop a space of environment that suits the needs of a human body for a long-term mission. Therefore the parameters of the system itself, the input and output mass flows have to be figured out. After finding the amount of parameters, numbers have to be derived for each one. Figure 6.1 shows the approach to the system.

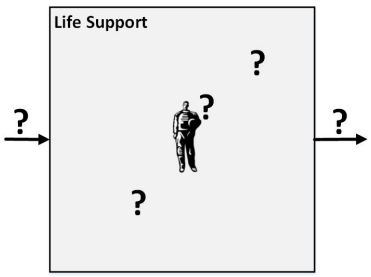


Figure 6.1: Brainstorming Life Support

A space with a volume V shall protect from the lunar environment that is hostile to life. A complement of X humans inhabite this space. Each human needs an atmosphere to breath. This atmosphere has to be well tempered, pressured and needs a suitable mixture of gas. Drinking of water and eating of food is necessary for the inhabitant. These are the first few parameters extended by many more in this chapter. Finally a concept shall control these parameters within a specified range to achieve the goal of life support. In our context to make it possible to live on the moon. This chapter will concentrate its research only for the physical human needs. A psychological point of view is not discussed.

6.1.1 Requirements

Metabolic values To ensure a healthy environment for a human it is a good idea to start with the metabolic values of the human body. The values are differentiated between gas, liquids and solids. During

this study the circular flow of gas and liquids are brought into focus. The circular flow of solids needs further study. In the following subchapters the different types of mass flow values are calculated. These values lead to the human metabolism Figure 6.2.

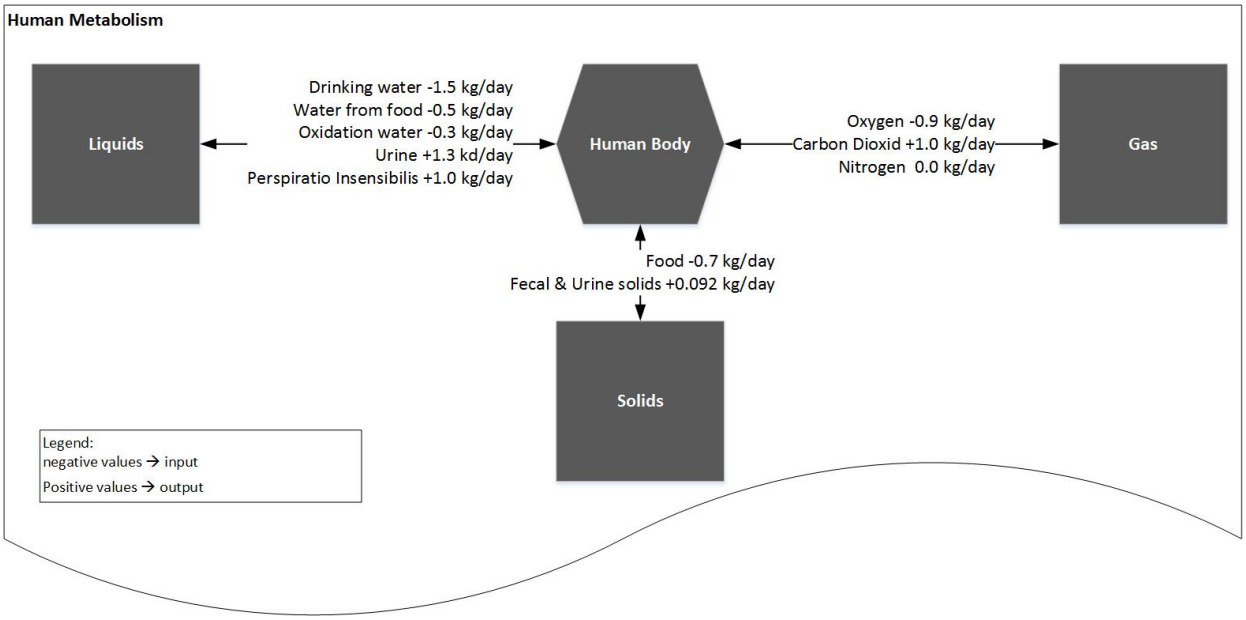


Figure 6.2: The Human Metabolism

Metabolic Values of Gas Starting with the gas. During each breath cycle the lungs consume about 28 % of the oxygen of the inhaled air. The exhaled air consists of a higher amount of carbon dioxide. The amount of nitrogen is not changed by the human metabolism (see Table 6.1). To figure out an average oxygen mass flow, which is one of the input streams of the human body, the amount of inhaled air per minute is of interest. This is depending on the kind of activity the body is up to and divers greatly. The Table 6.2. shows three activity phases as an example to calculate an average value representing the oxygen mass flow of one person. The calculation was derived on the basis of the ideal gas law. Therefore one mole of any gas has a volume of 22.41 at a temperature of 273.15 K and an ambient pressure of 1013.25 hPa. This way we derive the mass per liter of our two gas types of interest, oxygen and carbon dioxide.

Gas	Inspiration %	Expiration %
N_2	79.1	79.1
O_2	20.8	15.0
CO_2	0.03	4.0
Other	0.07	1.9

Table 6.1: Mixture inhaled / exhaled air [23]

$$CO_2 = 1.96 \frac{g}{l}$$
$$O_2 = 1.43 \frac{g}{l}$$

The amount of air, which passes the human body during a day, depends on the activity that is done. This activity can be described by

the pulse of a human. Following table 6.2 shows the activity related mass flows of oxygen and carbon dioxide.

Activity	Pulse $\frac{1}{\text{min}}$	Breath Cycles $\frac{1}{\text{min}}$	Respiratory Volume l	$\frac{\text{l}}{\text{min}}$	O_2 $\frac{\text{l}}{\text{min}}$	CO_2 $\frac{\text{l}}{\text{min}}$	O_2 $\frac{\text{kg}}{\text{d}}$	CO_2 $(\frac{\text{kg}}{\text{d}})$
Sleep	60	12	0.35	4	0.2	0.16	0.41	0.45
Average	70	16	0.5	8	0.4	0.3	0.82	0.85
Workout	140	25	2	50	2.5	2	5.11	5.65

Table 6.2: Activity related oxygen and carbon dioxide mass flow

An example day scenario may consist of 7 h of sleep, 16 hour duties with average pulse and 1 h of workout. Following values for mass flows are derived from the example scenario:

- Consumption of Oxygen
  - Average Input $0.88 \approx 0.9\ \frac{\text{kg}}{\text{d}}$
  - Peak Input $3.6\ \frac{\text{g}}{\text{min}} O2$
- Production of Carbon dioxide
  - Average Output $0.93 \approx 1.00\ \frac{\text{kg}}{\text{d}}$
  - Peak Output $3.9\ \frac{\text{g}}{\text{min}} CO2$
- Recovery from Carbon dioxide

$$1.00\,\text{kg}\ CO_2 \xrightarrow{Sabatier} 0.819\,\text{kg}\ H_2O \xrightarrow{Electrolysis} 0.727\,\text{kg}\ O_2$$

- Production of oxygen from Electrolysis

$$0.195\,\text{kg}\ H_2O \xrightarrow{Electrolysis} 0.173\,\text{kg}\ O_2 \text{ and } 0.02\,\text{kg}\ H_2$$

Metabolic Values of Liquids We start with the daily metabolic drinking water consumption per person. To figure out a mass flow of a person living on a moon base the comparison of known values from the earth and from the space station ISS are considered.

	Drinking $\frac{\text{kg}}{\text{d}}$	Food H_2O $\frac{\text{kg}}{\text{d}}$
Earth	1.2	0.9
ISS	1.3	0.5
Moon Base	1.5	0.5

Table 6.3: Metabolic consumption of water [44]

The water requirement of an adult person is around 3.5 % of the body mass. For a 70 kg person this results in up to 2.4 l. A part of 0.3 l of this value is called oxidation water. In addition to the consumption of water by drinking and water from food, the human body gains this oxidation water in the process of the reduction of fat. [78]. In this study the oxidation water is not considered. The crew of the moon base will follow a normal workday cycle. The artificial atmosphere will have less relative humidity compared to the earth. Airplanes as well as the ISS use a quite dry air to prevent corrosion. This leads to a rather higher demand of water per person to prevent dehydration due to increased loss of water by perspiratio insensibilis. The perspiratio insensibilis is water being part of the sweat and breath that can be

recovered by the atmosphere subsystem. The used value for the moon base is therefore increased by 10 % compared to the one found during the research. Table 6.3 shows the average daily amount of water consumption per person.

A human body requires water, but also produces water by discarding urine, feces, breath and sweat.

- Metabolic produced water
  - Urin 1.3 $\frac{kg}{d}$ [23]
  - Perspiratio insensibilis (dry air) 1.0 $\frac{kg}{d}$ [78] 0.9 $\frac{kg}{d}$ increased by 10 %)
- Recovery of metabolic produced water
  - Water Urine Recovery 0.9 $\frac{kg}{d}$
  - Perspiratio insensibilis from ambient air 1.0 $\frac{kg}{d}$

Metabolic Values of Solids The human body produces solids like urine solids (0.06 kg), fecal (0.032 kg) and sweat (0.018 $\frac{kg}{d}$ per person [42]. Regarding this source a total sum of 0.11 $\frac{kg}{d}$ per person can be assumed.

Non-metabolic water consumption The water consumption consists of more than only the metabolic values. It is interesting to compare these two water requirements and the difference to the common values on earth to the one used on the ISS. Where as the metabolic water requirement is similar to the requirement on earth, the non-metabolic requirement can be cut short, because these values are more connected to the human wellbeing than to the health.

The situatio for a moon base is different to the space station ISS. On the one hand the whole project is based on the fact that water can be gathered on the moon and on the other hand the inhabitants of the base will stay for long-term missions. Therefore a higher degree of wellbeing correlates with the high long-term performance of the crew. That is why an increased non-metabolic water consumption compared to the ISS is assumed as basis for the moon base. In other words the inhabitants will be able to take a shower once in a while.

Non metabolic solids By trash and food packaging a total of 1.3 $\frac{kg}{d}$ per person can be assumed for the ISS [44]. It has to be researched in more detail if the moon base can do better than that, due to the fact that it produces its own food and does not need only packed food. During this concept the focus was set to the atmosphere and water system. The food production is discussed in the next subchapter of the life support systems.

	Earth	ISS	Moon Base
Cooking	10	1.77	1.8
Hand Wash	10	3.18	3.2
Shower	30	2.27	5.0
Cleaning (clothes, dishes)	37	0.06	1
Toilet Flush	40	0.5	0.5
Total	117	7.78	11.5

Table 6.4: Consumption of water ($\frac{kg}{d}$)[25, 44]

Atmosphere In the previous chapter the metabolic aspect of the atmosphere has been shown. A viable atmosphere for humans has to have the right mixture of gases and the right total pressure. As already discussed the human body consumes oxygen and produces carbon dioxide. From this point of view an atmosphere of pure oxygen is possible and in deed acceptable. The disadvantage of a pure oxygen atmosphere is the increased fire hazard. Fire is one of the most dangerous hazards in aviation and space. To reduce this risk it is a convenient decision to choose an atmosphere, which equals the atmosphere on earth. Due to the high degree of nitrogen the risk of fire is easier under control.

Gas	**Volume Fraction** percent	**Mass** $\frac{kg}{m^3}$	**Per Building** $\frac{kg}{1000m}$
Nitrogen	79.1	0.975	975
Oxygen	20.9	0.298	298

Table 6.5: Mass of gas for filling the building

For standardization the International Civil Aviation Organization ICAO [90] defined an International Standard Atmosphere ISA. This atmosphere defines the atmosphere at sea level and the change in atmosphere with increasing height. At sea level on earth following values can be considered as a basis for our moon base:

- Pressure 1013.25 hPa
- Density 1.225 $\frac{kg}{m^3}$

These two examples shall help to understand in which range the pressure of the atmosphere may vary. A very low pressure of 700 hPa equals a height above sea level of 10.000 feet (about 3000 m). Starting from this height aviation pilots have to wear an oxygen mask, if they intend to fly longer periods at this level and the pressurization of the cabin is not working. A very high pressure is achieved by diving 10 m under water. The hydrostatic head would yield to a pressure of an extra one bar and a total of 2013 hPa.

The German federal agency for health and safety [22] gives following advice for a noncritical working environment: 730 hPa (about 2500 m sea level) up to 1113 hPa (about 1 m water head)

As basis for our moon base this range ensures a good performance of the human body.

6.1.2 Subsystems

The conventional life support systems are divided into following subsystems:

- Atmosphere System
- Water System

System circuits A viable point for the success of the moon base is a low input mass flow to the system. This input mass has to be either brought to the moon or it has to be mined on the moon, if it is available.

The task of the system design is to take advantage of produced elements and to convert them to an input element. In general systems fall into three categories:

Open loop: each required element will be put into the system

Semi closed loop: a part of the Input elements can be recycled, but resupply of some elements is still necessary.

Closed loop: The system is consistent in itself. All elements are part of a cycle

A gathering of facts:

- The distance to the moon is about 1000 times the distance to the ISS. This distance correlates with the high effort that is necessary to resupply mass from our earth to the moon.
- This moon base concept is dependent on the fact that water can be mined on the moon.
- Until 2030 technology development can be taken into account. The state of the art technology from today might be outperformed. This concept should consider technology, which is today in an early stage of development.

Therefore goal is to achieve a semi closed to closed loop. The resupply from earth shall be kept low. The resources on the moon like water and solar energy shall be taken into account. Oxygen and hydrogen can be derived from the water resource, which reduces the resupply demand.

Atmosphere System This subsystem shall ensure the right mixture and pressure of the ambient air. All areas of the base are treated the same way with the same quality of air.

The following schematic shows the distribution and flow of oxygen, carbon dioxide and nitrogen. Nitrogen and oxygen can be refilled into the system. This is necessary due to leakage.

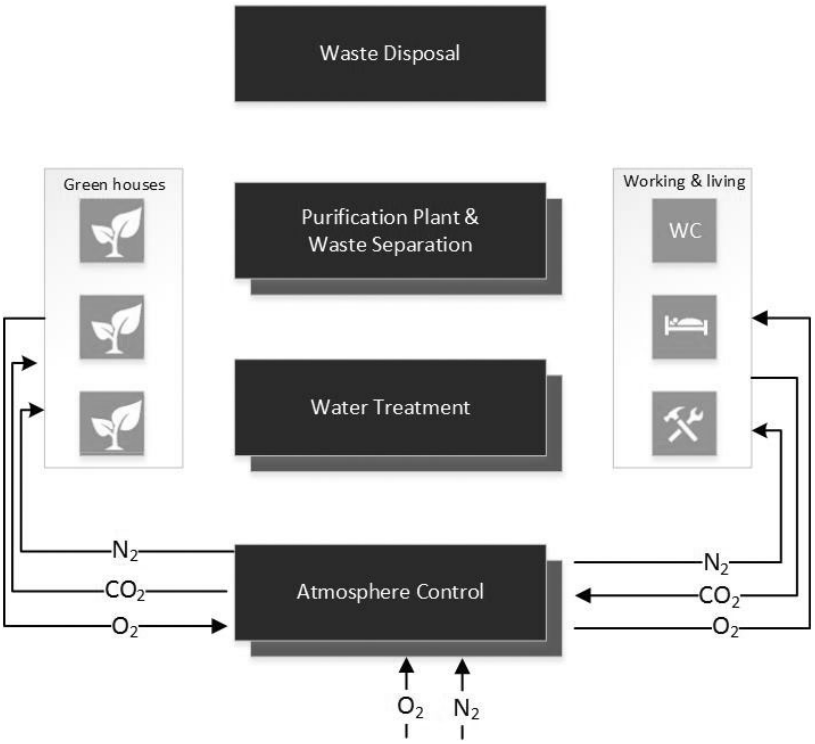


Figure 6.3: Distribution of gas

The main subsystems of the atmosphere control system are:

- CO2 Concentration Unit
- CO2 Reduction Unit
- O2 Generation Unit

Air: Initially the moon base is filled with 1000 m^3 air, which is brought from earth to the moon. Additionally a backup of 500 m^3 is calculated for unplanned situations like bigger leakage than 10 % per year. The process of electrolysis can balance the daily consumption of oxygen.

$$2H2O \rightarrow 2H2 + O2$$

The process of Sabatier can balance a part of the water needed for the electrolysis, by using the produced carbon dioxide and the hydrogen, which is a product of the electrolysis.

Nitrogen passes the human metabolism without any loss. Therefore there is only a need to refill nitrogen due to leakage. Nitrogen cannot be gathered on the moon. The loss of nitrogen is taken care of by resupplying air from the earth. An overall loss of maximum 10 % per year is assumed for this calculation.

To transport nitrogen different ways are possible. One way is to transport nitrogen stored in the propellant hydrazine. Hydrazine can be decomposed to nitrogen and ammoniac.

$$3N2H4 \rightarrow N2 + 4NH3$$

With a further ammoniac decomposition even more nitrogen and additionally hydrogen can be gained.

$$3N2H4 \rightarrow N2 + 4NH3$$

Due to the highly combustible characteristic of hydrazine a different way of storage is in respect to the safety of interest. Gas can be stored under high pressure to deliver a good volume to mass ratio. A high pressure is again a risk for the transport.

For the concept of MOON BASE 2030air will be transported and resupplied to the moon base in a cryogenic way. The benefits are a good volume to mass ratio combined with a more safe pressure.

CO2 Concentration Unit: Carbon dioxide is a poison part of the atmosphere. Therefore it is important to control the amount of carbon dioxide. Different systems are available and dependent on the further usage of the carbon dioxide. Since there are processes than can regain the oxygen from the carbon dioxide it makes sense to select a system that collects the gas and delivers a highly concentrated stream of carbon dioxide to the carbon dioxide reduction unit.

CO2 Reduction Unit: The CO2 Concentration Unit delivers a highly concentrated stream of carbon dioxide. Two concepts for the reduction will be considered.

The Sabatier process is already in use on board of the space station ISS since 2010. For the process a catalyst and a temperature of 450 K to 800 K is necessary. Due to the exothermic reaction the temperature has to be reached only once. After the reaction has

started, an exothermic reaction will keep the temperature within the specific range. If it reaches over 800 K the process itself slows down for cooling. Additionally the temperature is controlled by a system, which uses the radiators of the base. To convert 4 $\frac{kg}{d}$ carbon dioxide the system would have a mass of 0.4 t t and would require 0.05 $\frac{kW}{h}$ [42]. The methane can be stored. It is part of the long-term strategy of the resources to use this methane in the process of gathering oxygen from moon regolith.

Reaction equation of Sabatier

$$CO2 + 4H2 \rightarrow CH4 + 2H2O + heat \rightarrow CH4 + O2 + H2$$

$$1.0\,kg\ CO2\ \overrightarrow{Sabatier}\ 0.819\,kg\ H2O\ \overrightarrow{Electrolysis}\ 0.727\,kg\ O2$$

A maximum of 0.727 kg oxygen can be derived from 1.0 kg carbon dioxide.

H_2	O_2	C	CH_4	H_2O	CO_2
2.02	32.00	12.01	16.04	18.02	44.01

Table 6.6: Mass to mole ratio $\frac{g}{mol}$

The second option is the Bosch process. This reaction needs an iron catalyst and temperature of 700 K to 1000 K [42]. For the temperature a high power demand is necessary. The product of carbon leads to a problem, because it sticks to the catalyst and weakens the performance. A single pass of the gas leads to a conversion efficiency of 10 % [42].Therefore a recycling is necessary to remove 100 % of the gas from the input stream. This leads to a reduced input flow rate.

	kg	mole
Input		
CO_2	1	23
$4H_2$	0.19	23
Output		
CH_4	0.36	23
$2H_2O$	0.82	23

Table 6.7: Calculation Sabatier

Another disadvantage is a higher mass and power demand for the Bosch process compared to the Sabatier process. To convert 4 $\frac{kg}{d}$ carbon dioxide the Bosch system would have a mass of 2.8 t and would require 0.28 $\frac{kW}{h}$.

	kg	mole
Input		
$2H_2O$	0.82	23
Output		
O_2	0.73	23
$2H_2$	0.09	23

Table 6.8: Calculation Electrolysis

The big advantage is that no hydrogen is lost.

Reaction equation of Bosch

$$CO2 + 2H2 \rightarrow C + 2H2O + heat \rightarrow C + O2 + H2$$

The Bosch process is still in early stage of development. The main problem of the development of a Bosch System is the carbon, which sticks to the catalyst and weakens the overall performance.

Due to the lower mass, the higher status of development and the successfully usage on the ISS, the Process of Sabatier is selected for this concept.

O2 Generation Unit: This unit uses the process of electrolysis to gather oxygen by the input of water. This process is described and in more details in Chapter 11.

Water System The following schematic 6.4 shows the flow of liquids of the moon base. The supply of water is subdivided into two potable water and hygienic water.

Potable water is enriched with mineral nutrients and has to be free of microorganism [1]. Hygienic water is used for hand washing, shower, toilet flush, pouring the garden etc. The wastewater is subdivided in grey water and black water. Whereas grey water consists of the water coming from the showers and hand washbasins, the black water is served by the toilets and consists of flush water, urine and fecal. Grey water needs less effort to recycle and to reuse as hygienic water. The water used for cleaning and dish washing is the only exception. It cannot be treated as grey water, since it includes to much other ingredients like fat.

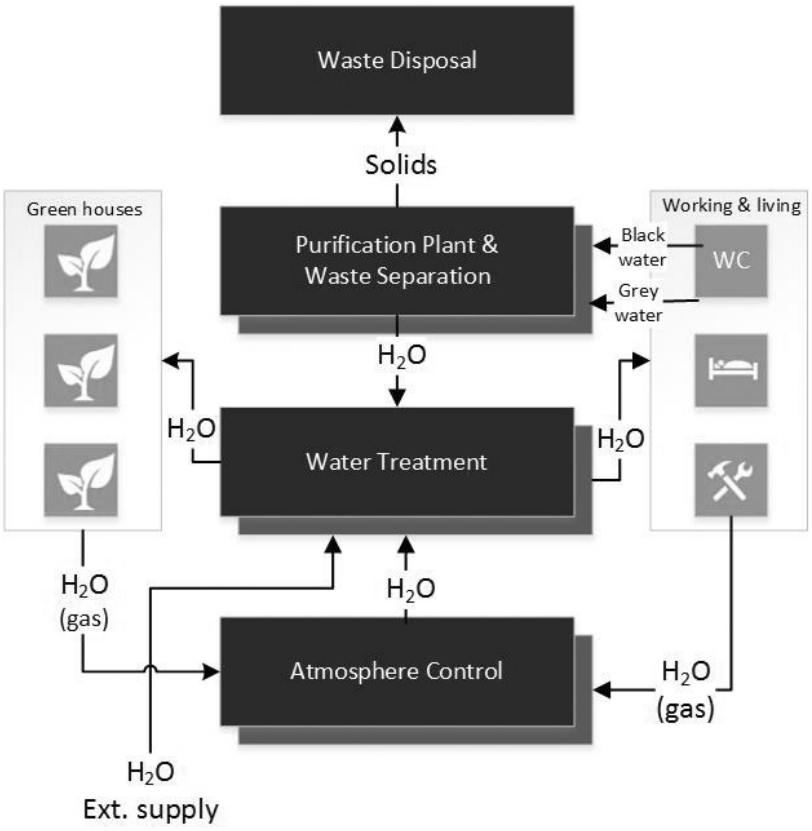


Figure 6.4: Water Distribution

To describe the flow of liquids in more detail, Table 6.9 shows the consumption of potable and hygienic water, the production of wastewater and finally the amount of recycled water.

The amount of the supply of external water shows the quality of

source	Consumption potable water	Consumption hygienic water	Waste grey water	Waste black water	Recycling Process Type	Recycling Factor	Recycling potable water	Recycling hygienic water
Water subsystem								
metabolic: drinking water	1.50							
metabolic: water in food	0.50							
food preparation	1.80		1.80		UED	0.99		1.78
Hand Wash		3.20	3.20		ED	0.99		3.17
Shower		5.00	5.00		ED	0.99		4.95
Cleaning (Clothes, dishes, etc.))		1.00	1.00		ED	0.99		0.99
Toilet flush, feces		0.50		0.50	Filtration, pouring of plants	0.80		0.40
Green garden		38.50						
metabolic: urine			1.30		VCD	0.70	0.91	
Atmosphere subsystem								
sabatier			0.82		Sabatier	1.00	0.82	
cabin air living complex			1.00		recovery from condensate, ED	0.99		0.99
cabin air green garden			32.00		recovery from condensate, ED	0.99		31.68
Intermediate result	3.80	48.20	44.82	1.80			1.73	43.96
Ressources								
External water supply			6.31		Water treatment	1.00	2.07	4.24
Total							3.80	48.20

Table 6.9: Daily water cycle of one crew member



the system. 6.5 l water is used by the plants of the green garden and about 6 l have to be supplied to the system. The water of high quality coming from the Sabatier process and the urine recovery can be used to derive the used amount of potable water. The external water supply is water that can be gathered on the moon. For system design and safety matters an additional 20 % surplus has been added to the resupply mass of water resulting in a deman of 7.5 $\frac{l}{d}$.

Grey water: The recovery of hygiene water and potable water depends on the amount of detergent and mechanical impurities it contains. The grey water contains water from the showers, hand washbasins and cleaning of clothes. After passing a first step filter, which subtracts mechanical particles like hair and dirt the grey water can be recycled by one of the following options 6.10.

	Reverse Osmosis	**Multi Filtration**	**Electro Fialysis (ED)**
Pros	Cleanable by flushing Low power requirement	Efficiency of 99 % Lowest power requirement	Efficiency of 98 % Cleanable by flushing
Cons	Efficiency of 80 %	Not cleanable: 24 $\frac{kg}{a}$ resupply mass p.p.	Risk for transport and storage of brine Higher complexity High power consumption

Table 6.10: Grey water recovery [42]

The Reverse Osmosis and Multi Filtration methods have been already tested for space application. The low efficiency of the Reverse Osmosis does not meet the requirement of system circuit. The multi filtration is a good alternative for space application. For the fully operational moon base with a crew of twelve about 288 kg resupply mass is an expensive fact.

The high efficiency and low resupply mass of the Electro Dialysis make this technology interesting. It is an experienced technology on earth, which is used in hospitals commonly. For space application this technology has not been tried before and the involved brine of the Electro Dialysis brings a hazard with it.

In 2011 NASA did a proposal of solicitation for an Electro dialysis system for the water system of the ISS. This underlines that this technology is in early stage of development and it has to be put effort in this to achieve a highly effective system with no resupply mass.

The Electro Dialysis and the Multi Filtration technology are selected for the moon base. An encouragement of the Electro Dialysis technology combined with the well developed Multi Filtration would lead to a satisfying system circuit and a good redundancy.

For a crew of four:

Input mass flow: $8\,\frac{\text{kg}}{\text{h}}$ grey water

Efficiency: ca. 98 %

Black water: The black water consists of toilet flush mixed with fecal and an extra flow of flush water and urine.

The toilet flush with fecal has to pass a more rough filter. The process of Ultra Filtration therefore uses a semipermeable membrane. With the help of pressure water without macro particles passes the membranes. This water can be used for pouring the green garden complexes.

The urine will be treated separately und recycled to potable water. Urine recycling is a well-developed distillation process. It is used for years on the ISS and saves tons of water per year. For recovery the urine is distilled. On earth this is an easy process to heat a fluid up to its phase change temperature and then collect the separated steam. On the ISS the zero gravity environment makes it necessary to rotate the whole processing chamber. This artificial gravity makes it possible to separate steam from liquid.

On the moon 1/6 of the earth gravity persists and helps to simplify this process compared to the ISS. The Vapor Compression Distillation (VCD), the Thermoelectric Integrated Membrane Evaporation System (TIMES), the Vapor Phase Catalytic Ammonia Removal (VAPCAR) and Air Evaporation Systems (AES) are some of the competing technologies [42].

Table 6.11: Urine Recovery

	VCD	**TIMES**	**VAPCAR**	**AES**
Pros	Highly developed High flow rate Low power consumption	Efficiency of 91 % Non-moving distilling unit	Efficiency of 95 % Produces potable water No pretreatment	Efficiency of 100 % High reliability
Cons	Efficiency of 70 % Pretreatment of Input Post treatment of Output	Pretreatment of Input Post treatment of Output	Low technology level	Resupply of wicks Energy intensive

The VAPCAR system is at a low technology level. Science papers regarding to this technology count up many difficulties. It is an unsure option.

The AES has much potential and a high efficiency. On the other hand the resupply mass cold not be figured out during the research. The VCD and TIMES both fit the requirements and do not have a high resupply mass. The VCD is on the one hand well developed, but on the other hand less efficient. The TIMES is more efficient, but not that developed. For the moon base the development of these two technologies shall be encouraged. A system with a high reliability, good efficiency und low resupply mass shall be derived. The calculation is based on the low efficiency of VCD to be on the safe side, but it is supposed that a development of one of these technologies can be achieved.

For a crew of four:

Input mass flow: 5.2 $\frac{kg}{d}$ urine and 2.0 $\frac{kg}{d}$ flush water

VCD System:

Max Input mass flow: 32.64 $\frac{kg}{d}$

Mass: 101.2 kg

Power: 0.115 kW

Efficiency: 70 %

[42]

Condensed water from cabin air: The cabin air collects moisture of the crew (perspiratio insensibilis) and a high amount of condensate from the green garden. Per person a daily amount of 33 kg of condensate has been assumed. 1000 m^3 air of a temperature of 20 °C and a relative air humidity of 30 % can contain up to 5.5 kg of water [107]. A crew of four produces 5.5 $\frac{kg}{h}$ water moisture.

The required system shall have a performance of 1000 $\frac{m^3}{h}$ intake air and 132 $\frac{kg}{d}$ condenser water to fulfill the calculated requirements of a crew of four persons. The research for earth used air dehumidifier systems lead to a power requirement 1.4 kW.

The condenser water is no potable water. It has not been treated with high temperature like the water coming from the Sabatier Process. Therefore it has to be post treated to use it as potable water.

For a crew of four:

Mass: 68 kg

Power: 1.4 kW

Efficiency: 100 %

Datasheet (Kroll T120)

6.1.3 *Conclusion*

The following Figure 6.5 shows the selected atmosphere system circuit.

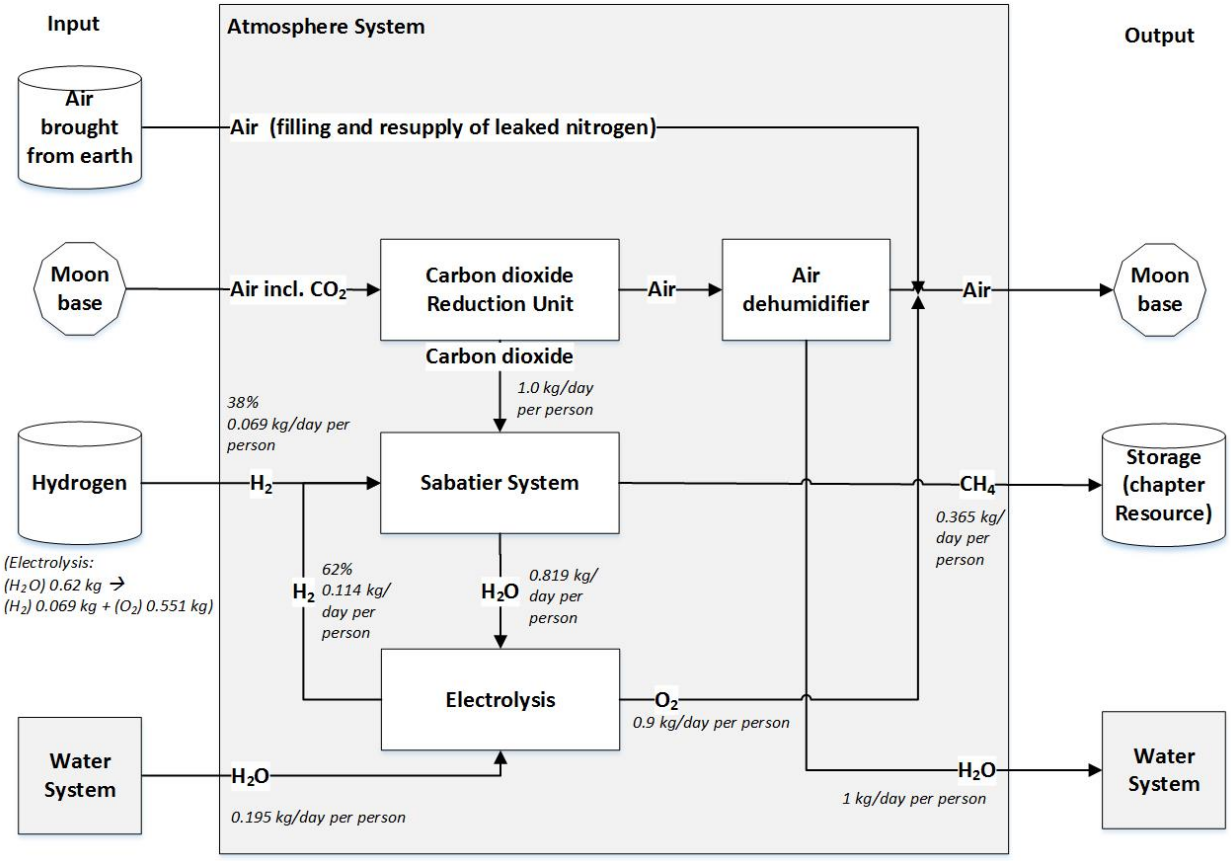


Figure 6.5: Atmosphere System Circuit

The sketch shows the big influence of the Sabatier process. Over 80 % of the water used for the electrolysis to gain oxygen is recovered by the Sabatier system.

The Electrolysis uses 1.014 kg water to gain 0.9 kg oxygen and 0.114 kg hydrogen. At this point the selected system shows a fact of a semi closed loop circuit. The Sabatier system gets only 62 % of its required hydrogen to process 1.0 kg of carbon dioxide. This is due to the loss of hydrogen, which is part of the methane, which is not used for the atmosphere system. The process to split methane and to gain hydrogen needs a lot of power and produces a lot of heat. As this technology is not well developed, it is not part of this concept. Further research would be benefit for closing the loop a bit more. As mentioned in the chapter System circuits, water is a resource found

on the moon, which will be taken into account for the semi closed loop of this concept.

To gain the missing 38 % of hydrogen 0.62 kg of water has to be additionally processed during the electrolysis and another 0.551 kg oxygen will be additionally produced, which can be stored. Another solution would be to waste some carbon dioxide, gain less water through the Sabatier process and requiring less hydrogen. The missing amount of water can then be substituted by the supply.

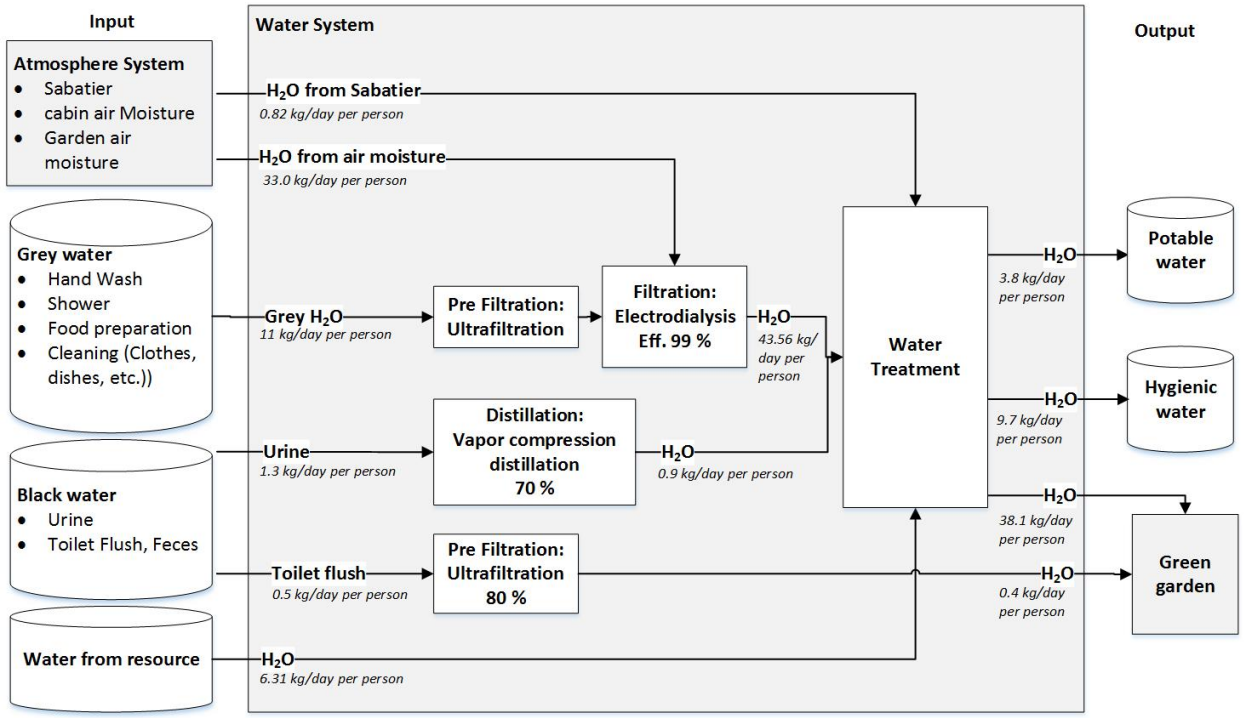


Figure 6.6: Water System Circuit

The Figure 6.6 explains the selected water system circuit and is based on Table 6.9 . Such a complete water system is shown in Figure 6.7. 6.31 kg of water have to be resupplied for each person every day. This might sound inefficient, but already includes the high water requirement of the green garden complexes of 38.5 $\frac{kg}{d}$ per person. 32.0 kg of this amount can be recovered, so that the plants consume 6.5 kg. The metabolic consumption of food water closes the loop.

For safety reasons all systems should be considered in a triple redundant way. To decide whether the systems are hot or cold redundant more progress of the development is necessary to derive more detailed information about system characteristics.

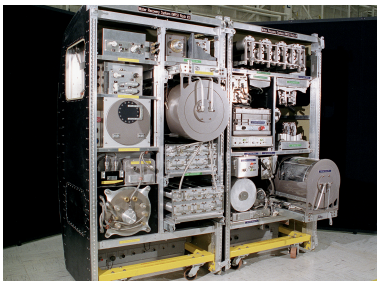


Figure 6.7: NASA: Water Recovery System. Credit: NASA

6.2 *Bioregenerative Life Support Systems and Food Supply*

by Wendelin Fischer

It has previously been discussed how chemical and physical processes can provide water and a life friendly atmosphere, containing oxygen, for humans on a lunar base station. Base stations in earth orbits, such as the ISS, have also proven the value and robustness of such life support systems. But besides water and oxygen, there are more nutrients the human metabolism needs as a constant intake. These substances include the energy providing macronutrients carbohydrates, proteins and fats as well as minerals and vitamins needed in smaller doses but still indispensable and therefore called micronutrients. Most of the nutrients are ingested with our food and have directly been provided as cargo from earth on all previous and current human space missions. On a long term lunar base station however there is a mandatory constraint of producing a lot more nutrients on the station itself, as transport costs are in terms of multiples of the costs of flights to low earth orbit space station. Thus producing food on the moon is a cornerstone of such a mission.

For the production of food a biochemical cycle has to be used, which is able to produce new food for humans out of their disposals. The direct production of food from the resources provided on the moon is not possible, due to the lack of carbon-compounds on the moon surface. The synthetic production of food products shall also be mentioned in this context, but it seems to only be capable of playing a minor role in the supply chain of a lunar base station in the near future, as research is unable to provide methods efficient enough to produce a diverse, healthy and sufficient synthetic diet for astronauts up to today.

The main focus has therefore be set to bioregenerative life support systems (BLSS), containing biological process to regenerate food out of organic disposals, energy and water. A complete BLSS usually has three stages, which depend on each other: One stage is the human who produces carbon dioxide and water by cellular respiration and excrements which have to be processed. The human requires food and oxygen as input for the cellular respiration. Both of them are received from the food producing stage, typically some kind of plants, which also consume the water and carbon dioxide produced by the human. The food producing stage does require energy, typically as light, and nutrients which it receives from the third stage, the waste processing. At this stage all inedible waste of the food producing stage and the human excrements and other biological waste is processed to some kind of nutrients. This cycle is shown in Figure 6.8.

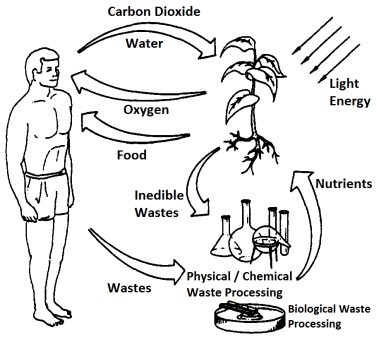


Figure 6.8: Schematic Cycle of a BLSS [Credits: [95]]

Human Food Demands To design an appropriate BLSS for food production an analysis of the human needs has to be carried out first. Dietitians recommend a daily energy intake of approximately 2500 kcal, depending on weight, sex, age and physical activity of a person. The energy input shall be splitted into carbohydrates, proteins and fats by approximately 55 %, 15 % and 30 % respectively [51]. Carbohydrates and proteins have an energy density of 4.12 $\frac{\text{kcal}}{\text{g}}$, while fats have a higher energy density of 9.35 $\frac{\text{kcal}}{\text{g}}$ [23]. This leads to total daily input masses of 335 g for carbohydrates, 91 g for proteins and 81 g for fats.

	relative amount	Required daily energy (kcal)	energy density ($\frac{\text{kcal}}{\text{g}}$)	Required daily mass (g)
carbohydrates	55 %	1375	4.11	335
proteins	15 %	375	4.11	91
fats	30 %	750	9.31	81
sum	100 %	2500	–	507

Table 6.12: Amounts of daily human energy intake

A further classification of the three groups of macronutrients is still possible, as fats, for example, have to be further divided into different types of saturated and unsaturated acids. A wide range of them is required by the human body, but for the draft of a BLSS concept the data provided above shall be enough at this stage.

As mentioned before the human metabolism also requires micronutrients (vitamins and minerals) as a regular intake. Their quantities are also dependent on sex, weight, age and physical state and activity of a person, but nevertheless in terms of milli- and micrograms per day and therefore do not fall into account in the dimensioning of the life support system. An overview of the recommended daily allowances provided by the European Commission's Scientific Committee on Food is given in Table 6.13. When designing a BLSS in detail, an eye should be kept on all those substances, too. Organisms providing preferably all of them have to be chosen, to construct a fully closed BLSS. At this stage of the concept design, they will however not be further discussed. In case of a lunar base station it is also still possible to provide them in form of dietary supplements from earth without having to transport a lot of mass.

Micronutrient Reference	Labelling Value
Vitamin A	800 µg
Vitamin B1	1.1 mg
Vitamin B2	1.4 mg
Niacin	16 mg
Vitamin B6	1.4 mg
Folate	400 µg
Vitamin B12	2.5 µg
Vitamin C	80 mg
Vitamin D	5 µg
Vitamin E	12 mg
Vitamin K	75 mg
Pantothenic Acid	6 mg
Biotin	50 µg
Calcium	1000 mg
Phosphorus	700 mg
Potassium	2000 mg
Sodium	600 mg
Chlorine	800 mg
Iron	14 mg
Zinc	10 mg
Copper	1 mg
Iodine	150 µg
Selenium	55 µg
Magnesium	375 mg
Manganese	2 mg
Chromium	40 µg
Molybdenum	50 µg
Fluorine	3.5 mg

Table 6.13: Reference Labeling Values for nutrients within the European Union as suggested by the European Commission's Scientific Committee on Food [81]

Types of Producible Food Before classifying food, the most important properties and parameters for all groups of biologically producible food have to be defined first. The parameters listed below are combined from [43] and [110]:

Growth Rate: The growth rate of a system is expressed as the mass per time per area production ratio. A plant can for example produce 50 $\frac{g}{m^2 d}$ of biomass. Sometimes it is also defined in relation to volume instead of area. This is especially the case for primitive water systems such as algae.

Harvest Index: The harvest index is the ratio of edible mass to produced biomass. Systems with a harvest index of 70 % produce 70 g of edible and 30 g of inedible biomass when producing a total of 100 g of biomass.

Consumed Substances: Water and CO_2 are the main substances consumed by biological food producers. Minerals are essential for most systems, too, but do not fall into account in terms of mass per time. Livestock does also consume macronutrients in amounts which have to be taken into account, but for most others this is not the case. All consumed substances are measured as mass per time per area or volume of crops.

Lighting Power and Period: All systems conducting photosynthesis require light. The lighting power and period depend very much on the system itself. Lighting power is expressed as power per area and lighting periods as the percentage of illuminated time, usually in relation to 24 h.

Crew Time Requirement: All systems have to be maintained and harvested. This is usually the job of a human crew member. The averaged daily time consumed by a biological system is the crew time requirement. It is defined in relation to the treated area.

Food producible on the moon, is generally classified into four groups: microbial systems, algal systems, higher plants and livestock [43]. Although most editors only take into account higher plants as food suppliers for a lunar base station an eye has to be kept on all the other groups, too. They shall therefore be explained in the following section and examples shall point out their advantages and disadvantages for the life support system of a lunar base station.

Microbial Systems: These organisms consist of single independent cells or small groups of them, such as bacteria, viruses, fungi, and different types of micro-algae. On earth such organisms play an

indispensable role in all kinds of ecosystems. They disperse most of our secretions and they serve as food in multiple ways, for example as plankton in the ocean, just to mention a couple [50]. Their advantages for a BLSS are their robustness against environmental effects, such as radiation, pressure or the lack of regular sunlight and their high growth rate as well as their immense protein and micronutrient contents. For food production micro organisms however also have one big disadvantage, which is their high acid content. This, and the fact that most people are unfamiliar and sometimes also antipathetic with eating protozoal fungi as a main dish, limit them as food providers. [41] Nevertheless microbial systems may play a different, very important role on a lunar base station: The treatment of organic disposals and the generation of fertilizer could be a major task for different bacteria cultures.

Algal Systems: Algal systems differ from microbial systems by their number of cells and size. Besides small single cell systems, algal organisms can reach sizes of several tens of meters on earth and are therefore no longer called microbial. Algae share most of their properties with other microbial organisms, but some differences also have to be pointed out: Their acid content is much lower than that of fungi and bacteria, which make them better food providers. Nonetheless they are not as robust as comparable smaller organisms. They depend very much on daylight and do not offers such robust long term stabilities. [41] On a lunar base station algae may however play an important role in the oxygen generation and gase exchange systems, as they are capable of producing oxygen by photosynthesis, an essential reaction in bioregenerative life support system. [92]

Higher Plants: As on earth, higher plants will play the main role as food providers in any bioregenerative life support system on a lunar base station. Higher plants are able to provide humans with a diet containing all essential nutrients, and at the same time regenerate the atmosphere by the transformation of carbon dioxide to oxygen. [41] However for this kind of diet a combination of numerous plants, requiring different biospheres and fertilizers, is essential, especially for the production of several minerals and vitamins, such as chlorine or vitamin B12. The growth rate of higher plants is usually slower than that of more primitive systems, but at the same time they are more stable in reference to illumination phases and nutrition supply.

Livestock: For setting up a larger and more diverse BLSS livestock

may also be taken into account. Their advantages lay in their high protein and micronutrient contents as well as their psychological effects on humans. On the other hand livestock does consume more food than it actually produces and usually requires a lot of crew time and space. The most efficient livestock in terms of its food to produced edible mass ratio are aquacultures as shrimp or fish and poultry. [44]

Previously Realized BLSS Over the last decades numerous experiments of different dimensions have been carried out, to see whether a more or less closed bioregenerative life support system can be build for future human space stations and identify its major characteristics. Just to mention a view the Russian Bios-Experiments, the Japanese CEEF, Europe's MELISSA and the US Biosphere-2 project, have all had very different attempts but in the end delivered a lot of expertise and knowledge in the field of Bioregenerative Life Support Systems. In the following chapter two of them are especially pointed out, as they provide the most important facts for the design of a BLSS for our lunar base station.



Figure 6.9: The Biosphere-2 Complex [Credits: spacecolonization.wikia.com]

The first one is the series of Biosphere-2 experiments, which were carried out between 1991 and 1994. [68] It is the biggest closed environment experiment, also containing humans. The Biosphere-2 complex has a size of more than 3 acres, containing very different biomes from savannah to an ocean, placed in the deserts of Arizona. Animals and fish were also used as food within the experiments. The longest experiment lasted for two years and provided a enormous experience in the design of closed biological life support systems.

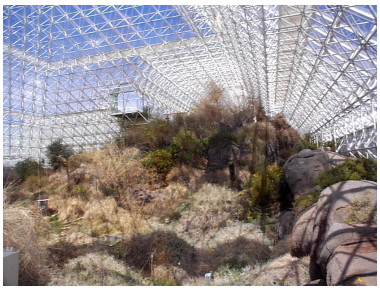


Figure 6.10: The Biosphere-2 Complex [Credits: vulgare.net]

The second project to mention here is the Prototype Lunar Greenhouse, recently developed at the University of Arizona with funding from NASA. This project is dedicated for lunar base stations like MOON BASE 2030. It consists of a round tube, with 5.5 m length and 2.1 m diameter, resulting a volume of 19.04 m^3. Within this tube four different crop species (lettuce, strawberries, tomatoes, and sweet potatoes) are grown. During the experiment time all input and output parameters of the system are monitored. Fertilizer, water and CO_2 are added, to keep the atmosphere and soil regulated. As the crops are not grown on even ground within the tube, the total growth rate estimations can only be reported in terms of volume. The results of the experiments are gathered in [83], the main parameters listed in table 6.14. When looking closer at those values, one can see that there is a daily mass loss of approximately 1.4 kg. No information about this is provided by the authors of the paper. It is assumed at this mass is lost by air leakages of the greenhouse as water vapor, carbon



Figure 6.11: The Prototype Lunar Greenhouse from the outside [Credits: ag.arizona.edu/lunargreenhouse/]

dioxide and oxygen.

Concept of a Lunar BLSS The greenhouses for MOON BASE 2030aim to feed all astronauts present at the base with the calorie diet previously suggested. It is however not expected to provide all necessary nutritions for the live support of the station. Regular dietary supplements addition as well as a conventional atmosphere regulation, which is able to control the gas exchange of the station without the help of the BLSS are present at the lunar base station. As MOON BASE 2030will be the first space station with a fully functional BLSS, it may also be seen as a scientific experiment, which may be replaced by conventional methods at any time. This is an important fact that has to be seen in the design and review of the system, as a life support system without functional redundant secondary units would require other levels of redundancy. One additional aim of the lunar greenhouses, besides the nutrition supply, shall be the provision of some crew recreation facilities within the plant habitat.

The greenhouse design is mainly based on the prototype design of the University of Arizona. It consists of three curved tubes with a length of 11.5 m each. The 2.5 m diameter is slightly bigger than that of the prototype greenhouse, which leads to a total volume of 172 m^3 for each complex. If we leave a length of four meters in each of the three tubes of one complex for leisure time facilities, as for example a sofa, hammock or fountain, a resulting average cultivable volume of 27.6 m^3 per astronaut is left. This is the equivalent volume of 1.5 prototype greenhouses per astronaut. The mass for building one of those greenhouses is estimated to 2 t. If we assume the same biological input and output per volume as achieved in the prototype, the parameters listed in table 6.15 may be assumed:

	Prototype Greenhouse	Lunar Greenhouse per Astronaut	Lunar Greenhouse per Complex
Water input	25.70 kg	38.55 kg	154.20 kg
Fertilizer input	0.07 kg	0.11 kg	0.44 kg
CO_2 input	0.22 kg	0.33 kg	1.32 kg
Condensed water output	21.40 kg	32.10 kg	128.40 kg
Biomass output	2.26 kg	3.39 kg	13.56 kg
O_2 output	0.16 kg	0.24 kg	0.96 kg

The fertilizer required for the lunar greenhouse will mainly be won from biological wastes and inedible biomass. A relative amount of 0.8 is estimated for this. The other 112 daily grams of each greenhouse, mainly containing minerals which can not be regenerated on the



Figure 6.12: The Prototype Lunar Greenhouse with planted settlings [Credits: ag.arizona.edu/lunargreenhouse/]



Figure 6.13: The Prototype Lunar Greenhouse close to harvest [Credits: ag.arizona.edu/lunargreenhouse/]

Type	Daily Amount
Produced biomass	2.26 kg
Condensed water	21.4 kg
Produced O_2	0.16 kg
Consumed fertilizer	0.07 kg
Poured water	25.7 kg
Consumed Energy	100.3 kW h
Consumed CO_2	0.22 kg
Required labor	35.9 min

Table 6.14: Prototype Lunar Greenhouse Parameters

Table 6.15: Lunar Greenhouse Biochemical Input and Output Parameters

moon, will be provided from earth. This sums up to an annual mass of approximately 41 kg per year per greenhouse.

The previously mentioned mass loss of the prototype system has to be taken into account here, too. For the MOON BASE 2030greenhouses it adds up to 2.1 kg per astronaut, or 8.4 kg per complex. As there is no information available about its composition at that stage of the MOON BASE 2030study, no assumption about resource recoveries from it, can be made. It is therefore only counted as lost mass, which has to be disposed.

The prototype greenhouse requires a daily human labor time of 35.9 min. If we assume the same work for the lunar greenhouse a total of 4 h and 45 min would be required. By optimizing working processes this crew time might be limited to an average of 3 h.

The prototype greenhouse has six 1 kW water cooled high pressure sodium lamps, each enlightening approximately one meter of greenhouse. Those lamps offer optimal lighting conditions, but require a lot of energy at the same time. With the emergence of new lighting technologies, as light-emitting diodes, these lamps would be replaced with less energy consuming ones until the start of the mission. Studies in this direction are already ongoing. [101] New lamps could be optimized to the absorption spectrum of the plant. Another method to save light energy would be to cover the surface of the tubes with reflecting foil, which is not done at the prototype, or to spread the light sources over the tube as described in [108]. If we assume an energy consumption of 250 W per meter cultivated tube, a total energy consumption of 6 kW may be assumed for the greenhouses of one complex. The lighting cycles shall be kept at 17 h light followed by 10 h darkness.

The amount of kcal which will be produced by the greenhouses may only be estimated roughly. For a detailed analysis numerous additional experiments would have to be carried out, especially to determine an accurate growth rate of each crop within the lunar greenhouse. [83] list lettuce, strawberries, sweet potatoes and tomatoes as the crops which have been grown in the prototype lunar greenhouse. However a detailed analysis of the proportion of produced biomass of each of the crops is not available. All four crops are present on the NASA list of candidate crops for controlled ecological life support systems [68], but besides the sweet potato with 86 kcal per 100 g, the energy amount of all of them is below 35 kcal per 100 g. They are valuable for the human vitamin supply, but do not offer a great service when it comes to energy production. For this aim other candidate crops have to be selected, as for example soybeans (446 kcal per

100 g), peanuts (567 kcal per 100 g), quinoa (368 kcal per 100 g) or oats (389 kcal per 100 g). While legumes (soybeans or peanuts for example) have to provide the required protein and fat contents, grain is the main carbohydrate supplier.

	kcal per 100 g	carbohydrates [g] per 100 g	proteins [g] per 100 g	fat [g] per 100 g
soybeans	446	30	36	20
peanuts	567	16	26	49
quinoa	368	64	14	6
oats	389	66	17	7
sweet potato	86	20	1.6	0.0
strawberry	33	8	0.7	0.3
tomato	18	3.9	0.9	0.2
lettuce	15	2.9	1.4	0.2

Table 6.16: Macronutrient Contents of Selected Crops [80]

Taking these corps together a simplified exemplary diet could for example look like the one in Table 6.17.

	food mass [g]	kcal	carbo-hydrates [g]	proteins [g]	fat [g]	harvest index	biomass [g]
soybeans	200	892	60	72	40	0.35	570
peanuts	50	283	8	13	24	0.22	230
oats	400	1556	264	68	28	0.5	800
total	650	2631	332	153	92	-	1600

Table 6.17: Exemplary Astronaut Diet Ingredients

For the calculation of the required biomass for this diet, a harvest index of 0.22 is assumed for peanuts and 0.35 for soybeans following [110] and a harvest index of 0.5 is assumed for oat, following [87], leading to a total biomass of 1.6 kg. If we assume the previously mentioned biomass production rate of 3.4 kg per astronaut per day at the lunar greenhouse, this diet could easily be provided. One important effect might however play a negative role in this: The growth rate of nuts and legumes will not be as high as the ones of the prototype lunar greenhouse, which will let the biomass production rate of our greenhouses drop. For the exact production rates of a series of different candidate crops further research has to be carried out. However, this calculation shows that the production of the bigger part of macronutrient can be provided by the lunar greenhouses.

Food Supply at the Lunar Base In the following section, an approach to the mass calculation of the food required for the space station in each building phase shall be made. Due to the availability of water on the moon, the food provided from earth may be dehydrated. This is a main difference to the current food supply of the international space station, where water has to be provided from earth together with the food. A comparable system, for which dehydrated food was used as well, is the Gemini program. Here 0.58 kilograms of food were available for every astronaut for one day. This food included dehydrated juices, as well as freeze-dried and dehydrated foods. [27] The duration of the Gemini missions was, in contrast to the retention time of astronauts at the lunar base station, limited to a few days. This simplified the metabolic balance of those menus a lot. For the lunar base station the menus have to be elaborated a lot more intense to provide all micronutrient required. Some unprocessed fruits and vegetables might for example be shipped to the moon, to provide vitamins and minerals. Taking this into account, an amount of 700 g (mainly dry mass, but also frozen fruits and vegetables) will be supposed for a complete earthy food supply at the lunar base station.

From the time when the first astronauts arrive, until the time when the first crops may be harvested on the moon, the food has to be supplied from earth in total. A time period of 6 month is assumed for this. For the time when one complex is working, until the second one is build up, a rate of 0.6 is assumed for imported food and 0.4 for harvested moon crops. From the time when the crew is extended to 8 astronauts, the relative amount of harvested food is assumed to increase to 0.6, due to the experience gained from the first complex, and the increasing crop diversity with the increasing number of greenhouses. An overview of the metabolic mass flow of one astronaut and its proportion of the greenhouses during the Operational Phase is drafted in Figure 6.14.

For safety reasons, as the greenhouses might for example get contaminated with some kind of parasite or illness, a safety buffer of half a years food supply has to be stored in each complex in addition to the other food. The calculated food shipping masses are gathered in Table 6.18.

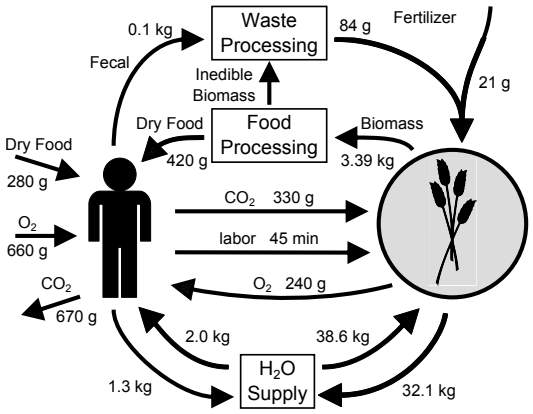


Figure 6.14: The metabolic mass exchange between an astronaut and a greenhouse

For the storage of food one International Standard Payload Rack is assigned to each astronaut. This rack holds the food provided from earth, as well as the food harvested on the moon. For the monitoring of the control parameters of the greenhouses, one additional rack is assigned to each complex, adding up to five racks per complex for the BLSS and Food Supply.

time or event to supply food	Food provided from earth [kg]
Initial storage filling of Complex 1	500
First six month of supplied base phase	500
Rest of supplied base phase	300 per 6 month
Initial storage filling of Complex 2	500
Extension phase	400 per 6 month
Initial storage filling of Complex 3	500
Operational phase	600 per 6 month

Table 6.18: Exemplary Astronaut Diet Ingredients

Summary and Outlook In the past, all manned space mission have completely been provided with food from earth. In the scope of building MOON BASE 2030, the approach of installing the first regenerative life support system, able to produce some of the food required by the astronauts, has been taken. As this is the first experiment of its kind, the safety of the base cannot only rely on the success of the greenhouses. For this reason, and due to the availability of regular transport capacities from earth, the system is not designed as a totally closed BLSS. This would have cost a multiple of space, energy and building resources, as the variety of different sorts of biological systems would have to be drastically expanded. Additional food supplies from earth are therefore counted into the provision plan. The design of the BLSS however shows, that the provision of some major food ingredients can be provided by a space born life support system. Some psychological requirements of human crew members have also been covered by including space for crew recreation space within the plant habitat.

As a next step, the design of a waste management facility has to be tackled. This system has to supply fertilizer from the inedible biomass and wastes. It is not covered within this study. For a longterm lunar base station the import of animals might also be discussed. If the bioregenerative life support system proves to work well after some



years, insects for the plant pollination, or aquacultures for food supply might be added. Small birds or rodents might also be brought for psychological reasons. If some more space is available, the variety of plants can also be increased. Fruits and vegetables may be grown and the cropped portion of the food supply increased. A multiplicity of options is available to expand the BLSS, some already research within the life support community, some only sketched as ideas. The experiences gathered within the BLSS of the lunar base station might in any way drastically increase the durability and efficiency of a totally closed system for longterm spaceflights to other planets and further away.

7
Environmental Hazards

by Dennis van der Wals

This chapter collects all information about the mission environment, the Moon, and its hazards. Both have a massive influence on the mission planning and all effects, summarized at the end of each part, where taken into account for our moonbase. In which way the mission plan is adapted to the effects is collected in the conclusion, Section 7.7.

7.1 The Moon

To plan a Mission to the Moon, some facts about the Earth's natural satellite are collect in Table 7.1.

Lunar Regolith *Regolith* is a general term for fragmental and unconsolidated rock.[56] It is used to describe the high varied character of the lunar ground. The past lunar missions gave us some information of the typical lunar ground, shown in figure 7.1.

The missing atmosphere, unprotected bombardment of space debris and radiation makes so lunar regolith a very light material with a typical density of $1.5 \times 10^2 \frac{\text{kg}}{\text{m}^3}$.

The thickness of the regolith layer has a range from 1 to rarely exceeding 20 m. Less thickness on the maria than on the other parts on the moon. These lose rocks are so the expected ground to be found and the place for the moonbase.

Lunar Soil is a synonymous for *Lunar Regolith*, but technically used to describe the finer-grained fractions of the unconsolidated rocks, with a size smaller than 1 cm. The mean grain size of *soil* is 4×10^{-5} m to 80×10^{-5} m, the average 6×10^{-5} µm to 8×10^{-5} µm.[56]

So the typical ground seems to be solid enough to place a base and dedicated solar panels on it without fearing they are sliding away

Mass	$0.073\,42 \times 10^{24}\,\mathrm{kg}$
Volume	$2.1958 \times 10^{19}\,\mathrm{m}^3$
Equatorial radius	$1738 \times 10^{3}\,\mathrm{m}$
Polar radius	$1736 \times 10^{3}\,\mathrm{m}$
Volumetric mean radius	$1737 \times 10^{3}\,\mathrm{m}$
Ellipticity	0.0012
Mean density	$3344\,\frac{\mathrm{kg}}{\mathrm{m}^3}$
Surface gravity	$1.62\,\frac{\mathrm{m}}{\mathrm{s}^2}$
Escape velocity	$2.38 \times 10^{3}\,\frac{\mathrm{m}}{\mathrm{s}}$
Specific gravitational constant (GM)	$0.0049 \times 10^{15}\,\frac{\mathrm{m}^3}{\mathrm{s}^2}$
Bond albedo	0.11
Solar irradiance	$1367.6\,\frac{\mathrm{W}}{\mathrm{m}^2}$
J_2	202.7×10^{-6}
Inclination	$6°41'$
Mean surface temperature	107 °C day; −153 °C night
Temperature extremes	−233 °C to 123 °C
Atmosphere	$\approx 10^{10}\,\frac{\text{molecules}}{\mathrm{m}^3}$ day; $2 \times 10^{11}\,\frac{\text{molecules}}{\mathrm{m}^3}$ night
Heat flow average	$\approx 29 \times 10^{-3}\,\frac{\mathrm{W}}{\mathrm{m}^2}$
Seismic energy	$2 \times 10^{10}\,\frac{\mathrm{J}}{\mathrm{a}}$ to $10^{14}\,\frac{\mathrm{J}}{\mathrm{a}}$

Table 7.1: Factsheet of the Moon. SOURCE:[39]

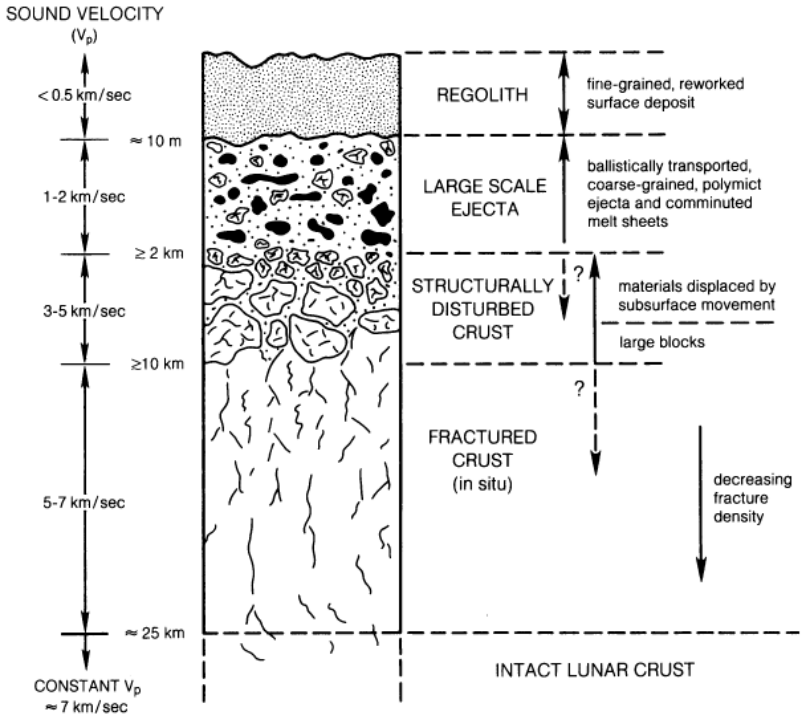


Figure 7.1: Lunar Regolith. SOURCE: [56]

or falling down. Further important things regarding the ground are mentioned in the following points.

Generally we know something about it from the past missions to the Moon, the typical composition of the Lunar ground is discussed in another chapter.

Effects on Mission To build a base on the Moon, the typical lunar ground must be understood, so one can decide if it can hold the base and the astronauts. Further discussion about the problems of floating *soil* is made in Section 7.5.

Atmosphere Because of its low gravity, the moon has an extremely tenuous atmosphere, which is often assumed as not existing. The gas concentration is about $2 \times 10^{11} \frac{\text{molecules}}{\text{m}^3}$ at night and $10^{10} \frac{\text{molecules}}{\text{m}^3}$ at day [56] with a total mass of 3×10^4 kg [31]. Most Elements of moons atmosphere are derived from the solar wind, but also ionization from solar wind and the interplanetary electric field are the main cause for remove of the gases. If the lunar atmosphere reaches more than 100 times its actual mass, thermal escape could become the main cause of removing gases, which means the moon could get an long-live atmosphere.

Element	Abundance at day $\frac{\text{molecules}}{\text{m}^3}$	Abundance at night $\frac{\text{molecules}}{\text{m}^3}$
Ne	$\approx 4 \times 10^9$ to 10^{10}	10^{10}
He	$\approx 8 \times 10^8$ to 4.7×10^{10}	4 to 7×10^{10}
H_2	≈ 2.5 to 9.9×10^9	10×10^{10} to 1.5×10^{11}
Ar	$\approx 2 \times 10^9$	$< 10^8$
CH_4	$\approx 1.2 \times 10^9$	
CO_2	$\approx 10^9$	
NH_3	$\approx 4 \times 10^8$	
OH+H_2O	$\approx 0.5 \times 10^6$	

Table 7.2: Atmosphere of the Moon. SOURCE:[56]

Effects on Mission Astronauts must be pressurized and delivered with oxygen by Space suits, Rovers or an artificial atmosphere in the base. Without atmosphere the Moon misses a natural shield against debris and radiation from space like the Earth has, but it makes the Moon a perfect place for sensitive operations and mechanics, because it is very clean. The waste gas clouds of astronauts can highly contaminate the lunar gases and even enhance the mass of the moons atmosphere by more than 100 times of its actual



mass. Those contamination can accelerate the corrosion of metals from cables and rovers. This should be taken into account during mission planning.

7.2 *Radiation*

Radiation in Space is a primary threat to astronauts. Micrometeoroids, Thermal and Atmospheric threats can be handled easy by every spacesuit, but protecting against the radiation in space is difficult [30]. On the earth's surface, the space radiation is filtered and blocked by the earth's atmosphere and magnetic shield. Those natural shielding is also the cause of the lack of knowledge about the radiation in space, especially on the moon.

Radiation describes the movement of particles and waves. It is typically measured in MeV. Further units occurring with radiation are:

Gray $\frac{\mathrm{J}}{\mathrm{kg}}$; used to describe the amount of absorbed energy by biological material when exposed to radiation.

Sievert $\frac{\mathrm{J}}{\mathrm{kg}}$; Based on Gray with an indicator for the hazardousness of a radiation type, the quality factor. Particel radiation with greater mass ($> 1\,\mathrm{u}$) create more damage with the same energy than others.

For handling the radiation and its effects on the moon, all these units need to be used.

There is a difference between ionizing and non-ionizing radiation. Ionizing radiation contains particles and high energetic rays from gamma to high ultra violet radiation, non-ionizing radiation describes rays with an energy lower than ultra violet radiation and is much less hazardous.

Ionization means liberating an electron from an atom or molecule. Ionized atoms and molecules are very reactive and attack near chemical bonds. This can damage cells and DNA of the astronauts. Hitting electric circuits can create errors when changing the charge state of a memory module or destroying sensitive electrical components.

Particle Radiation Ionizing radiation contains particles with a high velocity and so high energy.

Alpha particle Helium nucleus, can be shielded by a sheet of paper, high damage when incorporated.

Beta particle Electron or positron; electrons can be shielded by a thin material, but deceleration will emit x-rays; positron annihilate with electrons and emit gamma rays.

Neutrons No charge, therefore no typical ionization and not easy to be shielded. Hitting an atom can destabilize its nucleus and make it radioactive.

Nuclei Also heavy nuclei with $Z > 2$ are emitted into space with similar but more dangerous reactions than *alpha particle*.

Z = atomic number

Charged particles could be shielded with an electromagnetic field, similar to the earth's protection by its magnetic field. Neutrons need shielding material.

Electromagnetic Radiation Electromagnetic radiation can not be stopped by shielding material, but dampened.

Gamma ray Absorption can emit protons, electrons, neutrons or x-ray. Combination of heavy and light material should be used to protect astronauts against high and low energetic gamma radiation, to deal with secondary radiation effects.

X-Ray Similar to gamma ray, but less energetic.

UV radiation No major radiation problem.

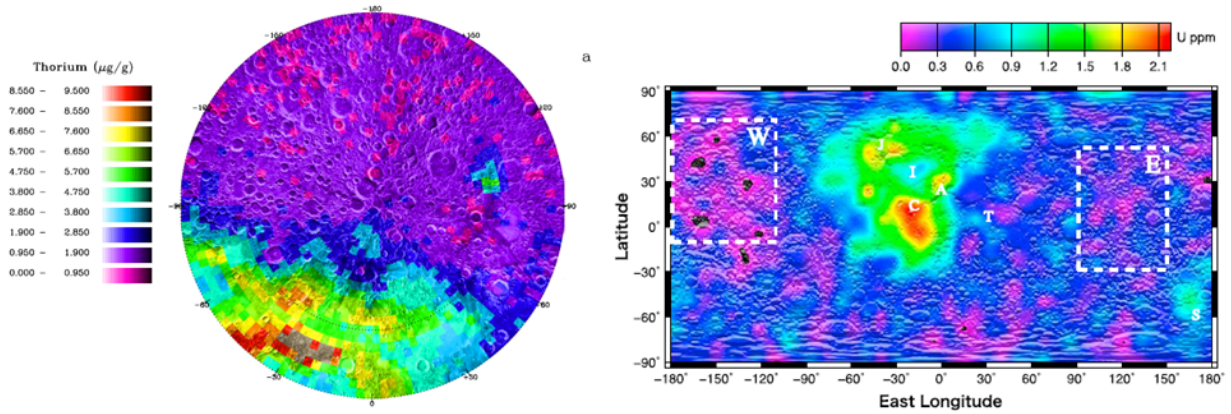
Sources of ionizing Radiation on the Moon On the moon we can find 4 major sources of radiation [103]:

Galactic Cosmic Rays *GCR* is a source of radiation containing 85 % Protons, 14 % Alpha-Particles and 1 % Heavy Nuclei with a varying intensity over the eleven year cycle of suns activity. It is a medium dangerous source of radiation with hazardous effects on biological material.

Coronal Mass Eruption *CME* is an event whose frequency is dependent on the sun cycles. The sun ejects a great flux of high energetic particles with a great medical danger. Hitting material of any kind can destabilize their nuclei by spallation and make them radioactive. When the *CME* occurs, it can be detected 30 to 40 minutes before it reaches the lunar surface.

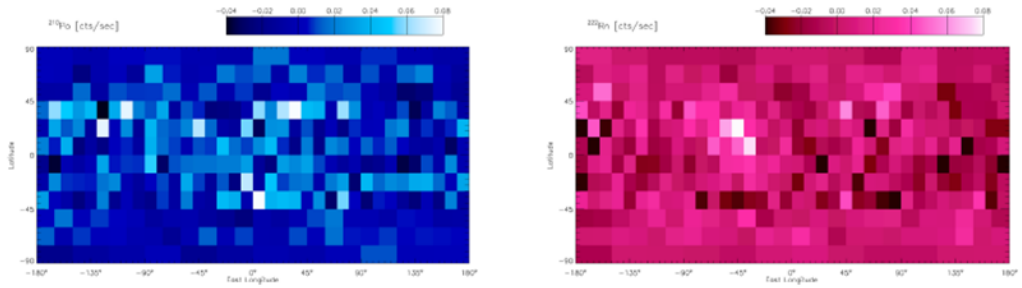
Solar Cosmic Rays Solar Cosmic Rays *SCR* is a constant radiation emitted by the sun with a low flux of high energetic particles and destructive effects on cells and DNA.

Radioactive Lunar soil Similar to earth, radioactive material is found on the moon, like Thorium [64], Uranium [40], [115] and Radon [65]. Exposed to high energetic ionizing radiation of space, the lunar surface became a source of secondary radiation. Typically not radioactive material is destabilized and emits fast neutrons and gamma ray.



(1) Radioactive Thorium on lunar north pole

(2) Radioactive Uranium on lunar surface



(3) Radioactive Polonium on lunar surface

(4) Radioactive Radon on lunar surface

Figure 7.2: Different radioactive materials on lunar surface. SOURCE: [65], [64], [115]

Radiation effects on Humans The human body is able to repair a lot of damages itself. Critical for surviving is the amount of damage that occurs faster, than it can be repaired. So the total dose absorbed over a year is not very informative. 500 mSv per year can be survived, but not if it is a combination of 100 mSv over the whole year and 400 mSv for a few seconds.
A critical dose for humans is 3 to 4.5 Gy during a few minutes. This will lead with a chance of 50 % to death beneath 30 days.
[32] [35]

Typical effects of ionizing radiation to the human body are:

- Interferes with cell division,
- Reduction in red blood cells,
- Repress immune system;
- Redding of skin,
- Cataracts, lost of hair, bleeding;
- Genetic mutation,
- Cancer, death.

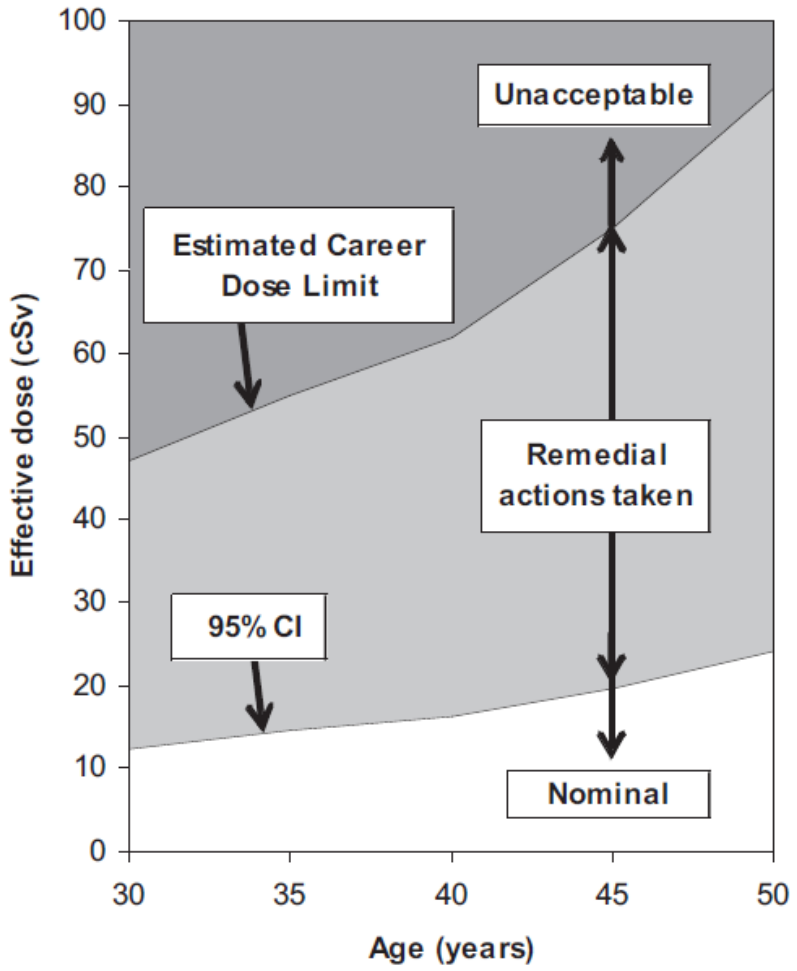


Figure 7.3: Radiation limits for 45 year old woman. SOURCE: [30]

The determination of the acceptable radiation depends on gender and age of a human as exemplary displayed in Figure 7.3.

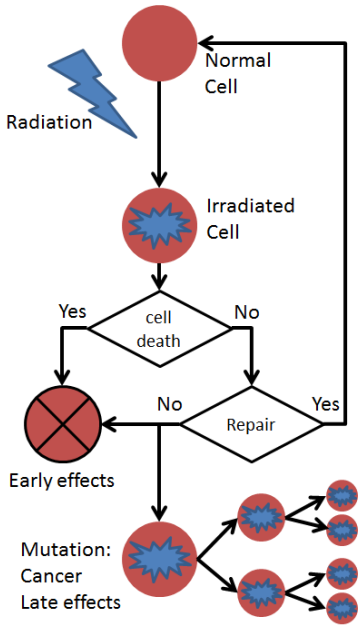


Figure 7.4: Effects of radiation to living cells. SOURCE: [30]

Protection against ionizing radiation There are a lot of options to protect astronauts on the lunar surface against the radiation. But most of them are problematic because of transportation and building issues. The target for radiation protection is to reach a level similar to the earth surface to enable a colonization at the end. In the beginning less protection can be used.
Practical ideas are:

Metal Walls.

Building underground or using lunar soil for radiation protection.

Using water as shield between metal walls.

Using active EM-Shields to stop charged particle bombardment.

Every protection is a protection by mass, where the radiation particles shall collide and stopped by impacting in a nucleus of the shielding matter. High-mass nuclei radiation is very complicated to stop because of its spallation effect (see Figure 7.5).

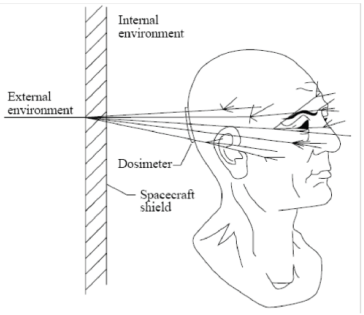


Figure 7.5: Shielding problems and spallation. SOURCE: [30]

Effects on Mission Radiation can damage biological material and electronic devices because of its high energy. Protection is necessary for astronauts and electrics. Mission planning has to take into account the individual ammount of absorbed radiation for every astronaut. The total time an astronaut can stay in the base is limited by this factor.

7.3 *Moonquakes*

The lunar ground is not a quite place, it is still active for not completely researched reasons. The lunar seismic activity is therefore part of the research work of our Moonbase. What is actually known about the seismic activity was collected by the Apollo missions and contains a total measurement time of 7.92 years. From this experiments, four different types of moonquakes could be identified[103]:

Source	Total	Major Events
Artificial impacts	9	5
Meteoroid impacts:	1700	95
Shallow moonquakes:	32	7
Deep moonquakes		
confirmed	973	9
unconfirmed	1800	7
Unclassified events	7300	0
Total	11 800	118

Table 7.3: Number of Seismic Events detected. SOURCE: [56]

Deep moonquakes were counted more than 7000 times during the measurements. 318 nests could be identified as source of these kinds of moonquakes in a depth of 7×10^5 m to 12×10^5 m. They are strongly associated with tides.

Thermal moonquakes are events at isolated locations in regular monthly intervals caused by heating and cooling of the lunar surface. Highest activity is recognizable two days after sunrise.

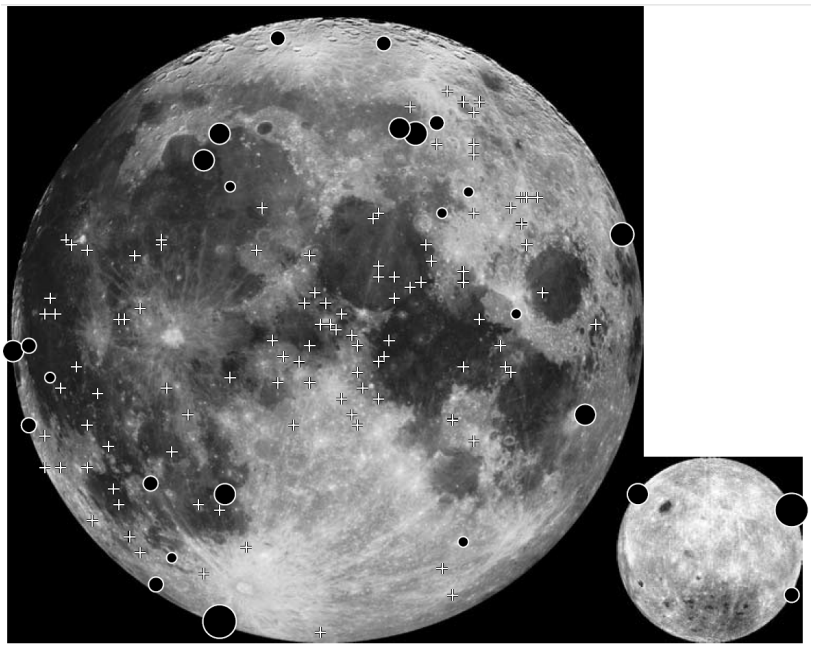


Figure 7.6: Distribution of shallow moonquakes. SOURCE: [31]

Shallow moonquakes are the heaviest sort of moonquakes, sourced in a depth of 5×10^4 m to 20×10^4 m. Their main cause could not be discovered until today and they need further research. (see Figure 7.6)

Meteoroid impacts also cause moonquakes and are handled in an extra point in this Section.

The strongest recognized moonquake had a Earth-equivalent magnitudes of 4. [56]

Magnitude	Effect	Est. Events (on Earth)
≤ 2.5	Not felt	900 000
2.5 to 5.4	Felt, minor damage	30.000
5.5 to 6	Slight damage to buildings	500

Table 7.4: Magnitudes

Effects on Mission Two types of dangerous moonquakes can be seen: Shallow moonquakes and meteoroid impact caused moonquakes. Both could have the power to damage the Moonbase but can not be predicted yet. From the known activity, the risk of losing the Mission because a hull damage by a moonquake is very low.

Landslides Another danger of moonquakes (and meteoroid impacts) are landslides on the Moon. The loose ground especially at the edge of a crater can be and travel many kilometers.

During the Apollo 17 mission one of these landslides could be observed triggered by debris.

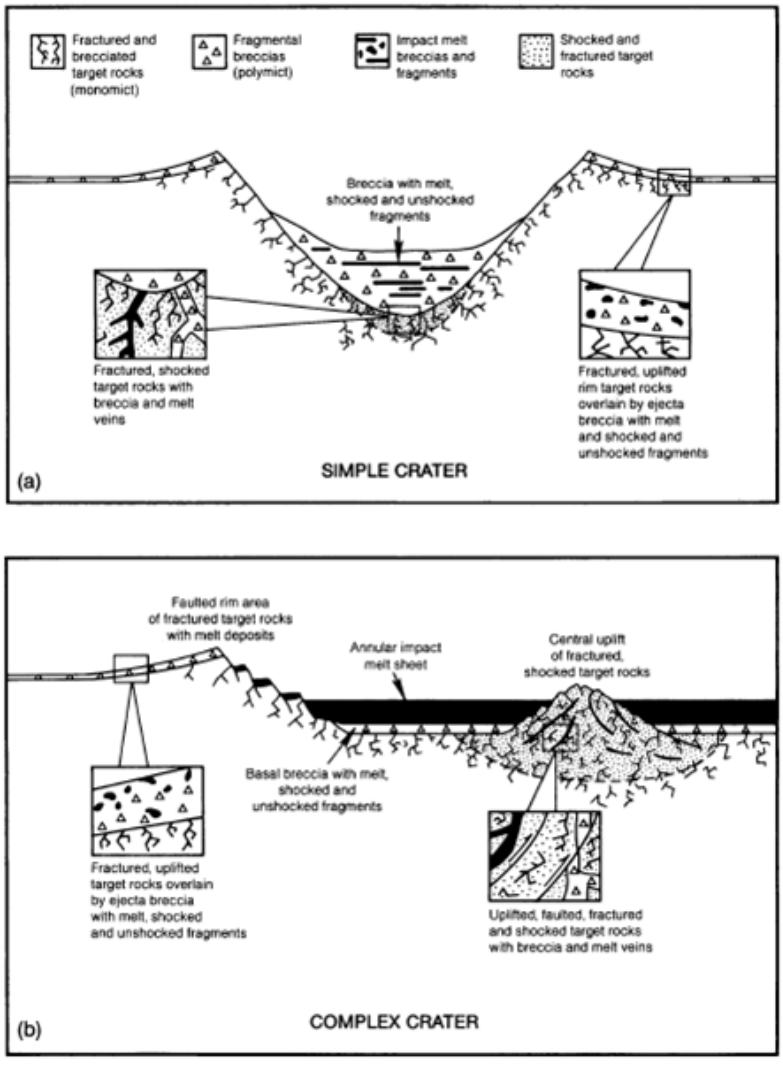


Figure 7.7: Lunar ground at crater edges. SOURCE: [56]

Effects on Mission A landslide can create problems like spilling the base, rover or astronauts and even destroying the solar panels that are build on crater edges.

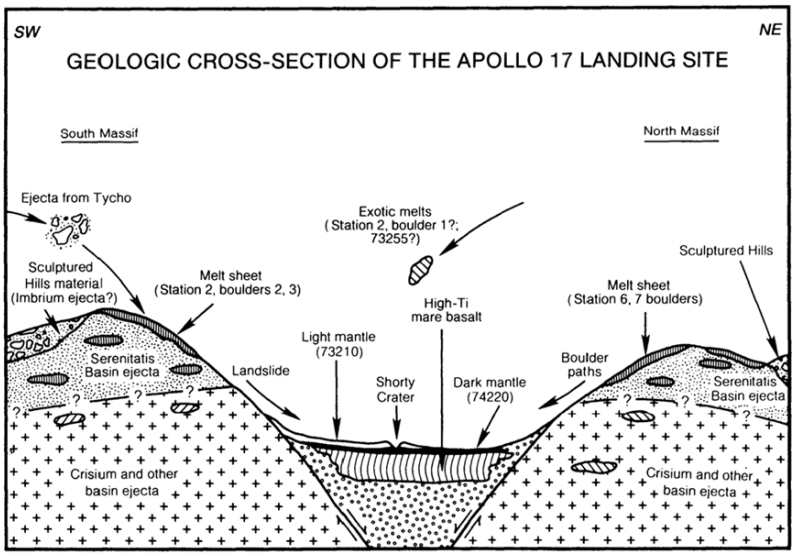


Figure 7.8: Landslide during Apollo 17 mission. SOURCE: [56]

7.4 *Meteoroids*

The term meteoroid describes a solid body naturally occurring ind and traveling through space, that is too small to be called an asteroid or comet, but a mass more than 10^{-5} kg. Smaller meteoroids are called Micrometeoroids.[56] From actual research, the rate of meteoroid impacting into a field of the size of a moonbase and equipment could be expected as once a year for a mass of about one to ten milligram. Heavier meteoroids occur less frequent, smaller more frequent. The total bombardment of the lunar surface is less than the Earth's atmosphere, which might be because of the lower mass of the moon. But most of these meteoroids can not reach the Earth's surface. The typical velocity for meteoroid hitting the moon could range from $13 \times 10^3 \frac{\mathrm{m}}{\mathrm{s}}$ to $18 \times 10^3 \frac{\mathrm{m}}{\mathrm{s}}$. Differences of their flux are correlated to those seen on Earth. Being hit by a mass of 1 g at this velocity would result in a crater of a few centimeters in metal. The probability of such a meteoroid striking an astronaut on the lunar surface is about one chance in 10^6 to 10^8 for a cumulative EVA of one year.

Effects on Mission The rovers and base are not highly damaged by small particles, but they are a danger for astronauts in space suites. If the flux of those Meteoroids rises, the astronauts should enter the base and wait, until it falls again. The most critical structures for such small bodies would be the solar panels, which would have to be replaced at some point, when damage is to high. But penetrated by a few hits would probably not lead to a complete



malfunction of a solar panel. Meteoroids of a high mass and with enough power to damage a rover or even the base are not a high risk, because they are very seldom.

7.5 Lunar Dust

The lunar dust is lunar soil at the surface. It has a high adhesion. Eugene Cernan, commander of Apollo 17, said: "... one of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it's restrictive friction-like action to everything it gets in" [100] It has a typical size of 20×10^{-6} m to 100×10^{-6} m and a low electric conductivity, so it get charged on day-side by temperature rise, infrared and ultra-violet radiation. This creates large electric fields from day to night side and dust transport. The effects of charged dust a very complicated because of their interaction with electric and magnetic fields in the next Section.

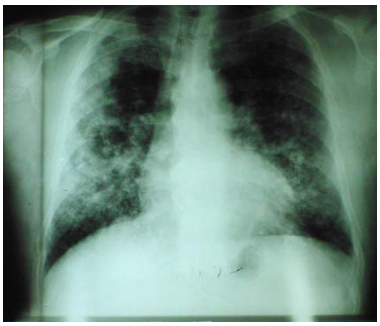


Figure 7.9: Chest X-ray showing bilateral pulmonary fibrosis characteristic of silicosis. Photo credit Robert Wood Johnson Medical School. [60]

Effects on Mission Lunar dust is hard to filter and destructive to electrics and mechanics. The biological effects on humans are potential skin effects, difficult breathing, inhalation toxicity and ocular effects.[60] Dust floating and transportation at the terminator [1] could significantly reduce the visibility.[100] Adherence of dust can damage structure surfaces and reduce the efficiency of solar panels.

[1] A *terminator* is a moving line separating the illuminated day side and the dark night side of a planet.

7.6 Electric and Magnetic Fields

The Moon has no own Magnetic field. Therefore the surface has no protection against the space and solar radiation. As mentioned before, solar rays hitting the lunar surface can charge the dust particles and so create small electric and magnetic fields. As much is known about the electric fields, the less is known about the magnetic fields. Measurements show just a low magnetic activity. The strongest event was about 400×10^{-9} T, which is half the Earth's magnetic field flux.

The electric fields need some more attention. They can reach values up to several hundred volts per meter and produce a lot of dust movement on the Moon. Especially at the terminator the electric fields reach high values and generate a high flow of lunar dust, reaching into a height up to 10^5 m, and the terminator is always near our base at the pole.

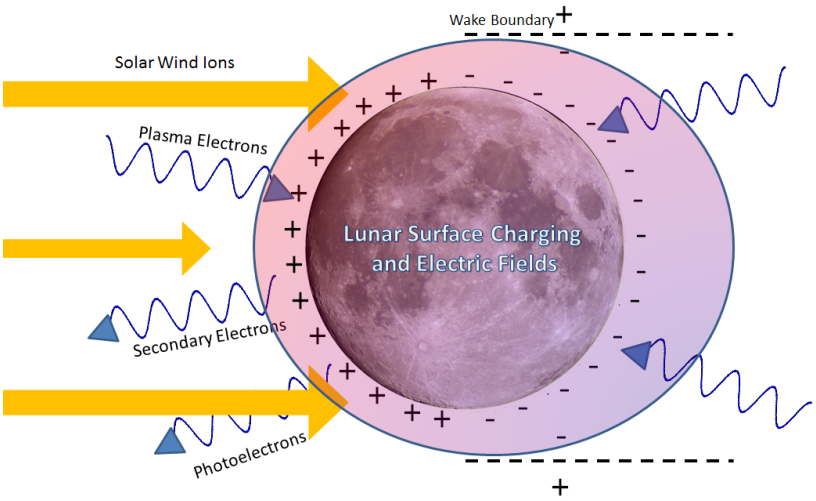


Figure 7.10: Lunar surface charging and electric fields. SOURCE: NASA

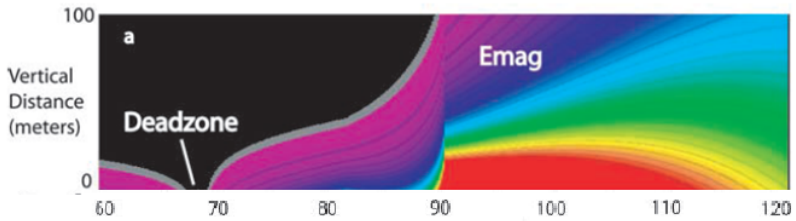


Figure 7.11: Electric field strengths at the lunar pole. The color red indicates $|E| > 1.5 \frac{\text{V}}{\text{m}}$ and black indicates $|E| = 0 \frac{\text{V}}{\text{m}}$. X-axes shows angle from subsunpoint. SOURCE: [49]

Effects on Mission The small magnetic fields do not have any hazardous influences on our mission. The electric fields run dust transport, especially at the terminator, which has to be taken into account for mission planning.

7.6.1 Transient Lunar Phenomena

The transient lunar phenomena (*TLP* or *LTP*) are mainly optical effects affecting an area of about 10^5 m radius of the lunar surface, reported by observers watching the moon with telescopes. Their cause and even their reality is still discussed. Most of the 1500 views of *TLP*s are made by amateurs under extreme conditions, only 103 of those reports are rated as robust. [31] Most researches suggest the main cause as lunar outgasing from rest vulcanic activity. That is also supported by the fact, that most *TLP*s where obeserved at isolated spots.

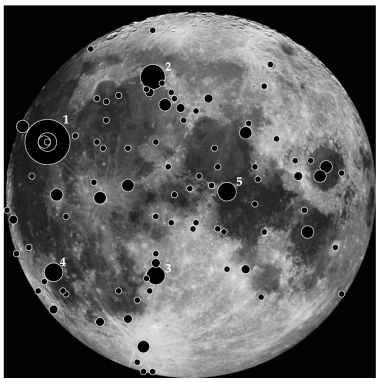


Figure 7.12: Distrubution of *TLP*. Source [31]

Effects on Mission Depending on the existence and cause of *TLP*s, the mission could be affected. If lunar outgasing is the main cause, the base and astronauts could be affected, damaged or even thrown into space. Further research could be supported by the lunar seismic network (see Section 2.3).

7.7 Conclusion

What we know about the harsh environment of the moon gives us some things to be aware of. Those reasons, like radiation protection, choice of build place for the moonbase or mission planning are summarized here.

Lunar Seismic Network To get to know more about the ground of the place for the planed moonbase, to ensure the ground is solid enough (see Section 7.1) and not in danger of moonquakes (see Section 7.3), Landslides (see Section 7.3) and lunar outgasing (see Section 7.6.1), a lunar seismographic network (sse Section 2.3) should be created on the moon 5 to 7 years before the first buildings reach the moon. Interpreting data from this network should deliver enough information about the risk for the moonbase placed at the north pole.

Radiation Protection As mentioned in Section 7.2, the lunar regolith seems to be the best choice as shielding material against the space radiation for the lunar base. Compared to the discussion of regolith shielding in [56] and in [30], we need a regolith roof with a density



of $0.5 \times 10^3 \frac{\text{kg}}{\text{m}^2}$ to $7 \times 10^3 \frac{\text{kg}}{\text{m}^2}$. These values are very different, as a compromise, we recommend a density of $4 \times 10^3 \frac{\text{kg}}{\text{m}^2}$. The thickness of these layer depends on the density of the used regolith and so on the building process, that is not discussed here. Such roof can also protect against most common meteoroids (see Section 7.4) and contain an artificial atmosphere (see Section 7.1)

Developed from data of past missions to the moon and researches of space organizations, the predicted radiation limits for astronauts on our mission are collected in Table 7.5 and the radiation of the different environments in Table 7.6. A special radiation officer at the moonbase should be chosen, which is responsible for the health in respect to the absorbed radiation dose of the astronauts. He takes care of their dosimeters and decides with the mission control about the crew members of each EVA.

Max dose per year	500 mSv
Acceptable dose for mission	100 mSv
Max dose during career	700 mSv
Max dose during 30 days	250 mSv

Table 7.5: Chosen radiation dose limits for astronauts on our mission based on [30]

When a maximum limit from Table 7.5 is reached in the associated time limit, the affected astronaut must abort his mission immediately, go back to earth and get medical assurance. With proper planning , this case is very unlikely. The acceptable limit should not be reached by the given mission plan, but it can be exceeded if necessary. This has to be determined by the chosen radiation officer and the mission planning mentioned in Figure 7.13.

Moon surface:	$100 \frac{\text{mSv}}{\text{a}}$
Moonbase	$2.5 \frac{\text{mSv}}{\text{a}}$
	$\leq 20 \frac{\text{mSv}}{\text{d}}$ during *CME*s
Rover	$0.2 \frac{\text{mSv}}{\text{d}}$
Space suite	$1.4 \frac{\text{mSv}}{\text{d}}$

Table 7.6: Predicted radiation for different environments based on [30]

During the *CME-Events*, that can last for days, the astronauts in the rover - on the way to or from the solar panels - are protected good enough to reach the base without further health problems, but their higher absorbed dose must be taken into account for upcoming missions.

Buildplace A good research of the building place and avoiding a place next to a crater can help as prevention against the fatal consequences of a landslide (see Section 7.3). A pleasant distance to a crater seems to be two times of the height of its edges. The ground should be stable (see Section 7.1) and free of source for eventual *TLP*s (see Section 7.6.1).

Dust protection To be aware of adhesive lunar dust (see Section 7.5), the rovers should be parked in a garage, with lose doors or gates to be protected against the dust. Each rover can carry two suitports with two space suits. Those suiteports are an alternative to airlocks, where the space suite stays outside the base. This solution prevents the base from contamination with lunar dust. For each rover, two additional suitports should be integrated into the base, so the usage

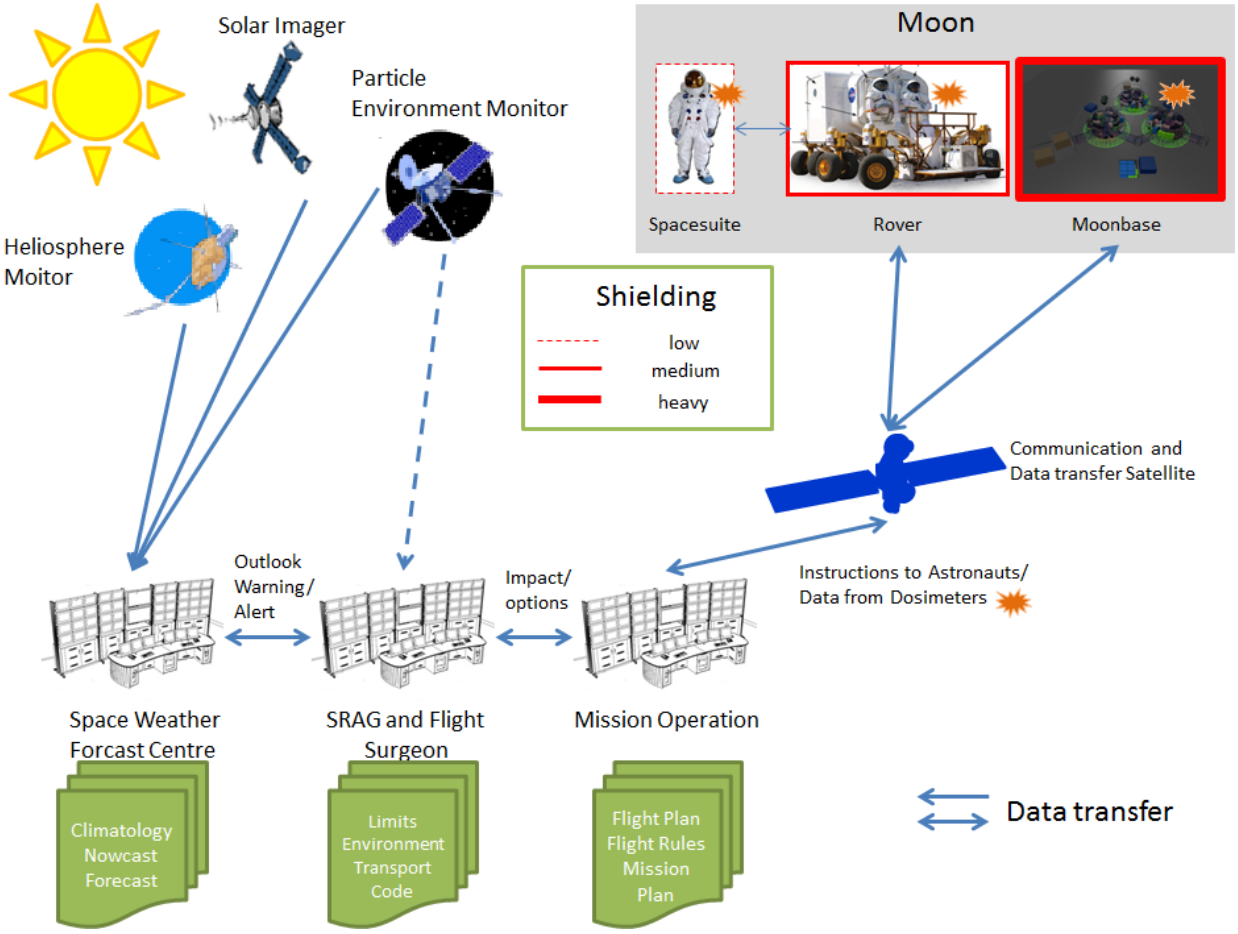


Figure 7.13: Radiation Control Management. SOURCE: [30]



of an airlock is reduced a lot. Using the airlock is a good chance for lunar dust to contaminate the base. Such operation should be reduced to a minimum. Filters in the base should be able to clean the rest of the dust, so a small contamination does not have unhealthy effects.

The rovers and solar panels need to be cleaned regularly from dust. Such objectives need to be taken into account for mission planning.

In case of emergency A little summary of possible emergency cases, the best reaction and some requirements derived from those are summarized in Table 7.7.

Type	harm	harm rate	risk	procedure	requirement
Coronal mass eruption (*CME*)	high dose of radiation	high	medium	escape to base/basement	Moonbase with radiation shielding
Moonquake	damage to shell, landslides	high	low	escape to base	Moonbase with adequate structure/ground
Landslides	covering of rovers, astronauts, moonbase, slackening of fundament	high	low	escape to base	Moonbase with adequate structure/ground
Meteoroid impact ($< 0.1\,kg$)	damage to astronauts, solar panels, light shielding	medium	high	escape to base/rover	Moonbase/Rover with adequate shielding
Meteoroid impact ($\geq 0.1\,kg$)	damage to all structures, landslides, moonquakes	high	low	shutdown/evacuation of defect base parts or whole base	Moonbase with adequate shielding and inner airlocks, evacuation scenario
dust coating	reduction of solar panel efficiency, damage to surfaces and mechanics	low	medium	cleaning of surfaces	cleaning equipment
dust contamination	illnes, damage to surfaces, mechanics and electrics	high	medium	less usage of airlocks, air filtering	filters, suitlocks
power blackout	malfunction of all systems	high	medium	repair power supply, evacuation of base	backup battery, evacuation scenario
communication blackout	no information about situation on base	low	medium	repair of communication systems, sending rescue team, evacuation of base	rescue team, evacuation scenario
disease/infection	contagion of astronauts/experiments	low	low	isolation of crew member, mission abortion, first aid	medical in crew, medicine in base
shell damage	loss of atmosphere	high	medium	evacuation and locking down of affected parts	inner airlocks
radiation shield damage	high dose of radiation	high	low	escape to functional shielding, evacuation of base	evacuation scenario
lack of resources	depending on resource	high	unpredicted	evacuation of base	evacuation scenario
fire	damage to astronauts and equipment	high	low	lockdown and evacuation of affected base parts	inner airlocks, extinguisher
leaking of dangerous gases/material		high	low	lockdown and cleaning of affected base parts	inner airlocks, cleaning material

Table 7.7: Emergency cases



8
Logistics

by Helge Mohn

How do we reach the moon? How do we travel in space and transport cargo beyond an earth orbit? How much propellant is necessary and what phases of transport exist? Are vehicles available up to day or within the next years that can perform such a journey with such a mass requirement?

The logistics for a moon base concept deals with more than only the organization of transportation of mass and persons. The transport itself is of interest, too. This chapter shall inform about physical boundaries, answer the question of feasibility with nowadays technology and finally draft a flight schedule and analyze it. The demanded flight schedule shall cover the outbound transport of mass and crew to the moon and the return transport back to the earth. A fleet of vehicles shall form a supply chain that enables life on the moon.

8.1 Phases of transport

To calculate the position and velocity of an earth satellite the calculation can be done with help of the two-body problem. On the way to the moon this is not possible, because the mass of the moon cannot be neglected. The system can be described as a three-body problem. The position and velocity of a transport vehicle can only be derived by numerical methods. To calculate approximate values following simplification can be used. Each body in the three-body system has its own gravisphere. Within a gravisphere of a body the sum of gravitational forces points towards this body. The gravisphere of the probe is neglectable, but the gravitational force of the moon is a sixth part of the one of the earth. Therefore the journey to the moon can be split up in a part within the gravitational force of the earth and a part within the gravitational force of the moon. During the first phase a correcting factor for the perturbation effects of the

gravitational force of the moon has to be applied and in the second part vice versa. This way the three-body problem leads to a two body-problem and enables a calculation of approximate values. [86] For the further development of the concept the delta-v from Table 8.1 are used. Figure 8.1 shows the gravisphere of the earth and the moon. It is derived from the SMART 1 project [112], which was an ESA lunar probe with an experimental ion engine. Due to the low thrust, the probe was affected a long time by the perturbation of both gravitational forces. The sphere has a radius of about 60,000 km in case of the moon and about 400,000 km in case of the earth. The lagrange libration points are positioned where the sum of gravitational force equals zero. It is an option to reach these points on the journey to the moon. For the derived concept it has been disliked due to the higher delta-v requirement and therefore due to a higher requirement of propellant and the regularly demand and high amount of intended flights.

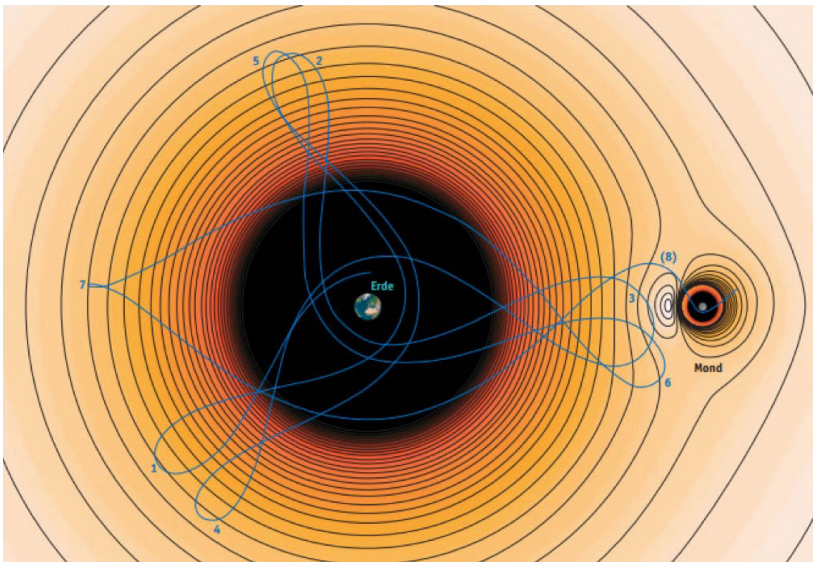


Figure 8.1: Gravisphere [112]

Phase	**Delta-V** km/s
Earth -> LEO	9.3
Trans Lunar Injection (TLI) incl. Corrections (MCC)	3.2
Lower Lunar Orbit (LO) Injection	0.9
LO ->Descent Moon	2.1
Ascent Moon -> LO	1.9
Trans Earth Injection (TEI)	0.9
LEO Entry Injection Aerobrake	0.1
LEO Entry No Aerobrake	3.2
Engine exit velocity	4.5

Table 8.1: Delta-V for each phase

These delta-v values are the basis for the calculation of propellant mass, which is done later in this chapter. Figure 8.2 shows the selected options for the outbound routing to the moon and for the return flight. Starting at the bottom of the figure at the earth with a launch to a LEO. The option for more than one launch is included to execute a rendezvous maneuver before starting the Trans Lunar Injection (TLI). For this phase an extra stage with extra propellant is possibel and used for the manned space ship. About 72 h flight time and 380,000 km later the Lunar Orbit (LO) injection balances the kinetic energy within the new gravisphere of the moon.

Due to mass concentrations so called Mascons the lunar orbit selection needs some attention. Lunar Mascons are the reason for perturbations of lower lunar orbits below 100 km, even though no atmosphere is present. Although the intended orbit is higher than 100 km the study [112] shall be respected. So called frozen orbits have an inclination with less disturbance. These inclinations are 27, 50, 76, and 86 degree. A lunar orbit with an inclination of 86 is close to the lunar poles and therefore the best choice.

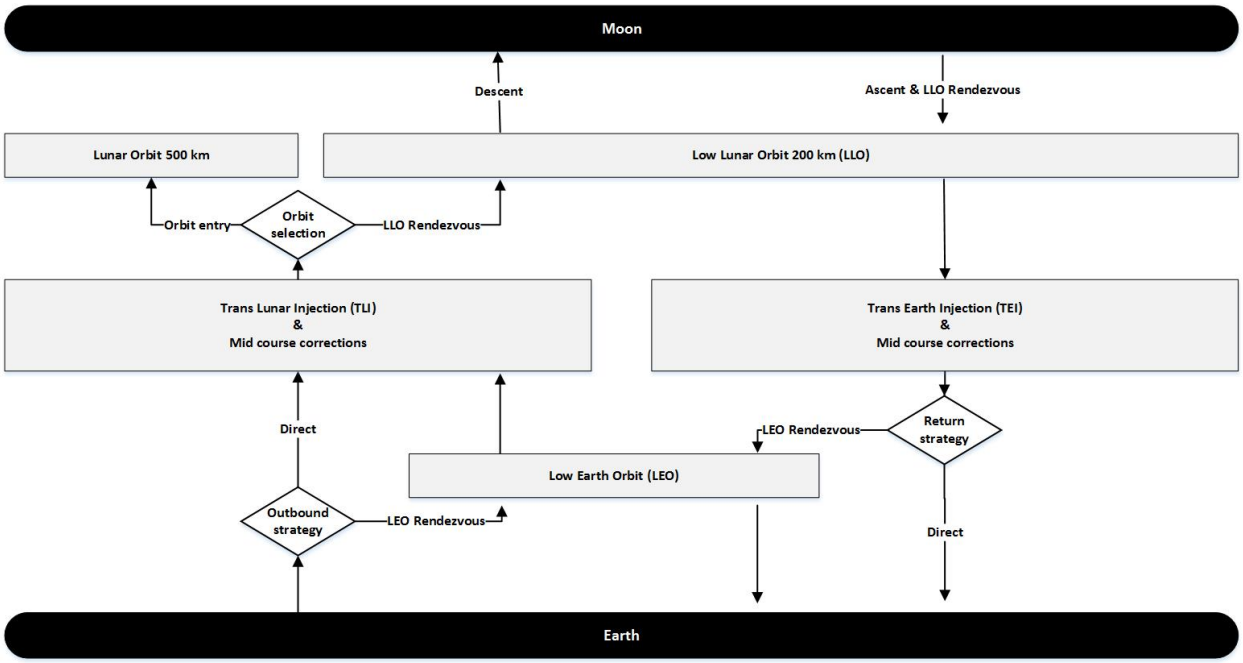


Figure 8.2: Routing

The Lunar Relay Satellites for the communication purpose and satellites for exploration are injected in an orbit of 500 km altitude. The flights for cargo or crew will enter an orbit of 200 km with an inclination of 86 degree. From this orbit a descent to the lunar surface

is possible every 2.1 hours, since the base at the northern pole will be passed during each revolution. [44] Like in the Apollo missions a moon lander is necessary to reach the surface of the moon. Therefore a rendezvous maneuver is taken place in the LLO. These missions shall be executed with and without a crew. The moon lander shall be able to land cargo missions with no need of pilots. In case of a crewed flight a space ship is waiting for up to 210 days in the LLO with no crew on board. Enough propellant mass is on board the space ship to start the Trans Earth Injection (TEI). For the beginning of the moon base the space ship shall have the capability to return directly to the earth. Therefore a heat shield has to be part of the system. This concept enables a quicker return and gives an additional safety factor for an evacuation. For a longterm consideration a space ship without a heat shield could be a shuttle between the LEO and the LLO. To return to the LEO an additional propellant mass has to be brought along. The amount of this mass depends on the strategy to enter the LEO. The delta-v can either be reached by the engines or by the use of the atmosphere, a so called aerobrake [41] . A refueling with a space station like the ISS and a crew exchange could be a longterm strategy. The big benefit is, that the space ship itself stays in the orbit and the biggest amount of propellant for the flight to the moon could be saved.

8.2 Propellant

During the process of collecting the required mass for the moon base and the decision for a refuel-able moon lander, the question of how much fuel the descent and ascent dependeing on the mass of payload appeared. During the research a similar calculation was found in [41]. It differs by different mass values of the transport vehicles and the return strategy. For our concept a direct return to the earth has been selected. Therefore the following calculation 8.3 is adapted to our scenario and analyzed for different mass values 8.2 .

	Mass t
Orion Spacecraft Dry Mass	14.2
Lunarlift Dry Mass	7.8
Tanks TLI	3.9
Tanks TEI	2.0
Propellant of Orion	7.9
Payload descent (LLO, Lunar Surface)	14.5
Payload ascent (Lunar Surface, LLO)	1.0

Table 8.2: Mass Values for Calculation of Propellant

The Table 8.4 gives the answer to the question, how the payload mass is connected to the mass of propellant. From zero t to the

	Mass t
Orion Return flight: LLO –> Earth	
Mass of Orion back in LEO	14.2
Prior LEO Injection	14.2
Propellant for LEO Injection	0.0
Mass Orion at LLO Departure	17.3
Propellant for TEI from LLO	3.1
Lunar Lift Ascent (Moon–>LLO)	
Mass of Lunar Lift in LLO	8.8
Mass of Lunar Lift at Departure from Moon	13.4
Propellant Mass for Ascent	4.6
Lunar Lift Descent (LLO–>Moon)	
Mass at Arrival at Lunar Surface	26.9
Mass at Departure from LLO	42.9
Propellant Mass for Descent	16.0
Orion outbound flight (LEO–>LLO)	
Orion from LEO to LLO	54.5
Mass at LLO Injection	66.6
Propellant for LLO Injection	12.1
Mass at Departure from LEO	70.5
Mass at TLI from LEO	143.5
	73.0
Total Propellant LEO-Moon-Earth	96.8

Table 8.3: Calculation for Propellant

	LEO–>Moon–>Earth	LunarLift Two Ways
Payload	X	X
Propellant Payload	X * 2.6	X * 0.6
Propellant Basis	58.9	12.0
Total	X*2.6 + 58.9	X * 0.6 + 12.0

Table 8.4: Propellant mass in respect to Payload (t)

maximum value of 14.5 t all propellant values have been compared. A linear increase of propellant mass in respect to payload and the used calculation has been derived [41]. For each ton of payload a propellant basis plus the payload mass times the payload propellant delivers the amount of required propellant for the whole flight from LEO to the surface of the moon an back to the surface of the earth. Additionally we derive the amount of propellant for the descent and ascent of the moon lander. This formula is included in the flight schedule calculation. Each flight has a specific payload mass and therefore a specific mass of propellant for the moon lander.

8.3 Transport Vehicles

The situation reminds on the situation during the beginning of the Apollo program. To bring hundred of tons of mass to the moon super heavy lift launch vehicles are required (see Figure 8.3). Following launch vehicles have been considered.

	SLS Block II	**Saturn 5**	**SLS Block I**	**Falcon Heavy**
Status	ca 2021	until 1973	ca 2017	Test 2014
Mass LEO	130	118.0	70	53.0
Mass GTO				21.2
Mass LO	50.7	47.0	ca 20	about 10

Table 8.5: Super Heavy Lift Vehicle (>50 mT LEO)

	Long March 5-504	**Atlas V Heavy**	**Delta IV Heavy**	**Ariane 5ES**
Status	ca 2015	Active	Active	Active
Mass LEO	25	29	23.0	20.0
Mass GTO	14.0	13.0	13	8.0
Mass LO				

Table 8.6: Heavy Lift Vehicle (>20 mT LEO)

	Ariane 6	**Falcon 9 v1.1**	**Soyus 2 Fregat**	**Minotaur-5 (1)**
Status	ca 2020	since 2013		Active (LADEE)
Mass LEO		10.5	8.5	
Mass GTO	6.5	4.9		0.7
Mass LO		2.5	2.4	0.46

Table 8.7: Medium Lift Vehicle (> 2 mT)

A manned transport needs a launch vehicle with a launch abort system. This crewed flight will take a space ship into LEO and then execute a rendezvous maneuver with a Trans Lunar Injection stage. This TLI stage and additional cargo will be brought aboard an additional cargo launcher. A cargo flight is planned for a direct trajectory like the approach trajectory with no rendezvous maneuver from earth to a lower lunar orbit. Whether this cargo flight enters the LEO short while or not is not restricted by this concept and has to be further determined.

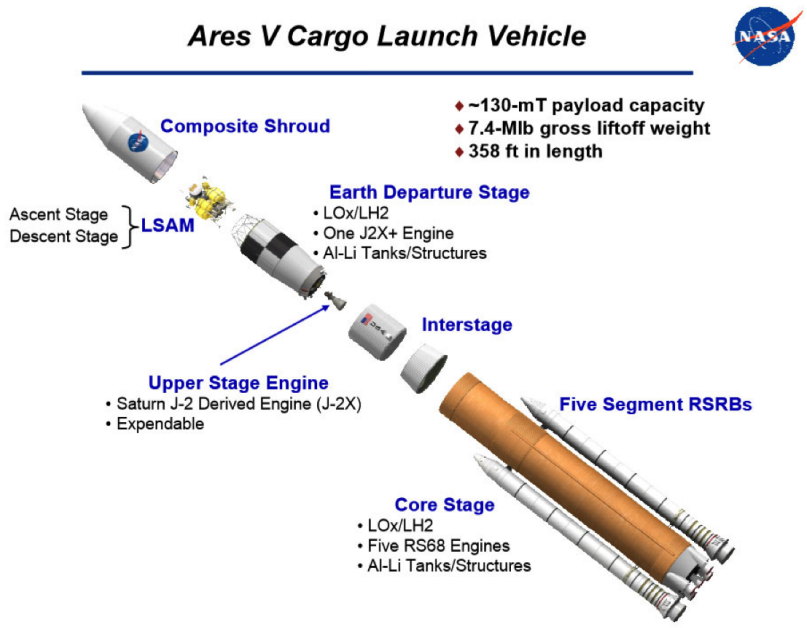


Figure 8.3: Nasa Ares Block I

For a manned mission to the moon a space craft is required and some features like the heat-shield for the reentry have already been described. The propellant mass calculation is based for the NASA concept of the Orion Multi Purpose Crew vehicle. The Dragon module of SpaceX has been rejected, because its design is optimized for serving the ISS and not to operate in trans earth missions. The Orion concept offers a Launch Abort System, a reentry capability and supports the strategy of the moon based Lunar Lift. The Crew Module and Service Module have a Dry Mass of 22.1 t. The Service Module has a capacity of 7.9 t propellant. This amount fits the TEI propellant demand as calculated in Table 8.3. For landing back on earth only the Crew Module is planned. For the TLI an additional trans lunar stage will execute a rendezvous in LEO. This stage is disposed, after its usage.



Figure 8.4: NASA Orion-MPCV

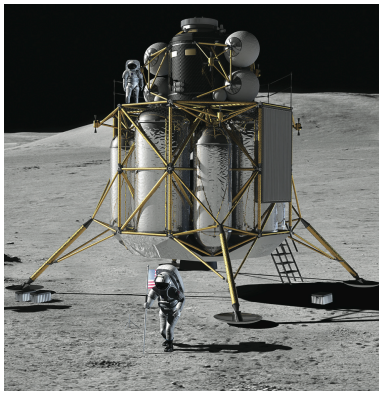


Figure 8.5: NASA Altair

There is no big choice of moon lander systems, because since the Apollo program no human has stepped on the moon anymore. The concept from Apollo and further new concepts have been researched. The Chinese mission Chang?e 3 landed on the 14th of December 2013 with a soft landing on the moon. This hovering and soft landing method enables the moon lander to land close to the base at the northern pole. A landing within one km can therefore be assumed. To reduce the amount of lunar dust pollution, an area of 100 m x 100

m shall be sintered. The payload of Chang?e was about 140 kg. For the moon base concept we need a lander like the NASA Altair concept that enables to land 14.5 t of cargo or four astronauts with 0.5 t cargo (see Figure 8.6). Different to the Altair concept the Moon Base 2030 needs a transport vehicle to fly between a lower lunar orbit and the lunar surface several times. Therefore a single stage for descent and ascent with a refuel capability is considered. Like the descent stage a propellant of LOX and LH2 is preferred, since for a long term idea this fuel can be produced on the moon, since we have systems to gather water. For the concept a resupply of the propellant is assumed, which is reasonable for the first years. Since this concept differs from the Altair concept by a single stage and a refuel capability the described moon lander concept is called Lunar Lift during this concept.

By the Numbers	Apollo Lunar Module	Altair Lunar Lander
Crew Size (max)	2	4
Surface Duration (max)	3 days	7 days (Sortie missions), Up to 210 days (Outpost missions)
Landing site capability	Near side, equatorial	Global
Stages	2	2
Overall height	7.04 m (23.1 ft.)	9.9 m (32.5 ft.)
Width at tanks	4.22 m (13.8 ft.)	8.8 m (28.9 ft.)
Width at footpads (diag.)	9.45 m (31 ft.)	14.9 m (48.9 ft.)
Crew module pressurized volume	6.65 m^3 (235 cu. ft.)	17.5 m^3 (618 cu. ft.) – crew module + airlock
Ascent Stage mass	4,805 kg (10,571 lbs.)	6141 kg (13,510 lbs.)
Ascent Stage engines	1 – UDMH-NTO	1 – MMH-NTO
Ascent engine thrust	15.6 Kn (3,500 lbf.)	24.5 Kn (5,500 lbf.)
Descent Stage mass	11,666 kg (25,665 lbs.)	37,045 kg (81,500 lbs.)
Descent Stage engines	1 – UDMH-NTO	1 – pump-fed, throttling, LOX/LH2
Descent engine thrust	44.1 Kn (9,900 lbf.)	83.0 Kn (18,650 lbf.)

Figure 8.6: Nasa Altair Fact Sheet

8.4 *Flight Schedule*

All bits of information from the previous chapters flow into the flight schedule. The flight schedule is the presentation of the logistics. To start with the one-time mass. This mass is necessary for build up of the moon base and for the extension. Figure 8.7 shows the division between the mass requirement of the topics of the overall concept per phase. This figure is accompanied by the Table 8.8, 8.9 and 8.10. These table show the specific distribution of each payload item to a flight. Each flight has a flight number, date, a destination and an optimized flight allocated launch vehicle. A flight number following a 'C' is a crewed flight. A flight number following a '1' or '2' is an organized together with the flight number ending with a '0'. The column showing the underload shows how much additional mass can be transported with this transport vehicle. Some underload is necessary due to the max payload of the Lunar Lift. The propellant for the Lunar Lift is part of this calculation and adjusted to the specific payload demand. The volume of the payload has not been considered

for each flight, but it has been checked that it is within limits of the Orion transport volume. A payload chamber for a launch vehicle is in addition not a fixed value and can be adjusted within limits. The mass has been conceived as the more limiting factor.

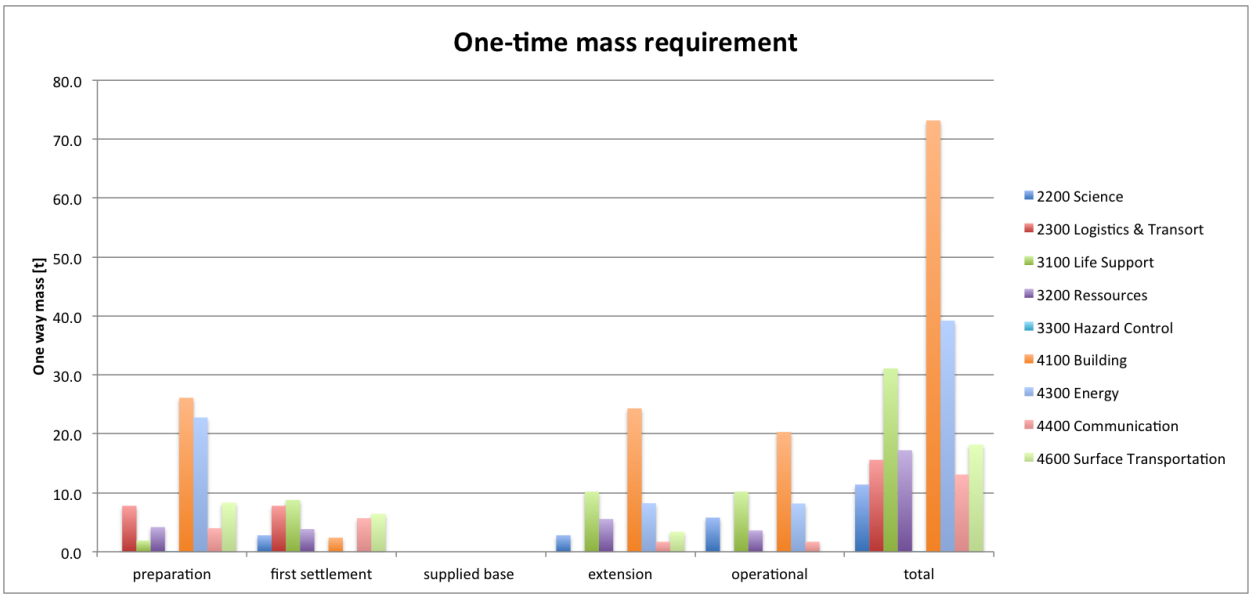


Figure 8.7: One-time Mass

The Resupply Mass is shown in Figure 8.8 and Table 8.11. This mass shows the resupply demand of spare parts and consumable goods. These flights happen in a regular way, which is related to the phase of the moon base.

The final figure 8.9 shows how much one-time mass is brought to the moon surface (grey plane) and when this amount is increased by inbound flights to the moon (bars). In total a sum of 220 t of mass will be landed on the moon. The propellant required to do so, as well as the mass for the satellites orbiting the moon are not part of this diagram. 29 launches from earth are necessary to transport this one-time mass to the moon. As conclusion the logistics has come to values that are a challenge. What has been expected? The required technic is not developed by today, but concepts and concrete ongoing implementations are in progress. To increase the feasibility the concept of producing the Lunar Lift propellant on the moon on the one hand and to develop a new space ship that is not capable of landing back on earth on the other hand, should be encouraged. A space ship that is low in mass, refuel-able and is capable of using aerobrake concepts to enter the LEO on the return flight to a space station, would yield to even better values. It is ok that the whole

Flight #	Year	Destination	Launcher	Payload	Amount	Unit	Total	Underload
p1-10	2020	LEO	SLS Block II				130.00	0.00
				Possible Payload			130.00	
p1-20C	2020	LEO	SLS Block I				70.00	0.00
				Orion - MPCV			21.25	
				Possible Payload			48.75	
p1-30	2022	LO	Falcon 9				2.40	0.10
				Satellite	1	2.40	2.40	
p1-40	2022	LO	Minota UR-5				0.40	0.06
				Seismologic Sensors	10	0.01	0.10	
				Deploy Unit	10	0.03	0.30	
p1-50	2022	LO	Falcon 9				2.00	0.50
				Relay Satellites	2	1.00	2.00	
p2-10	2023	LLO	SLS Block II				32.50	17.50
				Lunar Lift (reuse)	1	7.80	7.80	
				Lunar Lift Propellant	1	17.92	17.92	
				Athlete Rover	1	2.30	2.30	
				Rover unpressurized	2	0.70	1.40	
				Moveable Solar Array 15 kW	2	0.54	1.08	
				Solar Array for Printing 5.5 kW	1	0.20	0.20	
				Tools	1	0.80	0.80	
				Antenna	2	0.50	1.00	
				Water Tank	15	0.11	1.69	
				Racks Science	2	0.70	1.40	
p3-10	2024	LLO	SLS Block II				46.56	3.44
				Lunar Lift Propellant	1	20.46	20.46	
				MISWE Rover	1	2.50	2.50	
				Athlete Rover	1	2.30	2.30	
				Tower of housing complex	1	9.30	9.30	
				Air lock	3	4.00	12.00	
p3-11	2024	LLO	SLS Block I				19.20	0.80
				Lunar Lift Propellant	1	19.20	19.20	
p4-10	2024	LLO	SLS Block II				48.38	1.62
				Lunar Lift Propellant	1	20.62	20.62	
				Radiator 50%	2	2.03	4.05	
				Building deployment structure	1	0.58	0.58	
				Solar Array	2	0.20	0.40	
				Solar Array Mounting	1	1.00	1.00	
				High Voltage Cable	1	5.60	5.60	
				Water Tank 1,25	2	0.11	0.23	
				Cargo Box	4	0.03	0.13	
				DC-DC Downconverter	2	0.10	0.20	
				Electrolyzer	2	0.90	1.80	
				H2-Tank	8	0.03	0.26	
				O2-Tank	8	0.02	0.13	
				O2-Liquifier	2	1.00	2.00	
				H2-Liquifier	2	1.00	2.00	
				Racks Energy	8	1.00	8.00	
				Racks Science	2	0.70	1.40	
p4-11	2024	LLO	SLS Block I				20.00	0.00
				Lunar Lift Propellant	1	20.04	20.00	
f-10	2029	LLO	SLS Block II				30.41	19.59
				Lunar Lift Propellant	1	18.90	18.90	
				Fuel Cell	2	0.90	1.80	
				Racks Food	4	0.05	0.20	
				Air(Nitrogen, Oxygen) 100 m3	15	0.13	1.91	
				Green houses (3 parts)	1	2.00	2.00	
				Racks Life Support	8	0.70	5.60	

Table 8.8: Flight Schedule Part 1 (mass t)

Flight #	Year	Destination	Launcher	Payload	Amount	Unit	Total	Underload
f-20	2029	LLO	SLS Block II				44.21	5.79
				Lunar Lift Propellant	1	20.63	20.63	
				food (Backup per base)	1	0.50	0.50	
				food (first half year)	1	0.50	0.50	
				Furniture	1	1.00	1.00	
				MISWE Rover	1	2.50	2.50	
				Water Tank	12	0.11	1.32	
				Racks Printing and Repair	2	0.70	1.40	
				Racks Communication	1	0.70	0.70	
				Rover pressurized	2	3.00	6.00	
				Water Tank 1,25	2	0.11	0.22	
				Cargo Box	4	0.06	0.24	
				Lunar Lift (reuse)	1	7.80	7.80	
f-30	2029	LO	Falcon Heavy				10.00	0.00
				Relay Satellites	5	1.00	5.00	
				Propellant for Deploying	1	5.00	5.00	
f-40C	2030	LEO/LLO	Falcon Heavy				30.32	22.68
				crew	4	0.08	0.32	
				Orion - MPCV	1	30.00	30.00	
f-41	2030	LEO/LLO	SLS Block II				93.70	36.30
				TLI stage	1	73.00	73.00	
				Lunar Lift Propellant	1	20.70	20.70	
x1-10	2035	LLO	SLS Block II				45.43	4.57
				Lunar Lift Propellant	1	19.25	19.25	
				Rover unpressurized	2	0.70	1.40	
				PUP (Portable Utility Pallet)	2	1.00	2.00	
				Tower of housing complex	1	9.30	9.30	
				Racks Printing and Repair	2	0.70	1.40	
				Air lock	2	4.00	8.00	
				Furniture	1	1.00	1.00	
				Building deployment structure	1	0.58	0.58	
				Antenna	2	0.50	1.00	
				Racks Communication	1	0.70	0.70	
				Solar Array	2	0.40	0.80	
x1-11	2035	LLO	SLS Block I				19.25	0.75
				Lunar Lift Propellant	1	19.25	19.25	
x1-20	2035	LLO	SLS Block II				40.43	9.57
				Lunar Lift Propellant	1	20.58	20.58	
				H2-Tank	5	0.03	0.16	
				O2-Tank	5	0.02	0.08	
				Racks Energy	8	1.00	8.00	
				Radiator	2	2.03	4.06	
				Green houses (3 parts)	1	2.00	2.00	
				MISWE Rover	2	2.50	5.00	
				Water Tank	5	0.11	0.55	
x1-30	2035	LLO	SLS Block II				30.25	19.75
				Lunar Lift Propellant	1	15.33	15.33	
				Lunar Lift Propellant	1	18.84	18.84	
				Air(Nitrogen, Oxygen) 100 m3	15	0.13	1.91	
				Racks Science	1	0.70	0.70	
				Racks Science	3	0.70	2.10	
				Solar Array	2	0.20	0.40	
				Racks Life Support	8	0.70	5.60	
				food (Backup per base)	1	0.50	0.50	
				Racks Food	4	0.05	0.20	
x1-31	2035	LLO	SLS Block I				17.28	2.72
				Lunar Lift Propellant	1	17.28	17.28	
x2-10C	2037.5	LEO/LLO	Falcon Heavy				30.32	22.68
				crew	4	0.08	0.32	
				Orion - MPCV	1	30.00	30.00	
x2-11	2037.5	LEO/LLO	SLS Block II				93.70	36.30
				TLI stage	1	73.00	73.00	
				Lunar Lift Propellant	1	20.70	20.70	

Table 8.9: Flight Schedule Part 2

Flight #	Year	Destination	Launcher	Payload	Amount	Unit	Total	Underload
x2-20	2037.5	LLO	SLS Block II				45.47	4.53
				Lunar Lift Propellant	1	20.16	20.16	
				Air(Nitrogen, Oxygen) 100 m3	15	0.13	1.91	
				Telescope	1	3.00	3.00	
				Solar Array	1	0.20	3.00	
				Air lock	1	4.00	4.00	
				Antenna	2	0.50	1.00	
				Racks Communication	1	0.70	0.70	
				Tower of housing complex	1	9.30	9.30	
				Furniture	1	1.00	1.00	
				Racks Printing and Repair	2	0.70	1.40	
x2-21	2037.5	LLO	SLS Block I				19.02	0.98
				Lunar Lift Propellant	1	19.02	19.02	
x2-30	2037.5	LLO	SLS Block II				35.09	14.91
				Lunar Lift Propellant	1	20.66	20.66	
				Building deployment structure	1	0.58	0.58	
				Racks Printing and Repair	2	0.70	1.40	
				Radiator 50%	2	2.03	4.05	
				Racks Life Support	8	0.70	5.60	
				food (Backup per base)	1	0.50	0.50	
				Racks Food	4	0.05	0.20	
				Racks Science	3	0.70	2.10	
x2-31	2037.5	LLO	SLS Block I				18.88	1.12
				Lunar Lift Propellant	1	14.58	14.58	
				Racks Science	1	0.70	0.70	
				MISWE Rover	1	2.50	2.50	
				Water Tank	10	0.11	1.10	
x2-40	2037.5	LLO	SLS Block II				34.80	15.20
				Lunar Lift Propellant	1	20.55	20.55	
				H2-Tank	4	0.03	0.13	
				O2-Tank	4	0.02	0.06	
				Racks Energy	8	1.00	8.00	
				Radiator	2	2.03	4.06	
				Green houses (3 parts)	1	2.00	2.00	
0-10C	2040	LEO/LLO	Falcon Heavy				30.32	22.68
				crew	4	0.08	0.32	
				Orion - MPCV	1	30.00	30.00	
0-11	2040	LEO/LLO	SLS Block II				93.70	36.30
				TLI stage	1	73.00	73.00	
				Lunar Lift Propellant	1	20.70	20.70	

Table 8.10: Flight Schedule Part 3

Flight #	Year	Destination	Launcher	Payload	amount	Unit	Total
s-cargo_halfyear	2030.5-2037.5	LLO	SLS Block I				16.7
				Lunar Lift Propellant	1	12.0	12.0
				Resupply Logistics	0.5	1.6	0.8
				Resupply Life Support	0.5	2.5	1.3
				Resupply Ressources	0.5	0.8	0.4
				Resupply Building	0.5	1.0	0.5
				Resupply Energy	0.5	1.7	0.9
				Resupply Communication	0.5	0.2	0.1
				Resupply SurfaceTransportation	0.5	1.5	0.8
x2-cargo_year	from 2038	LLO	SLS Block II				26.9
				Lunar Lift Propellant	1	12.0	12.0
				Resupply Logistics	1	1.6	1.6
				Resupply Life Support	1	2.7	2.7
				Resupply Ressources	1	0.8	0.8
				Resupply Building	1	5.3	5.3
				Resupply Energy	1	2.5	2.5
				Resupply Communication	1	0.3	0.3
				Resupply SurfaceTransportation	1	1.8	1.8
0-cargo_year	from 2040	LLO	SLS Block I				31.2
				Lunar Lift Propellant	1	12.0	12.0
				Resupply Logistics	1	1.6	1.6
				Resupply Life Support	1	4.0	4.0
				Resupply Ressources	1	0.8	0.8
				Resupply Building	1	7.3	7.3
				Resupply Energy	1	3.3	3.3
				Resupply Communication	1	0.4	0.4
				Resupply SurfaceTransportation	1	1.8	1.8
crewchange10C		LEO/LLO	SLS Block I				29.8
				crew	4	0.1	0.3
				Orion - Multi Purpuse Crew Vehicle	1	29.5	29.5
crewchange11		LEO/LLO	SLS Block I				40.0
				TLI stage	1	40.0	40.0
				Lunar Lift Propellant	1	20.7	
returncrew12C		EARTH	Orion-MPCV				0.3
				crew	4	0.1	0.3

Table 8.11: Regular Flights

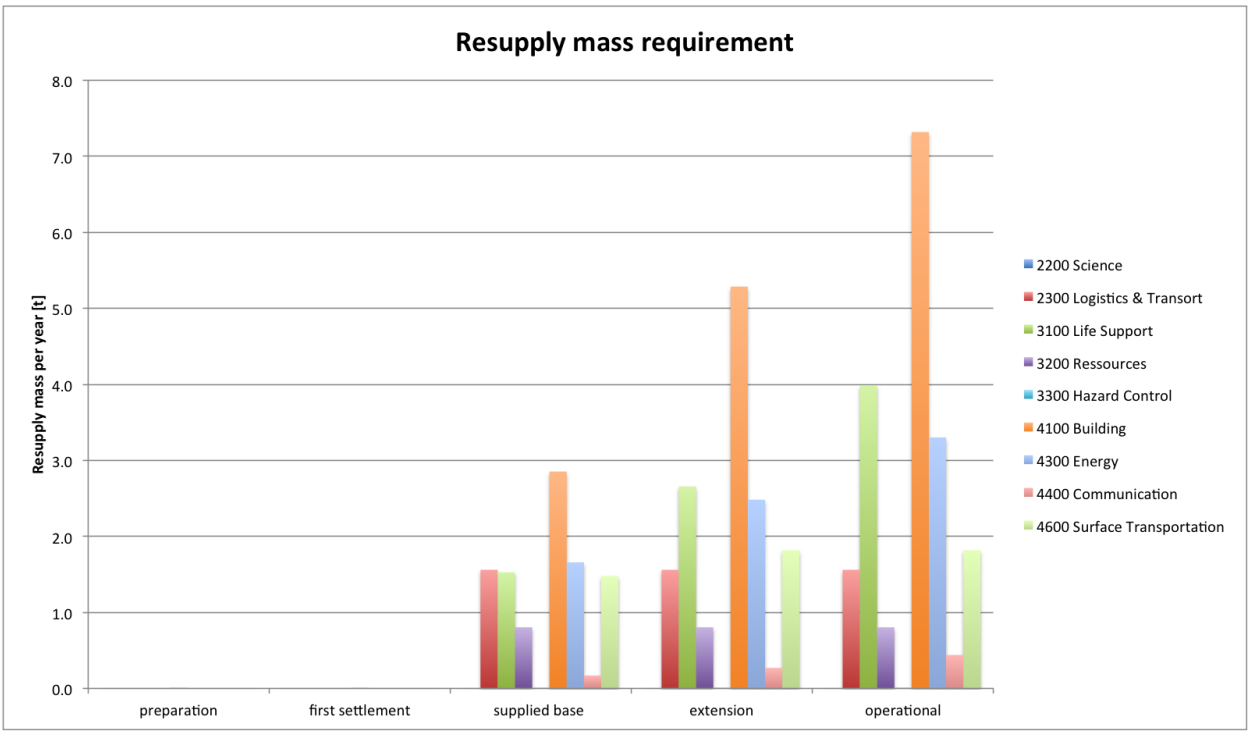


Figure 8.8: Resupply Mass

moon base concept is a challenge and it seems not to be out of reach.
It seems to be feasible.

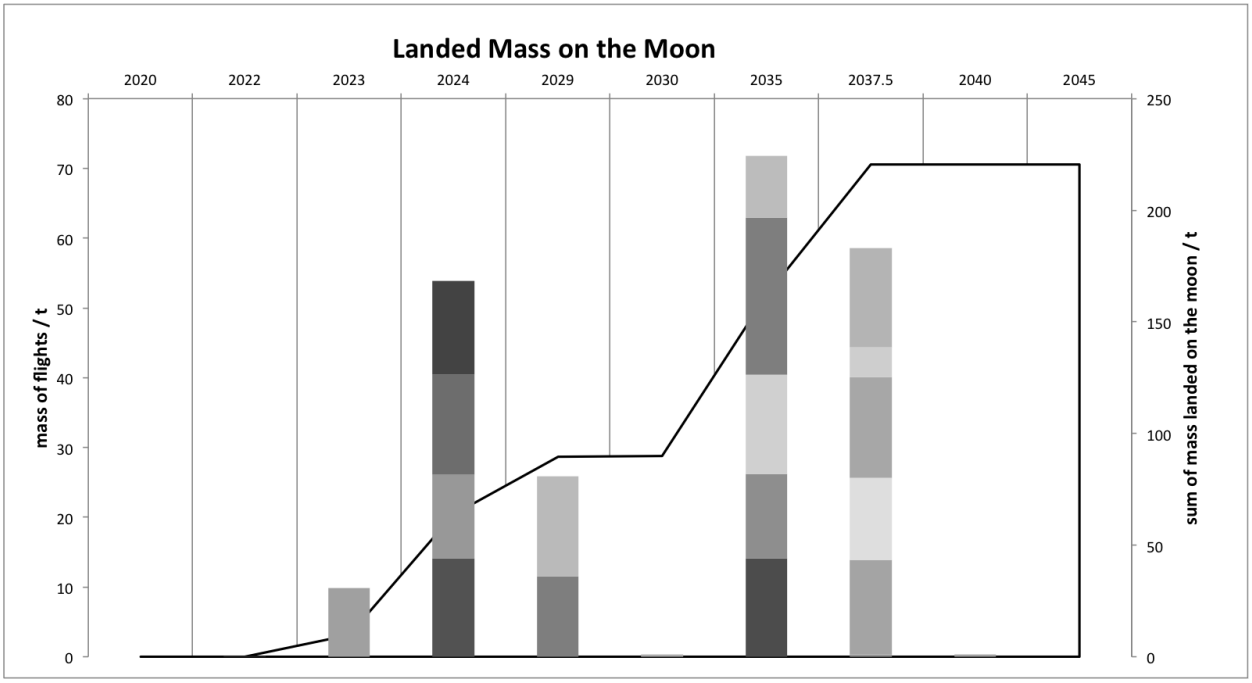


Figure 8.9: Landed Mass on the Moon

9
Power Supply

by Wendelin Fischer

Electrical energy is an essential requirement for any manned or unmanned space station. No robot, communication link, conventional life support system, or computer would work without electrical energy. It is consequently a primary task to provide a power link, robust enough to feed all devices essential for survival with their required amount of electrical energy in any kind of emergency. It is secondly important to design the power supply in a way that all devices of the space station are fed with enough energy to guarantee a smooth working flow at all times. For the design of such a centralized power supply, it is important to identify its main components first: First there are the energy consumers, which require a certain amount of energy at a specific time. The distribution of this energy is controlled by the power distribution unit, which is fed by the energy source and also has an energy storage in which it can store energy for the times, when the energy source does not provide enough energy to supply all consumers. A draft of this concept is given in Figure 9.1.

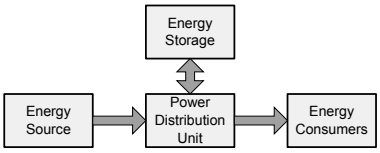


Figure 9.1: Power Distribution Schema

The design process of the power supply system will be the following: In the first step an analysis of the energy consumption of the lunar base station does take place. From the gathered values, technologies capable of providing the expected power will be investigated and reviewed, to provide the demands of possible energy storage systems. After the investigation of possible storage technologies the layout of the power supply system does take place. After finishing the design, an evaluation will be carried out. In addition to that the system will be simulated, as part of the lunar base, in Chapter 13. In the building process of the power supply of the lunar base station, this design process has to be repeated several times going deeper into each system with each iteration.

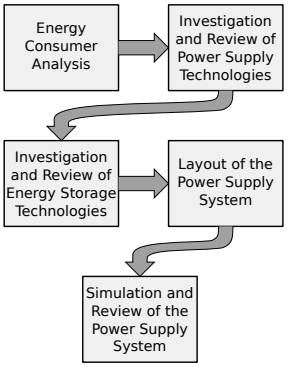


Figure 9.2: One Design Iteration of the Power Supply System

9.1 Energy Demand

The first design step, the identification and parameterization of all energy consumers of the space station, is carried out for all phases of the mission scenario.

During the first phase, Preparation, when there are just rovers but no humans on the moon, the energy demand differs a lot from all following phases. The rovers are working at different spots around the space station, are moving, and require energy in very irregular intervals. For this reason, and for the reason that the complete building process of a centralized energy supply system would not be possible without humans, it is decided, that all rovers are equipped with individual small power supplies, which are designed for their specific needs during the preparation phase. These systems are described in the dedicated chapters, in which the rovers are postulated. For this reason there is no energy demand to the central power supply system during the preparation phase.

In the next phase, supplied base, the first building complex is populated and all its systems are working. A list of them is given below. Each system is parameterized by a maximum power demand, which is the required power, when the system is running, a duty cycle which states the fraction of time the system is running in relation to the whole time, and the average power demand, which is derived from multiply the duty cycle with the maximum power demand.

- The first energy consumer is the life support system. It is divided into three subcategories: The first on is the infrastructure, which monitors and regulates the atmosphere, the sabatier processing unit, the water quality and water storage, the atmospheric pressure, the greenhouses of the complex and everything else which is part of the life support. The power demand of this unit is stated to approximately 1.7 kW, and it is running at all times, which results a duty cycle of 1 and an average power demand of again 1.7 kW. The second life support system is the oxygen production unit. Oxygen is produced by the electrolysis of water, which is done at the power storage unit, as explained in Section 6.1. For 1.5 kg of oxygen, which are required for one complex in 24 h (see Section 6.1), 9.4 kW h energy are required, resulting an average power demand of 0.4 kW, from a duty cycle of 1 and a maximum power demand of 0.4 kW. The third life support systems are the greenhouses. Here, the lighting is the main energy consumer, as the monitoring is already included in the infrastructure. For the lighting of one greenhouse 1.5 kW are required (see chapter 6.2). The lighting is



running 17 h of 24 h resulting a duty cycle of $\frac{17}{24}$, which leads to an average power demand of 4.15 kW for the four greenhouses of one complex. In total all life support systems sum up to an overall maximum power demand of 8.1 kW and 6.4 kW on average.

- The household appliances of one complex include the lighting, cooking facilities, crew recreation equipment and all other infrastructure required by the astronauts (see Chapter 5). The complex' lift is also taken into account here. They are specified with a maximum power demand of 20 kW, and have an overall duty cycle of 0.1, which leads to an average power demand of 2 kW.

- The communication utilities are split into the antenna with its amplifier and the communication infrastructure, including computers, network switches and data storage (see chapter 10). The antenna / amplifier block requires approximately 0.1 kW and is running the whole time. The same applies to the infrastructure, which does also require 0.1 kW. In total this sums up to a maximum and total energy demand of 0.2 kW.

- One complex also houses four scientific racks. One of these racks has a power supply 3.0 kW. Of course, the 3.0 kW are not consumed the whole time, therefore the duty cycle is determined to be 0.3, leading to an average power demand of 0.9 kW, which is the equivalent of an ISS rack's averaged demand. In total we consequently have a maximum power demand of 12 kW, and an average of 3.6 kW for four racks (see chapter 2.1).

- Since the Preparation Phase the printing, crew and transportation rovers may be charged with electric energy from the central power supply, too. At this time we have two crew and two transportation rovers. All four may be charged with a power of 5.0 kW each. From their working times a charging duty cycle of $\frac{2}{15}$ can be derived (see Section 12.6. This leads to an average power demand of 0.7 kW per rover. The two printing rovers (see Section 5.6) have an energy demand of 2.8 kW each. As they are only running half the time the average power consumption sums up to 1.4 kW each. In total we now have a maximum power demand of 25.6 kW, which leads to an average of 5.5 kW.

- To present an authentic overview of the moonbase's energy demand an overhead for all systems not taken into account yet has to be added, too. An example for this is the power supply monitoring system, which is not yet dimensioned. As the parameters of the previous system drafts are based on estimations in most cases, this

overhead has to be set high enough to allow some of the systems to exceed their parameters as well. Therefore a total of 50 % of the sum of all previous listed demands is added as additional expense power, to the average as well as to the maximum power demand.

In total we now have a maximum power demand of 98.9 kW and an average of 26.4 kW for the supplied base phase.

During the Extension Phase the second complex is populated and all systems are running. The power demand of this complex is the same as of the first complex, except for the following:

- A second communication antenna and amplifier is added on the second complex. However, this antenna is only working when the one on the first complex is not running. This means the duty cycle of both antennas drops to 0.5. The resulting average power demand for communication for both complexes is limited to 0.3 kW.

- For the second phase only two new crew transportation rovers are added to the base. They are charged with 5.0 kW at a duty cycle of $\frac{1}{10}$, leading to an average demand of 0.5 kW. This results in additional 10 kW to the maximum power demand and 1.0 kW to the averaged.

Taking this into account, the maximum power demand during the extension phase is 174.3 kW and the average rises to 46.0 kW.

A third complex is added for the operational phase. This complex again has the same parameters as the other two, except for the following:

- No additional antenna or amplifier is added on the third complex. Only the communication infrastructure has to be put into operation.

- No further rovers are added to the base during this phase. One printing rover for the base station is disabled, resulting a duty cycle and average demand of zero. For the two crew transport rover, available since the supplied base phase, the duty cycle rises to $\frac{1}{5}$, leading to an average demand of 1.0 kW per rover.

Summing up this leads to 234.6 kW maximum and 63.0 kW average power demand during the operational phase.

A list of all the systems and their power demand during each phase is given in Table 9.1 and a graphical overview in Figure 9.3

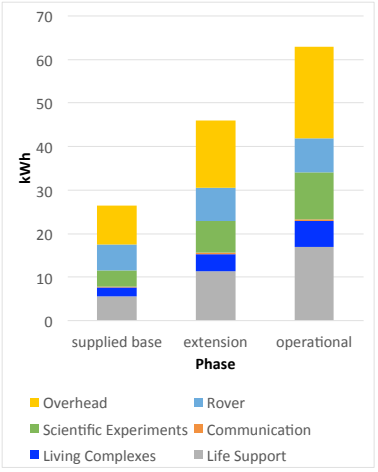


Figure 9.3: Average Power Demand for the Mission Scenario

	supplied base			extension			operational		
	Max Power [kW]	Duty Cycle	Average Power [kW]	Max Power [kW]	Duty Cycle	Average Power [kW]	Max Power [kW]	Duty Cycle	Average Power [kW]
Life Support Total	***8.1***	***29/37***	***6.4***	***16.2***	***29/37***	***12.7***	***24.3***	***29/37***	***19.1***
Infrastructure Complex A	1.7	1	1.7	1.7	1	1.7	1.7	1	1.7
Infrastructure Complex B	-	-	-	1.7	1	1.7	1.7	1	1.7
Infrastructure Complex C	-	-	-	-	-	-	1.7	1	1.7
Oxygen Production Complex A	0.4	1	0.4	0.4	1	0.4	0.4	1	0.4
Oxygen Production Complex B	-	-	-	0.4	1	0.4	0.4	1	0.4
Oxygen Production Complex C	-	-	-	-	-	-	0.4	1	0.4
Greenhouse Lighting Complex A	6.0	17/24	4.3	6.0	17/24	4.3	6.0	17/24	4.3
Greenhouse Lighting Complex B	-	-	-	6.0	17/24	4.3	6.0	17/24	4.3
Greenhouse Lighting Complex C	-	-	-	-	-	-	6.0	17/24	4.3
Living Complexes Total	***20.0***	***1/10***	***2.0***	***40.0***	***1/10***	***4.0***	***60.0***	***1/10***	***6.0***
Complex A	20.0	1/10	2.0	20.0	1/10	2.0	20.0	1/10	2.0
Complex B	-	-	-	20.0	1/10	2.0	20.0	1/10	2.0
Complex C	-	-	-	-	-	-	20.0	1/10	2.0
Communication Total	***0.2***	***1***	***0.2***	***0.4***	***3/4***	***0.3***	***0.5***	***4/5***	***0.4***
Amplifier, Antenna	0.1	1	0.1	0.2	1/2	0.1	0.2	1/2	0.1
Infrastructure	0.1	1	0.1	0.2	1	0.2	0.3	1	0.3
Scientific Experiments Total	***12.0***	***3/10***	***3.6***	***24.0***	***3/10***	***7.2***	***36***	***3/10***	***10.8***
Racks 1 to 4	12.0	3/10	3.6	12.0	3/10	3.6	12.0	3/10	3.6
Racks 5 to 8	-	-	-	12.0	3/10	3.6	12.0	3/10	3.6
Racks 9 to 12	-	-	-	-	-	-	12.0	3/10	3.6
Rover Total	***25.6***	***19/89***	***5.5***	***35.6***	***2/11***	***6.5***	***35.6***	***5/31***	***5.7***
Printing Rover 1	2.8	1/2	1.4	2.8	1/2	1.4	2.8	1/2	1.4
Printing Rover 2	2.8	1/2	1.4	2.8	1/2	1.4	2.8	0	0
Crew Rover 1	5.0	2/15	0.7	5.0	2/15	0.7	5.0	1/5	1.0
Crew Rover 2	5.0	2/15	0.7	5.0	2/15	0.7	5.0	1/5	1.0
Crew Rover 3	-	-	-	5.0	1/10	0.5	5.0	1/10	0.5
Crew Rover 4	-	-	-	5.0	1/10	0.5	5.0	1/10	0.5
Transport Rover 1	5.0	2/15	0.7	5.0	2/15	0.7	5.0	2/15	0.7
Transport Rover 2	5.0	2/15	0.7	5.0	2/15	0.7	5.0	2/15	0.7
Subtotal	***65.9***	-	***17.6***	***116.2***	-	***30.7***	***156.4***	-	***42.0***
Overhead 50 %	33.0	-	8.8	58.1	-	15.3	78.2	-	21.0
Total	***98.9***	-	***26.4***	***174.3***	-	***46.0***	***234.6***	-	***63.0***

Table 9.1: MOON BASE 2030Power Demand

9.2 Energy Sources

As a next step we will discuss possible energy sources for the power amounts calculated in the previous chapter. As there are no fossil fuels on the moon, there are only two main energy sources, in the category of supplying some tens of kilowatts, for a long term lunar base station: this is on the one hand nuclear power and on the other hand solar power. This is also stated by [44].

Nuclear power is the main power supply in most prominent long term lunar base studies, as for example the Constellation Program of NASA [66]. The benefits of such a energy source lie on hand: the high reliability, a continual power provision, the compact architecture, and a long lifetime. However, there are also disadvantages which come along with the use of nuclear power in space. They include the shielding of the reactor from humans and the resulting health risk, the disposal of radioactive wastes and the dangers which lie in the transport of nuclear materials to the moon, as some of the material might pollute the earth atmosphere in the case of an accident [113].

Solar power is the number one power source for all earthy spacecrafts. It is also used for present moon missions, such as the Chinese Chang'e-3 [102]. The advantages of solar systems for a lunar base station lie in their flexible dimensioning and their small mass. However, there are also disadvantages when using this kind of power source for the base station: The length of a lunar day is 29.53 earth days, leading to 14.26 earth days of lunar night each lunar day [44]. Huge amounts of energy have to be saved to bridge the night when no sun is shining at the base. When going to a polar region, as proposed in this study, the relative amount of nighttime might drop, however a site, high enough to overlook all surrounding hills, has to be chosen for the location of the solar panels, to have a good view of the sun. This site might not be suitable for the rest of the station, which leads to high cabling efforts and therefore higher transport masses for the power system.

9.3 Energy Storage

As described above, the biggest problem in the design of a power supply might derive from storing the produced energy. Especially when designing a solar supply system enormous amounts have to be available during the solar nights. For bridging short demand peaks, momentum technologies as fly wheels might be used, but for storing energy over hundreds of hours other technologies are required.

The first technology presented in this section is the use of batter-

ies. The advantage of batteries, is their simple design, robustness, and direct availability. Lithium-Ion-Batteries nowadays reach energy densities of 300 $\frac{\mathrm{W\,h}}{\mathrm{l}}$ or 160 $\frac{\mathrm{W\,h}}{\mathrm{kg}}$ [79]. When storing energy for a space station requiring 50 kW on average for 15 days, an energy amount of 18 MW h is needed. When using Lithium-Ion-Batteries this may be accomplished by a 60 000 l batterie block, having a mass of 113 t. As seen from this example, the use of conventional batteries is not efficient for powering a solar system, but it would be efficient enough for bridging small peaks on a nuclear driven system, or as a robust storage for single space station sub systems or as an emergency fill-in.

The second storage technology presented here is the electrolysis of water to hydrogen and oxygen. Due to the availability of water (see chapter 11.1), this technology offers a magnificent progress in today's design of a lunar base station. The reaction of water to hydrogen and oxygen has an reaction enthalpy of 571.7 $\frac{\mathrm{kJ}}{\mathrm{mol}}$ [17], which leads to a specific enthalpy of $h = 4.4075\,\frac{\mathrm{kW\,h}}{\mathrm{kg}}$.

$$2\,H_2O \rightarrow 2\,H_2 + O_2 \qquad \Delta H^0_{rxn} = 571.7\,\frac{\mathrm{kJ}}{\mathrm{mol}}$$

$$h = \frac{571.70\,\frac{\mathrm{kJ}}{\mathrm{mol}}}{2 \cdot 18.0153\,\frac{\mathrm{g}}{\mathrm{mol}}(H_2O)} \cdot 0.2778\,\frac{\mathrm{W\,h}}{\mathrm{kJ}} = 4.4075\,\frac{\mathrm{kW\,h}}{\mathrm{kg}}$$

Of course, not all of this energy can be used as electricity, therefore the design of an efficient fuel cell converting oxygen and hydrogen to water and electricity is a major task in the development of such a system. However, in the last decade great advances have been made in fuel cell technology. Comparable system are emerging on earth, especially in the fields of mobility and renewable energies [59]. The main difference between a fuel cell on Earth and one on the Moon, is the availability of oxygen in the atmosphere. Because no oxygen can be gathered from the Moon atmosphere it has to be saved in gaseous or liquid form. But for this kind of system there is also a reference on Earth. A cooperation of Siemens and the Howaldtswerke-Deutsche Werft AG has developed a fuel cell for the German submarine classes 212 and 214, which has been practically used for several years now [88]. The fuel cells aboard the submarines convert hydrogen and liquid oxygen, stored on-board to water with system powers of approximately 240 kW. Their system efficiencies reach up to 70 % [84]. The technique used here, is a combination of two Siemens BZM 120 fuel cell, providing a power of 120 kW each [93]. One of those fuel cells has a mass of 900 kg and a size of 0.5 m^3. For a space application those parameters could sure be optimized over the next years.

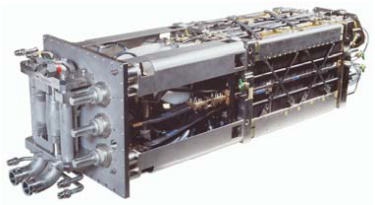


Figure 9.4: Siemens BZM 120 Fuel Cell [Credits: Siemens]

Mass	900 kg
Output Power	120 kW
Efficiency	70 %

Table 9.2: Fact sheet of a lunar fuel cell adopted from the Siemens BZM 120

When using a fuel cell, an electrolyzer converting water and electrical energy to hydrogen and oxygen is of course required, too. The

Mass	900 kg
Input Power	160 kW
Efficiency	80 %

Table 9.3: Assumed fact sheet of a lunar electrolyzer

same technology, Proton Exchange Membranes (PEM), as used for the fuel cell might be used for the electrolyzer. Their efficiencies are at above 70 % by now and might increase up to 90 % in the next decades [82]. As electrolyzers are usually stationary on Earth no reference design for a comparable system is available here yet. But as the technology does not differ a lot from the fuel cell's one, the parameters of the BZM 120 may be adopted here. Electrolyzers usually have a better efficiency than fuel cells, it is therefore assumed to be at eighty percent. Taking into account the energy losses of the electrolyzer and fuel cell, the input power of former is assumed to be slightly higher than the output power at 160 kW.

Storing oxygen and hydrogen is the next task in the development of a fuel cell energy storage system. For the previously mentioned 18 MW h and a fuel cell efficiency of 70 % an equivalent of 5834 kg of water is required. This leads to 5181 kg of oxygen and 653 kg of hydrogen, which have to be safely stored. The danger of storing oxygen and hydrogen, lies in the destructive reaction, if both gases get in contact. Stored at a pressure of 100 bar the oxygen requires 36 000 l volume and hydrogen 60 000 l at room temperature. Tanks of that size have a relatively high chance of getting hit by micro-meteorites on the Moon (see Chapter 7.4), which would cause pressure loss and gas evacuation resulting in the requirement of massive shielding, or the construction of underground tanks for both gases. Shielding would in consequence lead to higher transport expenses and underground tanks to a lot of construction work.

Another option is to liquefy both gases, resulting a much smaller size and consequently a lower meteorite hitting chance. From the lower pressure in those tanks, the risk of massive gas evacuation would also be limited in the case of an impact. 5181 kg of oxygen would than only require 4500 l, and 653 kg of hydrogen 9000 l. For oxygen the liquefaction process is relatively easy, as the boiling point is at 90 K, which is not too difficult to reach. An exemplary industrial liquefaction plant has a power consumption of 1100 kW at a rate of 60 $\frac{t}{d}$ [99], resulting in 440 $\frac{W}{kg}$. Of course, such a system would have to be adapted for the requirements of a lunar base station, but relatively cost effective systems do exist.

Mass	1000 kg
Input Power	22 kW
Liquefaction Rate	50 $\frac{kg}{h}$

Table 9.4: Assumed fact sheet of a lunar oxygen liquefier

The storage of hydrogen is a much more difficult task. For the liquefaction process a temperature of 20 K is required. Nowadays industrial plants cope with approximately 10 $\frac{kW\,h}{kg}$ of hydrogen, and are expected to reach an efficiency of up to 7 $\frac{kW\,h}{kg}$ [85]. Another option for storing hydrogen would be the use of metal hydrides, as described in [89], but this would again require heavy storage applications, as

they have at least 20 times the mass of the proposed hydrogen as hydrogen-reactant. However, this technology is for example used for the previously mentioned submarines, as it is very robust against shock and has to be taken into account for the design of a lunar fuel cell system, too.

Technologies for storing both liquefied gases under space conditions have been a research interests for many decades now, as launch vehicles as the space shuttle carriers need them, too. The current development is going into the direction of the use of composite materials, as for example the XCOR Aerospace systems [114]. Their advantages lie in their low mass, high robustness and thermal resistance, and non-flammability.

Mass	1000 kg
Input Power	35 kW
Liquefaction Rate	5 $\frac{kg}{h}$

Table 9.5: Assumed fact sheet of a lunar hydrogen liquefier

Summing up the previously mentioned systems the following efficiency calculation arises: When using 1 kW h of energy on an electrolyzer with an efficiency of 80 %, 182 g of water are transformed to 20 g of hydrogen and 161 g of oxygen. For the liquefaction of both gases at a 7 $\frac{kW\,h}{kg}$-H_2-converter and a 440 $\frac{kW}{kg}$-O_2-converter additional 0.212 kW h are needed. Putting both liquids back into a 70 % percent efficient fuel cell, 0.561 kW h of energy are regained. This means from 1.212 kW h initial energy, 0.561 kW h can be regained, resulting a roundtrip efficiency of 46.3 %, which is worse than that of most chemical batteries but compensable by bigger energy supplies.

9.4 Layout of the Power Supply System

Due to the dangers which lie in the use of a nuclear reactor for a lunar base station, its public acceptance problem, the progress made in solar and fuel cell technologies over the last decades, the discovery of water on the moon, and the fact that the last considerable manned lunar station plans, the Constitution Program, did rely on nuclear power, the system design in this study will primarily rely on solar power and the use of hydrogen and oxygen as energy storage.

The energy supply system of the base station is divided into two levels: a primary level wins energy at one or more solar plants, transports it to the base station, distributes it to the single complexes and stores the unused energy in at a fuel cell. The second level is separately build up in each of the complexes. It is fed by the power line coming from the first level, manages the power flow to each of the power demanding systems and has an energy storage in form of Lithium-Ion-Batteries, which hold enough energy to bridge a blackout of the complete first level for an evacuation scenario. This hierarchical system layout offers the advantage, that only the second level has to

be designed for the demands human emergency survival. This makes the design and construction of the first level components simpler, as the robustness and redundancy levels are lower, typically also resulting a lower component mass.

The location of the lunar base will be in the northern polar region (see Chapter 4). This keeps the benefit, that on some lunar days the sun might never set, but it also holds the danger, that the sun might be visible less than half a day during the lunar winter in that region, due to the 1.5° tilt of the moon axis to the ecliptic [44]. For this reason a series of different spots around the lunar north pole was analyzed for solar plant location sites. This analysis took place in cooperation with the Simulation Working Group and will further be explained in 13.4. A similar simulation took place to figure out the supply and storage demands based on the average and maximum demand values of the base station in its different building phases as stated in Chapter 3. The simulation gave out one scenario for the supplied base phase with one solar station. Two scenarios were given out for both the extension and the operational phase each. One scenario covered the base supply with only an extended solar station at the spot of the original station, the other one with an additional solar plant at a different spot some 28 km away. The input power demands from both stations and the storage capacities at a storage efficiency of 46 percent, as previously stated, are summarized in Table 9.6.

Table 9.6: Power Supply Scenarios

Phase	supp. base	extension		operational	
Scenario	1	2	3	4	5
Avg. Power Demand at Base [kW]	26.4	46.0	46.0	63.0	63.0
Input Power Solar Station A [kW]	110	190	140	260	190
Input Power Solar Station B [kW]	-	-	60	-	70
Energy storage Capacity [MW h]	10	16.5	11	22.5	16

A cost estimation of the scenarios is carried out next: For the simplicity of this study, the costs will only be measured as mass, that has to be transported to the Moon from Earth.

For the energy storage we assume the following: fuel cells, electrolyzers and liquefiers are provided in an appropriate number, independent of the number of MW h saved. Water is available on the Moon and does not have to be provided from Earth. The water is stored in balloon like tanks, which do not fall into account for the mass estimation. The mass that does fall into account is that of the liquid oxygen and hydrogen tanks. For their mass estimation, the

following rough estimation is applied: hydrogen and oxygen are stored in tank of 1000 and 500 liters respectively. From one of those hydrogen and oxygen tanks, approximately 0.2 MW h can be regained with a fuel cell efficiency of 70 % as previously explained. Following [15], the mass of one cubic hydrogen tank would then be estimated to 10 kg plus 17 kg insulation. For the oxygen, one tank would have a mass of 7 kg and 4 kg insulation. Adding 5 kg for connectors, pipes, frame, cooling and mechatronics to each tank, oxygen would sum up to 16 kg per tank and hydrogen to 32 kg per tank. Of course, the tanks shall not be used up to their limits each time the stored energy is needed, therefore a plus fifty percent margin is added to the stored energy demands of each table. The gathered storage masses of each scenario are calculated in Table 9.7. The results show, that for the scenarios with two separate solar plant sites a tank mass 240 kg can be saved in the end.

Table 9.7: Energy Storage Scenarios

Phase	supp. base	extension		operational	
Scenario	1	2	3	4	5
Required. Min. Capacity [MW h]	10	16.5	11	22.5	16
Number of Hydrogen Tanks	8	13	9	17	12
Number of Oxygen Tanks	8	13	9	17	12
Total Tank Mass [kg]	384	624	432	816	576
Storable Energy [MW h]	16	26	18	34	24
Required Water [t]	5.2	8.3	5.9	11.1	7.8

The next thing to look at are the power cables. At the solar plants, the generated direct current is converted to a medium voltage of some kilovolts. By that, the cable losses and mass can be minimized. The conversion process can be done very efficient today, values of more than 99 percent might even be reached. [29] No mass optimized medium voltage power cables for space applications do exist yet, therefore common earthy power cables have to be used as parameter reference for the cable evaluation.

From the Universal Cable XLPE Insulated Power Cables catalogue cable masses for insulated unarmoured aluminium cables for a series of different voltages were taken or approximated if not available.

From its cross-sectional area and the specific resistance of aluminium, the cable resistance for two strings of 5 km and 30 km cables were calculated, and the efficiency for loads of 80 kW for the 30 km cable and of 100 kW and 300 kW for the 5 km cable calculated. The results are gathered in Table 9.8 and Table 9.9. From these values it

becomes obvious, that the mass of the cable to a second solar plant site exceeds the mass of additional hydrogen and oxygen tanks by multiples. Scenario three and five are consequently no longer taken into account. When looking at the values for the first solar plant, one can also see, that the efficiency to cable mass ratios become best for the 11 kV power lines. An electromagnetic shielding is not required, as the magnetic field is in the terms of mT on the moon (see Section 7.6.

Other power transportation technologies were also investigated, but not taken into consideration: Optical power transmission would lead to major losses due to dust in the moon atmosphere and could also easily get damaged in case of a minor moon quake. Uninsulated power transmission proved to be to dangerous for humans crossing the cables and to much construction work would have to be carried out to lift the power lines high up over ground.

The next step in the design process of the power supply is the design of the solar plant. At the lunar north pole the sun's path through the sky is always on the horizon $\pm 1.5°$. Benefitting from this, a solar array would only have to be turnable on the vertical axis. Solar cells for space applications reach efficiencies of approximately 30 % by now [53]. From a solar constant of 1367 $\frac{W}{m^2}$, 410 W electrical power can be gained per squared meter. Meeting the requirements of the power scenarios 1, 2 and 4, two 60 kW solar arrays should be installed for the supplied base phase, two additional ones for the extension phase, and a final one for the operational phase. One of those solar arrays would require approximately 150 m^2. The exemplary space solar cell [53] has a mass of less than 116 $\frac{mg}{cm^2}$ = 1.16 $\frac{kg}{m^2}$, including cover glass and bypass diode, leading to a mass of 174 kg per array. Adding the mass of a construction frame, it might add up to 200 kg. To achieve the best possible sunlight gain, all arrays should be mounted on one single turning pole, to avoid mutual shadows. For this pole, including two redundant dc-dc-converters and a turning motor, another 1000 kg might be added to the system mass. The fundaments of the pole will be printed from regolith by one of the printing rovers. To limit the dust pollution on the solar panel a cleaning rover is also required. This kind of small and effective rovers are currently emerging on earth as shown in [106]. An exemplary design of the solar plant is given in Figure 9.5.

Volt.	11 kV			15 kV		
Cross section [mm^2]	Eff. at 100 kW	Eff. at 300 kW	Cable Mass [t] (two strings)	Eff. at 100 kW	Eff. at 300 kW	Cable Mass [t] (two strings)
4.00	0.95	0.85	*5.3*	0.97	0.92	*8.8*
6.00	0.96	0.90	*5.6*	0.98	0.94	*9.4*
10.00	0.98	0.94	*6.1*	0.99	0.96	*10.0*
16.00	0.99	0.96	7.0	0.99	0.98	*11.2*
25.00	0.99	0.97	8.4	1.00	0.99	12.6
35.00	0.99	0.98	9.4	1.00	0.99	13.8

Table 9.8: Cable Efficiencies for 5 km Cable [Italic mass values are approximated.]

Volt.	6.6 kV		11 kV		15 kV	
Cross section [mm^2]	Eff. at 80 kW	Cable Mass [t] (two strings)	Eff. at 80 kW	Cable Mass [t] (two strings)	Eff. at 80 kW	Cable Mass [t] (two strings)
4.00	0.72	30	0.88	32	0.93	53
6.00	0.80	32	0.92	33	0.95	56
10.00	0.87	34	0.95	37	0.97	60

Table 9.9: Cable Efficiencies for 30 km Cable [All mass values are approximated.]

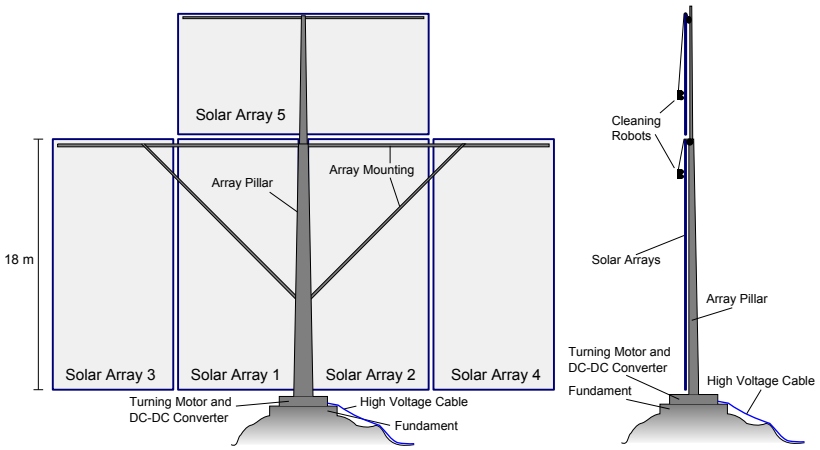


Figure 9.5: Solar Field in Back and Side View

With 120 kW power supply from the solar plant during the supplied base phase, 240 kW during the extension phase, and 300 kW during the operational phase, the 11 kV - 6.00 mm^2 - power cable, has a high enough efficiency to not only meet the bases input power demands for the energy supply scenarios 1, 2 and 4, but also the maximum power demand calculated from the complexes system power demands. To make the primary level of the power supply system complete, two more redundant dc-dc-converter with voltage protection (approximated to 100 kg each) are added to the base station, converting down from 11 kV to a common supply voltage of 400 V.

The approximated masses and required ready-to-operate mission phases of all components needed for the first level of the power supply are now gathered in Table 9.11:

Once the solar station is build up, a team of two astronauts should be scheduled for maintenance work every four weeks, to keep the station in a good condition. Due to the degradation caused by ionizing radiation, it also has to be mentioned that the solar cells should be replaced every 10 to 15 years.

For the monitoring of the whole first level of the power supply system some unit has to be installed at one of the complexes, preferably the first. This unit shall monitor the status of the solar plant, that of the fuel cells, liquefiers, and electrolyzers, the storage capacities of the oxygen and hydrogen tanks, as well as the power demand of the single complexes. One International Standard Payload Rack (ISPR) is proposed for this task, estimating a power demand of 200 W.

From the first level, each building complex is fed with a 400 kV direct current line. From there the second level of the power supply

Length	5 km
Cross section	6.00 mm^2
Strings	2
Mass	5.6 t
Voltage	11 kV
Efficiency at 100 kW	96 %
Efficiency at 300 kW	90 %

Table 9.10: Assumed fact sheet of the high voltage power cable

		supp. base		extension		operational	
	mass per unit [kg]	amount	mass [kg]	amount	mass [kg]	amount	mass [kg]
Solar Array	200	2	400	2	400	1	200
Solar Array Mounting	1000	1	1000				
High Voltage Cable	5600	1	5600				
DC-DC Down-converter	100	2	200				
Electrolyzer	900	2	1800				
O_2-Liquifier	1000	2	2000				
H_2-Liquifier	1000	2	2000				
Fuel Cell	900	2	1800				
H_2-Tank	32	8	256	5	160	4	128
O_2-Tank	16	8	128	5	80	4	64
Total			15 184		640		392

Table 9.11: Transportion Amounts for the First Level Power Supply System

system begins, at which all energy consumers are connected. This demands a much higher reliability as the first level, because some systems, as for example the atmosphere and pressure control, need a constant power supply, to ensure the safety of the crew.

The main component of the second level power supply is the power distribution unit (PDU). Here the 400 kV are inverted to a series of different voltages, depending on the demand of each consumer. In addition to that the energy usage is constantly monitored to avoid short circuits and excessive power consume of individual systems. If the input power unexpectedly drops, the PDU might also turn off single energy consumers, to avoid a blackout of the power system. As the PDU is a safety critical component of the base station, its redundancy level should at least include three units. For the PDU an energy forwarding efficiency of 97 percent can be assumed. For the mass and volume estimation, two ISPRs are assumed, including converters and monitoring unit. Having a tripple redundancy, six ISPRs are estimated in total.

The second component of the second power supply level is the emergency energy storage. This storage must be big enough to provide enough energy to ensure the safety of the crew in case of a total blackout of the first level for 48 h. During that time the crew may try to get the first level back online or evacuate the base. The following components shall be provided with power during this period:

- The life support infrastructure has to control the complex atmosphere and all other safety systems, however systems like the water and waste treatment can be turned of for the time of the blackout, as there should be enough water stored to bridge that gap. The life

support system will then require approximately 1.0 kW.

- The communication system has to work on all levels, requiring 200 W, to assure the communication inside the base, as well as to any team outside, and to earth.
- The power distribution unit has to work at a rudimentary level, to assure the power distribution and monitor the energy storage capacities. A power consumption of 200 W is assumed here.
- To assure some rudimentary functionalities of the living complex systems, as for example lighting, 500 W of power shall be saved for those systems.
- To offer the possibility of finding the blackout fault and a chance to revitalize the first energy supply level, its monitoring unit shall also be provided with 200 W power.

Summing up, each complex has to provide 2.1 kW over the evacuation time of 48 h, resulting an energy capacity of 100 kW h. Taking into account some safety margin, the storage system shall provide 150 kW h at the current design level.

For this kind of task a reliable, simple storage is required, typically provided by batteries. Taking Lithium-Ion-Batteries with energy densities of 300 $\frac{\mathrm{W\,h}}{\mathrm{l}}$ and 160 $\frac{\mathrm{W\,h}}{\mathrm{kg}}$ [79], a batterie mass of 940 kg is required, consuming 500 l space. For this task one additional ISPR is assigned, adding up to eight power supply ISPRs for the first, and seven for the other two complexes.

For the time when the first astronauts arrive, at the beginning of the Supplied Base Phase, a fully functional first level energy supply system is not expected. The main components shall already be built autonomously, but some tasks, as for example the commissioning of the single systems, humans will be required at the site. For this reason additional power is required for an approximated time span of two weeks, until the whole power supply system is working. The live supply will be managed by the two crew transportation rovers at that time, but for communication and the commissioning process, some extra energy has to be provided from the complex at the base station. Assuming an average energy consumption of about 1.5 kW at that time, a total power of 500 kW h is required over two weeks. The same applies for the evacuation scenario during the operational phase. At that time enough power has to be provided to guarantee the survival of two astronauts in one of the complexes. For those two scenarios, the battery block of the first complex is enlarged to 500 kWh, having



a total mass of about 3000 kg and a volume of 1500 l, which would still just fit into an ISPR.

Combining the first and second level, the whole energy supply system now sums up to the system sketch shown in Figure 9.6:

9.4.1 Review and Outlook

An energy supply system for a lunar base station requiring up to 250 kW power has been drafted. It relies on a solar power plant for energy provision and a fuel cell system, using water gained from the lunar surface, as energy storage. It is designed as a flexible system, which could easily be dimensioned smaller or bigger and additionally requiring no consumables from earth. The mass estimation also shows, that no out sticking components have to be transported to the moon for the building process of the system.

For a further research, the energy storage system should primarily be investigated further. An adoptable fuel cell system has already been found, but liquefaction systems, as proposed in this study, or other hydrogen and oxygen storage systems, for applications as a lunar base station do not yet exist.

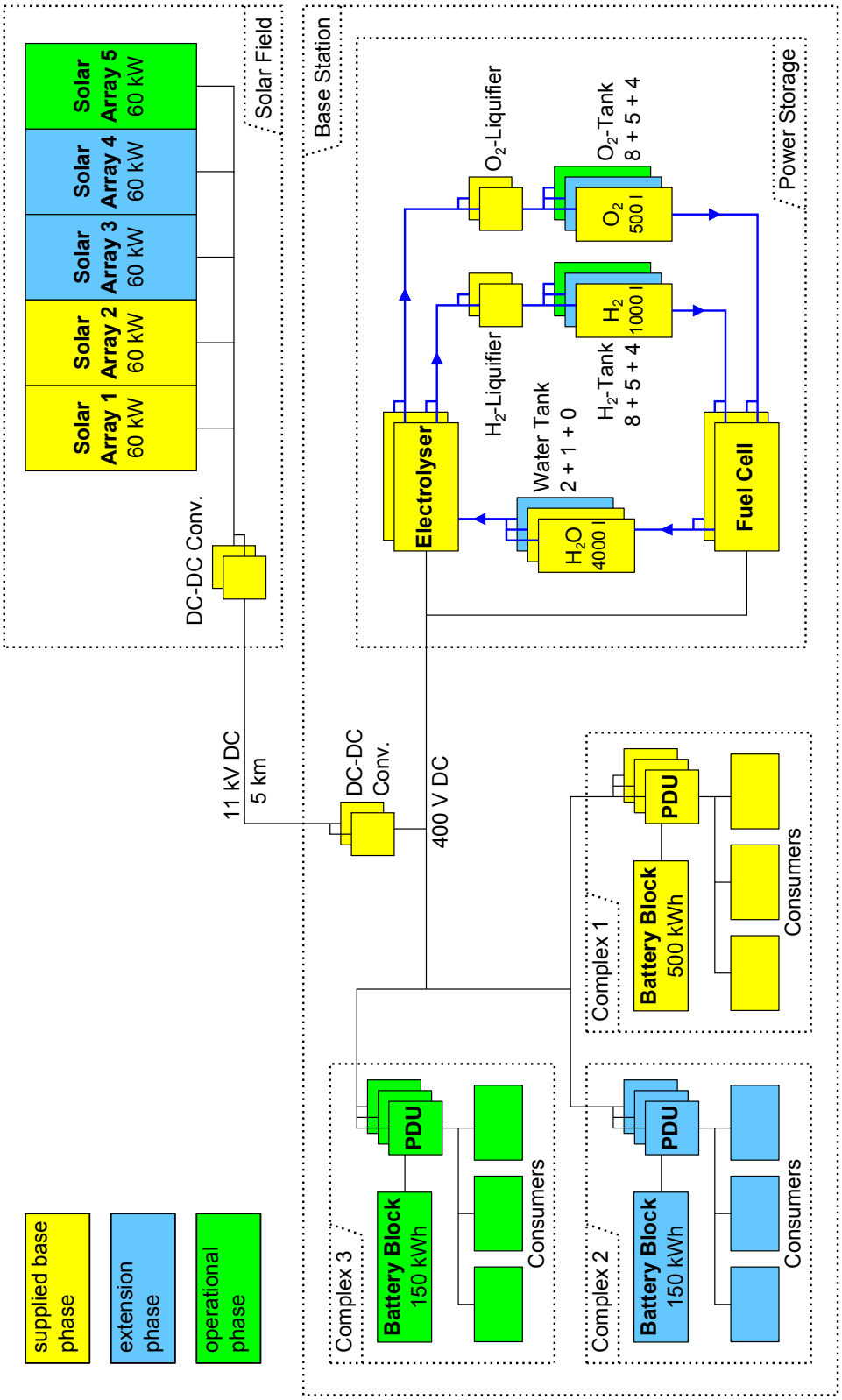


Figure 9.6: Energy Supply System

10
Communication

by Martin Wißmiller

10.1 Communication Concept

Communication is essential for a lunar base. The team on the Moon must always have at least basic communication with each other as well as to Earth. Every component of the base sends telemetry and receives telecommands, scientific experiments in later phases send larger amounts of data to Earth.

The communication concept can be split up into several levels:

1. Moon-to-Earth Communication
2. Long-Range Communication
3. Short-Range Communication
4. Base-Internal Communication

Although for Moon-to-Earth communication, a concept featuring several satellites was the most obvious approach, a direct communication link was also investigated. Unlike Earth, the Moon has quite no atmosphere that will reflect signals, so antennas always need direct sight contact. Calculations taking into account the moons 6.7° libration showed that a base at the Peary crater would be visible from Earth for around two weeks, but then not visible for another two weeks until a direct communication link could be established again. As our base at the northern rim of the Peary crater would disappear from Earth's view, we would either require a communication station at around 84°N - which is always visible, but around 170 kilometers from base; or a communication tower of around 38 km height at base which can always be seen from Earth.

A concept making use of Lagrange-Points was also considered. For example, using direct communication to Earth when possible, otherwise use satellites at L2 and L4/L5 as relay stations. Calculations showed that - taking moons surface and the moving satellite(s) around L2 into account - communication can not be always assured when the communication station is at base level; a two to three kilometer high tower would be required.

As a direct communication link would be either infeasible or require a lot of construction work in early phases far away from our main base, it is much easier to place several satellites in lunar orbit and use an antenna directly at the main base. This is the lowest effort for building the base. The satellites can also be placed in orbit independent from the status on the surface, reducing logistics effort.

At the main base, two antennas are required. As the antennas take some time to adjust to a new satellite, the communication link would interrupt for a few seconds every few minutes with just one antenna. With two antennas, a continuous connection can be assured and higher data rates can be reached using both antennas in parallel when required. Another backup antenna is not necessary as a few interruptions would be acceptable in case one antenna fails. An example communication station at just seven watt power, a 1 meter antenna diameter and at frequency of 2625 MHz could achieve 61 $\frac{\text{Mbit}}{\text{s}}$ to a satellite in orbit [44]. The power consumption can be estimated at around 72 W, including an amplifier ($\approx$50 W) and some hardware ($\approx$15 W).

A laser communication device was also proposed as NASA has just successfully tested laser communication from Earth to a satellite in lunar orbit with 622 $\frac{\text{Mbit}}{\text{s}}$ [74]. There is not much detailed information available and it is still under development. As our communication requirements are not really high, they can be fulfilled with well tested radio communication equipment. The laser communication however can be kept in mind for later phases in case bandwidth requirements raise drastically with the not yet known experiments.

Long-Range Communication for example for rovers and solar panels is also achieved via satellites. Short range communication can be achieved by a small dipole antenna as due to the Moon's environment and topography they can just send up to ten kilometers. Base-Internal Communication can be achieved by standard ethernet cables.

10.2 Satellites

As the base is located close to the north pole, any orbit over the poles will be adequate. Considering the Moon's topography and the antenna placed just at the top of the base, any orbit will have a horizon coverage of around 87° - with a hill on one side. As any orbit over the poles have a very similar horizon coverage over the base, a 0° inclination orbit would be reasonable since the satellites always have direct sight contact to Earth - other satellites acting as relay stations are not necessary. 10.5 to 10.5 show some example orbits over the base.

Orbits higher than 1200 km over the Moon are unstable because of third body effects by the Earth's gravity. At very low orbits, the Moon's highly non-spherical gravity field causes perturbations as well. Some scientific works suggest a 500 km altitude for polar orbits. At least 5 satellites are required for a continuous communication link, eight however would assure that two to three satellites are in sight of the communication station and would assure continuous communication even if one satellite has a major malfunction. Current comparable communication satellites for Moon orbits have a weight of around 1000 kg, consuming up to 700 W of power [91], End-of-Life can be expected after 20 to 30 years.

The number of communication satellites in orbit depends on mission phase:

1. one satellite at the start (phase p1) to receive data from the moonquake station
2. one satellite would be suitable at phase p2 to p4 for basic rover telecommands and telemetry, more however are adviced to enhance that capability and for basic redundancy
3. At phase s and later, when the first astronauts actually dwell on the Moon, a minimum of five satellites is required for continuous communication

The list above describes the minimum satellite required for the phase. Best case would be to have all satellites in orbit from phase p1 onwards.

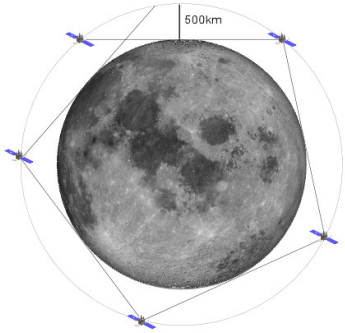


Figure 10.1: A minimum of five satellites is required to maintain continuous contact with the base (at a theoretical 90° horizon coverage)

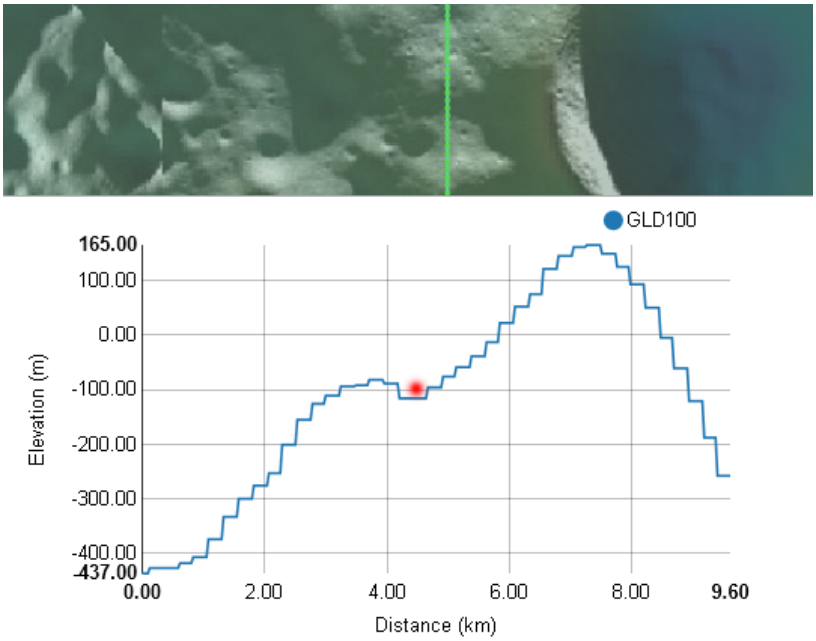


Figure 10.2: Height profile for a 0° polar orbit - the red dot marks the base

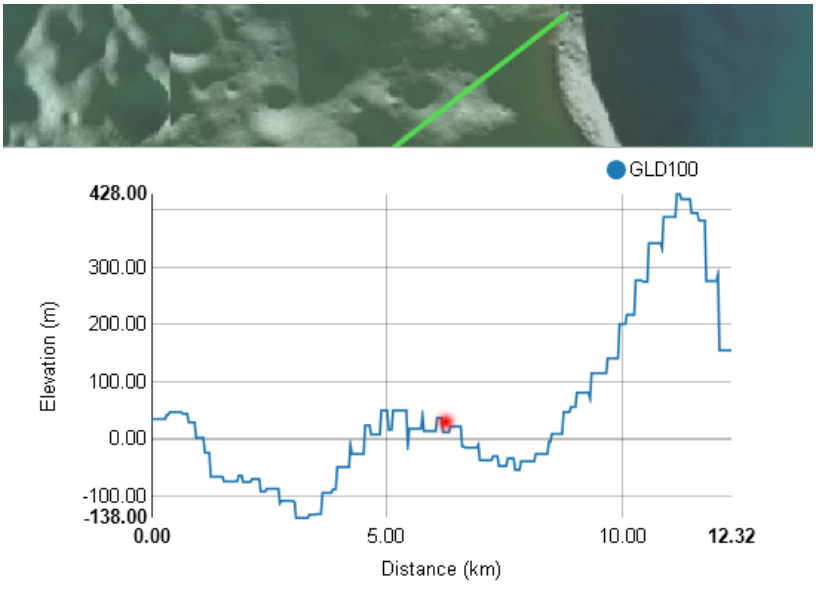


Figure 10.3: Height profile for a 40° polar orbit - the red dot marks the base

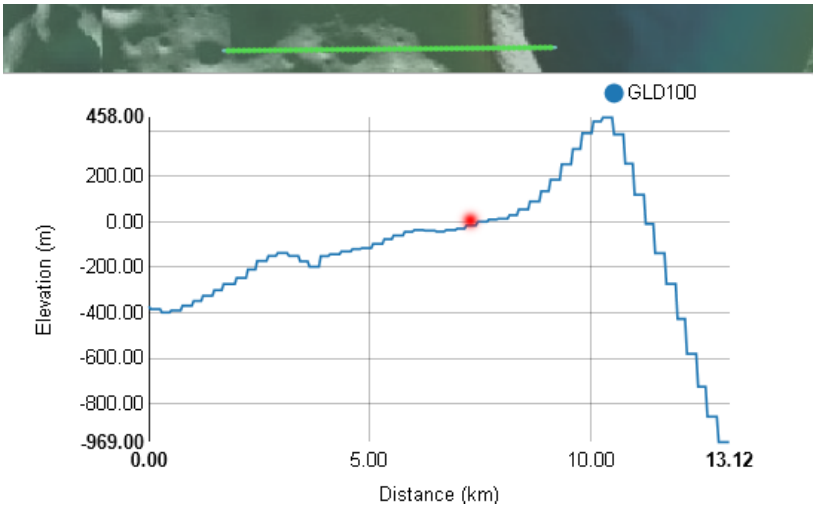


Figure 10.4: Height profile for a 90° polar orbit - the red dot marks the base

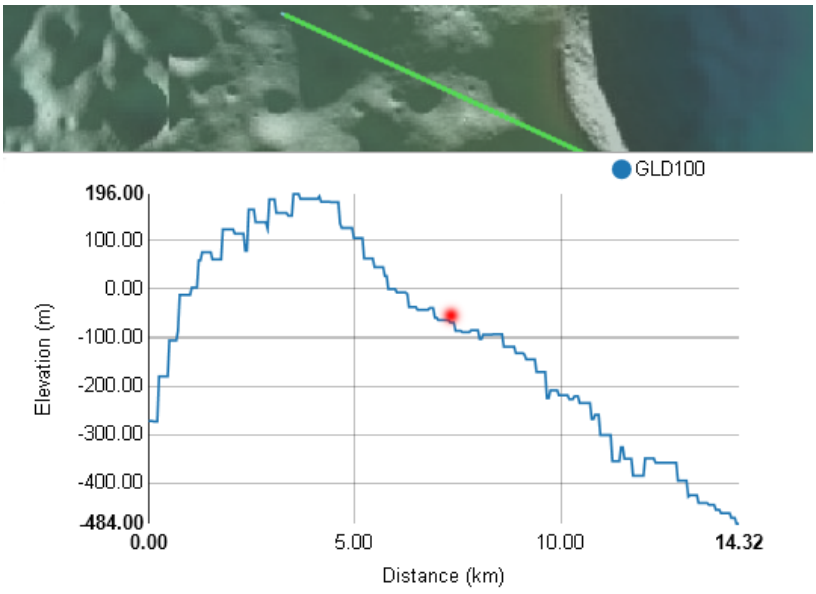


Figure 10.5: Height profile for a 150° polar orbit - the red dot marks the base

10.3 Bandwidth Estimation

Determining the required bandwidth is not an easy task as for this base there are still some unknown factors, especially on the scientific use side. However, for most other components the communication requirements can be roughly estimated.

While telemetry and telecommands are send continuously while the component (e.g. a rover) is in use, speech and video are only sent when in use. As the design of these components is not completely finalized at this early planning stage, the estimations are based on current similar models (rovers) and experiences with speech and video communication. The estimations of the observatory and other experiments are estimated in total for continuous connection and only apply in later phases.

Considering a worst case scenario where all communication channels are used at the same time, continuous 60 $\frac{\text{Mbit}}{\text{s}}$ including communication overhead is suitable even after the first settlement phase. At later phases however, communication capabilities may have to raised as communication requirements will not only raise per person, but also depending on the actual scientific use where we have high uncertainity at this early planning stage. 10.6 and 10.7 show total bandwidth estimations for the base and the satellites and table 10.3 shows esimation for bandwidth of a single unit.

Type of Data	Data Rates
Video HD	$\approx 4000\ \frac{\text{kbit}}{\text{s}}$
Speech	$64\ \frac{\text{kbit}}{\text{s}}$
Telecommands	$< 500\ \frac{\text{kbit}}{\text{s}}$
Telemetry	$< 500\ \frac{\text{kbit}}{\text{s}}$
Observatory	$15\,000\ \frac{\text{kbit}}{\text{s}}$
Other Experiments	$10\,000\ \frac{\text{kbit}}{\text{s}}$

Table 10.1: Bandwidth estimation of a single unit (like rovers etc.) - not all use everything at the same time

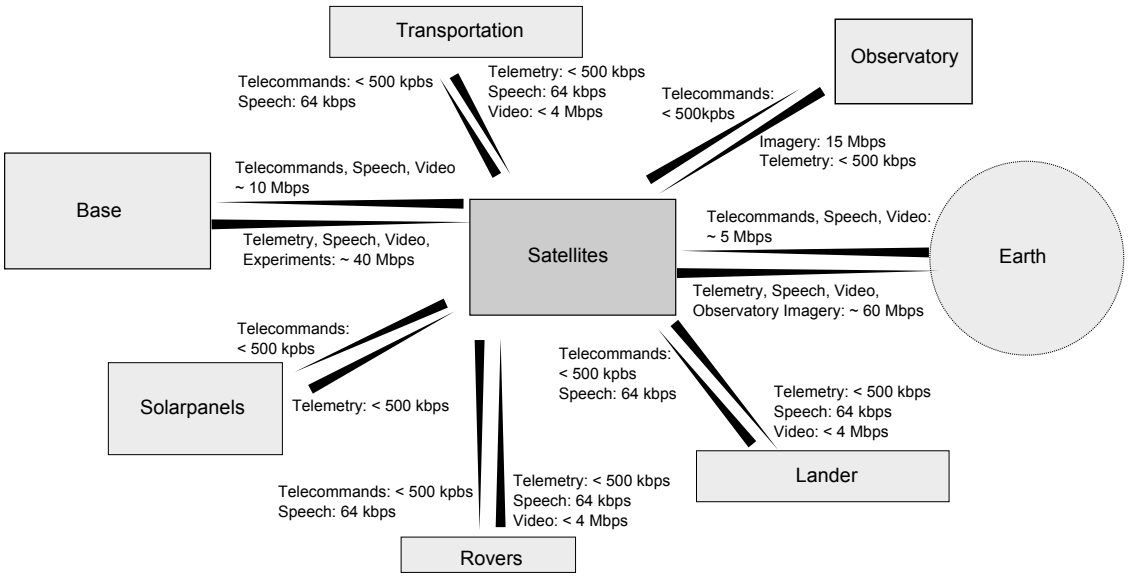


Figure 10.6: Bandwidth estimation of the Moon base components at phase x2

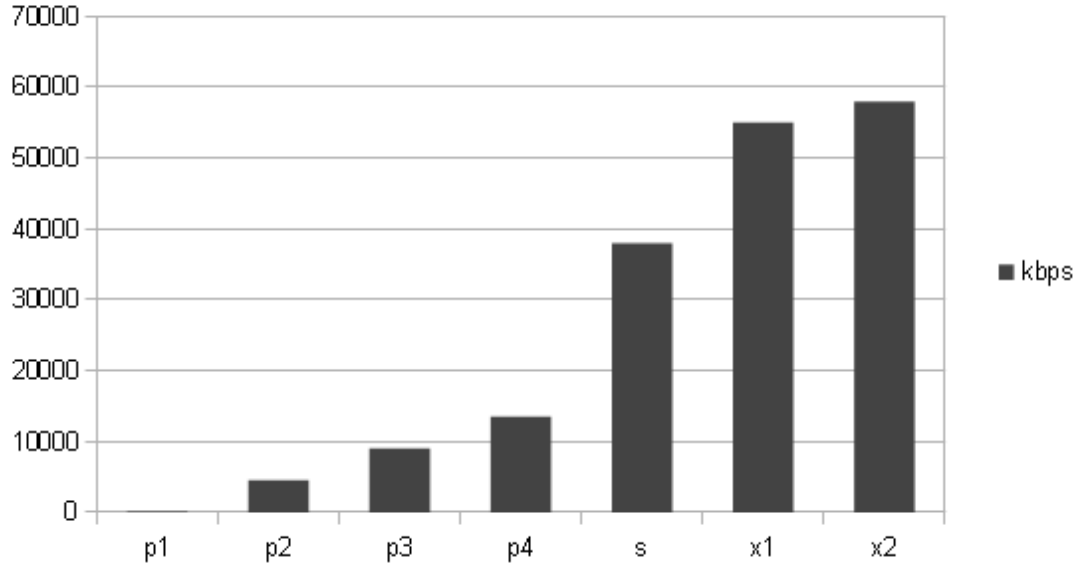


Figure 10.7: Bandwidth estimation for the satellites by phase

Although a lunar base is a mission that has never been put into practice before, our communication requirements are relatively low. Satellites and communication stations with similar specifications exist for decades. Therefore we can use current and well-tested equipment and it is unlikely that we will run into major problems regarding communication.

11
Resources

by Christina Hempfling

11.1 Water on the Moon

When it comes to planning a lunar base using the Moon's resources is a non negligible point. If they can be used, less material will have to be transported to the Moon which reduces the cost of such a mission. One of the major problems in the past has always been the question: can water be found on the Moon? It was long assumed that due to the following reasons [19], water can not be found:

- Lack of atmosphere: nothing can shield the water from sun rays
- Water molecules are not slowed down by bumping into other molecules, they maintain their speed
- Daytime on the Moon lasts for about 14 days which is enough time for water to be heated by the sun

But the lunar probe Chandrayaan-1 [26] and the Lunar Crater Observation and Sensing Satellite (LCROSS) [70] which were launched in 2008 and 2009, respectively, with the goal to detect water on the Moon proved otherwise. Based on the knowledge that the Moon has craters where no sunlight has and will ever touch the bottom, it was assumed – and proven with the instruments from Chandrayaan-1 and LCROSS – that these contain water in a frozen form. The fact that permanent shadowed craters are predominantly found at the poles of the Moon played an important role in the finding of the location for the lunar base. The nearest crater to our lunar base containing water ice is the Whipple Crater [97]. It is permanently shaded from the sun (see Figure 11.1) and thus water molecules coming from impacting meteorites are trapped under the extremely cold conditions (temperatures around 100 K). With a diameter of 15.7 km and an

estimated depth of the water ice layer of at least two to three meters [14], the Whipple Crater contains at least 98,000 t to 148,000 t of water ice. As can be seen later, this is enough to supply our lunar base for at least 20 years. Of course this water ice needs to be extracted and processed to become potable water. Two potential methods were approved for the MOON BASE 2030:

- using a rover to mine the surface and extract water ice
- using microwave technology to extract water from the ground

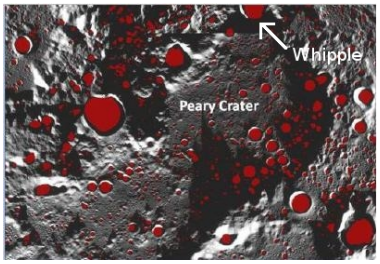


Figure 11.1: Permanently shadowed areas near the North Pole of the Moon are highlighted in red. [26]

11.2 *MISWE – A Rover to Extract Water From the Moon's Soil*

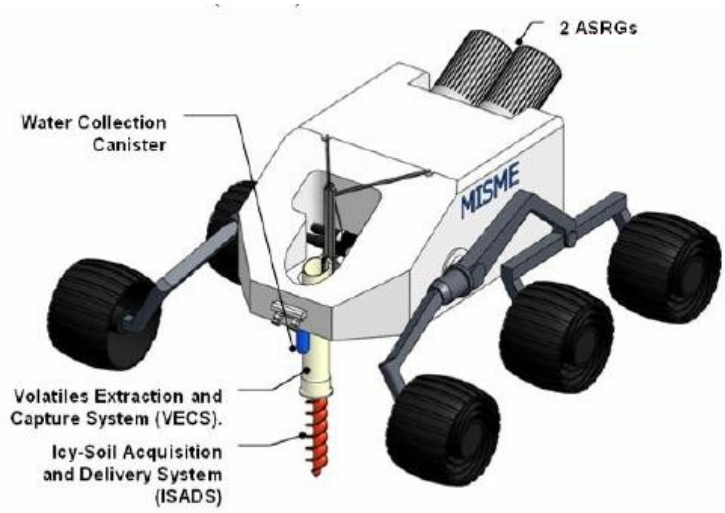


Figure 11.2: Mars In-Situ Water Extractor. Rover to extract water from the Moon's soil. [116]



Figure 11.3: Stowed position of MISWE rover. [116]

For the first phases of our lunar base, we will use a rover to mine the ground in the Whipple Crater and extract the water. Already concepts for such rovers exist and the focus was laid on a concept originally planned for Mars missions: MISWE (Mars In-Situ Water Extractor, see Figure 11.2) [116]. In order to mine the icy and very hard soil, MISWE consists of two systems:

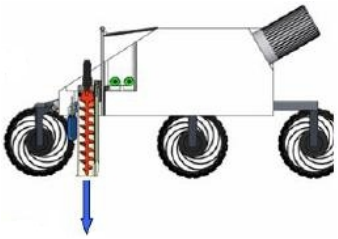


Figure 11.4: VECS is deployed and preloaded against the surface. [116]

- The *Icy-Soil Acquisition and Delivery System (ISADS)*. This system consists of a drill that is able to dig into the soil and transport the material on its flutes.
- The *Volatiles Extraction and Capture System (VECS)*. This system is in charge of heating the material and capturing the vaporized water in a canister where it can condense.

The procedure of gaining water is done in seven steps:

1. The rover navigates to a desired point and reaches a stowed position (see Figure 11.3).
2. The VECS is deployed until it is preloaded against the surface (see Figure 11.4).
3. Now the drill from the ISADS starts to dig into the ground and recovers the icy soil (see Figure 11.5).
4. After the ISADS is retracted into the VECS (see Figure 11.6) the VECS is preloaded against the surface to create a seal.
5. Now several steps take place:
   (a) The icy soil collected in the auger flutes is heated which results in a release of water vapor.
   (b) This vapor is collected in a canister and condenses there.
   (c) The resulting liquid water is pumped out of the canister in the rover's Warm Electronics Box (see Figure 11.7).
6. Then only the VECS is retracted, leaving the soil in the ISADS exposed. Now the auger rotates and the dry soil is ejected (see Figure 11.8).
7. Last, the drill is retracted and the rover drives to the next desired position.

Since MISWE is powered by an Advanced Stirling Radioisotope Generator (ASRG), the heat from this unit is used to keep the Warm Electronics Box warm so the extracted water does not freeze again. It is assumed that MISWE can extract three kilograms of water per hour [117] for asteroids and comets. For the Moon, a rate of two kilograms per hour is estimated.
In order to take this water to the lunar base, the following procedure is planned:

1. When the Warm Electronics Box is filled up MISWE navigates to water tanks able to connect directly to the lunar base structure. These tanks each have a capacity of 1,250 l. MISWE fills the water from the Warm Electronics Box into one of these tanks.
2. The chosen SEV rovers can each transport two of them – in total 2.5 t of water – to the lunar base.

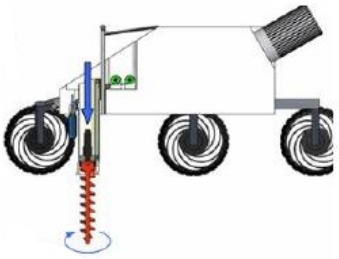


Figure 11.5: ISADS captures the icy soil. [116]

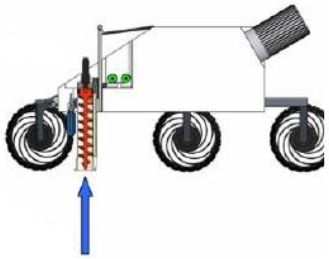


Figure 11.6: ISADS is retracted into VECS. [116]

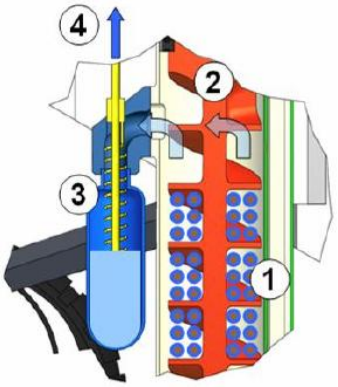


Figure 11.7: ① Icy soil is collected in flutes. ② Heating material and releasing water vapor. ③ Vapor condenses and is collected in a canister. ④ Liquid water is pumped into the Warm Electronics Box. [116]

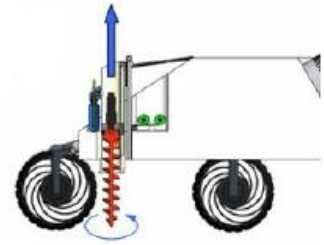


Figure 11.8: VECS is retracted, loose soil is ejected by rotation of the drill. [116]

3. With the heat from the radiator the tank connected to the base is heated and the water is channelled into the base.

4. Inside the base two tanks with each 500 l capacity will be filled. In order to be able to use this amount of water as potable water it needs to be let stand for about four minutes to be sure that it contains less than 0.1 µl of radioactive isotopes.

11.3 *Microwave Technology to Extract Water From the Moon's Soil*

Another interesting idea of how to extract water from the Moon comes from Edwin Ethridge from the Marshall Space Flight Center, Huntsville, Alabama [48]. In experiments he shows that the heating of regolith by microwaves causes the water ice to sublime and subsequently it can be collected by cooling it down again. Compared to MISWE two main advantages of this technology can be found:

- there is no need mine the soil, no drills are needed
- the microwaves can reach deeper into the soil than the drill used by MISWE

However, the microwave technology is not yet as efficient as MISWE. MISWE is able to extract two kilogram of water per hour whereas the microwave technology reaches 60 g to 360 g per hour [47]. Additionally, MISWE brings its own energy generator with it in form of the ASRGs but the microwave technology would have to be powered with the help of a power plant located on the Moon (e.g. solar arrays). Since such a plant will only be at work in the supplied base phase the extraction of water with microwaves would be able to start at that time at the earliest. MISWE on the other side can be sent up already in the Preparation phase and start filling tanks such that there will be a reservoir of water available when the first astronauts arrive at the base. This means that no water has to be brought from Earth which saves costs.

11.4 *Path from Base to Water Mining Place*

Our lunar base is located left of the Whipple Crater such that MISWE and the SEVs face the problem of finding a way into it. The requirements for this path come from constructional restrictions of the SEVs: they can only drive on ground with a maximum gradient of 40 degrees. With the help of a map of the Moon with appropriate tools [75] one can find a way from the base into the Whipple Crater that fulfills this requirement. Our lunar base is located at 89.487° latitude and 135.250° longitude (see Figure 11.9). The best way to access the water reservoir in the Whipple Crater is where its southern rim meets the Peary Crater. Here the gradients are smaller than on its western rim so the SEVs can drive there and drop MISWE at its working place (see Figure 11.10). After that, a way needs to be found that leads down from the base location into the Peary Crater (see Figure 11.11).

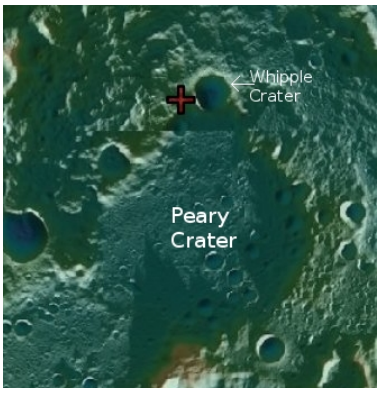


Figure 11.9: Map of the North Pole of th e Moon. Red cross marks the location of the base compared to Peary and Whipple Crater. [75]

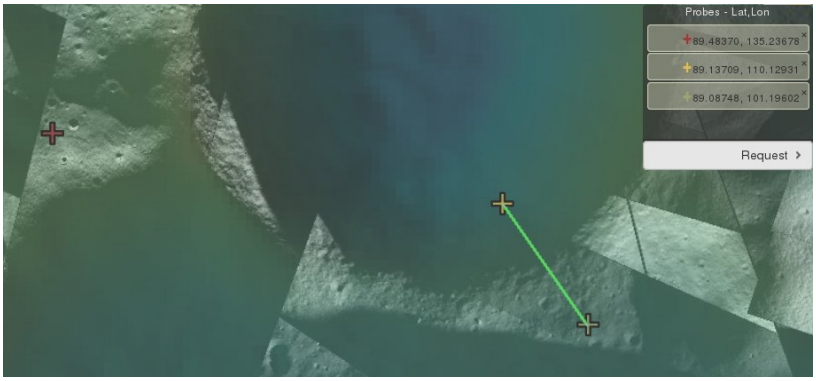


Figure 11.10: Route into Whipple Crater. The red cross marks the base location, the yellow point the starting position for MISWE to mine and the greenish point marks the end point of a path leading out of the Whipple Crater. If the SEV follows the path along the green line the maximum gradient will be less than 33 degrees. [75]

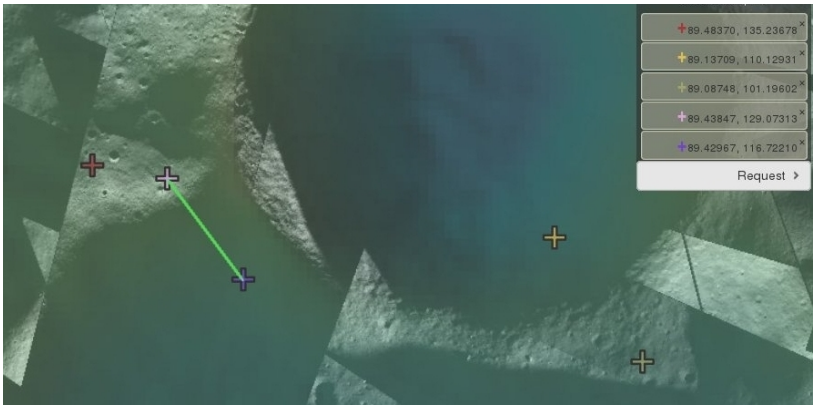


Figure 11.11: Route down into Peary Crater. The red cross marks the base location, the yellow and greenish point are the same as in Figure 11.10. The pink and the dark purple cross mark points of the route from the base into the Peary Crater. Following the green line, the SEVs have a route with a gradient less than 35 degrees. [75]

Adding more waypoints between the dark purple and the greenish point defines the complete route for the SEVs (see Figure 11.12). From the base to the Whipple Crater this route has a length of 23.29 km.

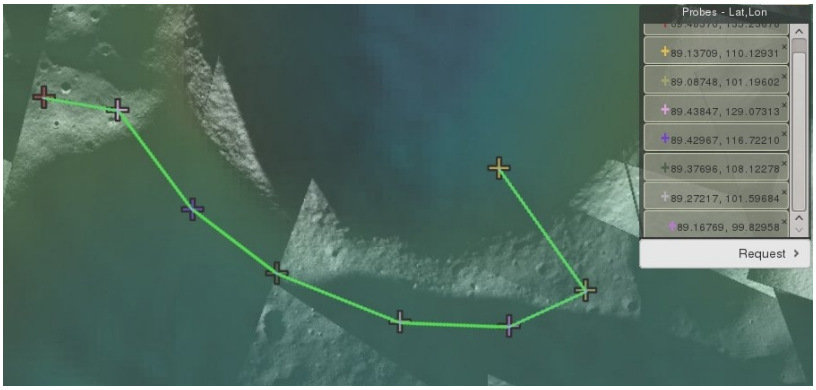


Figure 11.12: Path from Base to Water Mining Place. The green line shows the route the SEVs have to drive. [75]

11.5 *Oxygen on the Moon*

With the existence of water on the Moon the first major hurdle in establishing a lunar base is cleared. The second most important aspect is the production of oxygen for the inhabitants. As mentioned before, the Moon has no atmosphere and every gaseous element can escape from the Moon's surface. The upper surface layer is called *regolith* which describes "[...] the broken rock from impacts that seperates the Moon's bedrock from space [...]" [21]. The chemical elements regolith is mainly composed of can be seen in Table 11.1 [16].

Element	Percentage
Oxygen	40 %
Silicon	20 %
Iron	12 %
Calcium	8.5 %
Aluminium	7.3 %
Magnesium	4.8 %
Titanium	4.5 %
Sodium	0.33 %
Chromium	0.2 %
Remaining elements (Manganese, Potassium...)	2.9 %

Table 11.1: Identified lunar resources and their percentages of quantity on the Moon. [16]

Surprisingly, it consists almost halfway through of oxygen – in form

of metal oxides. These can be used to generate oxygen on the Moon which saves the cost of bringing it from the Earth. There are several ways of winning oxygen out of regolith and it is a subject of current research to find the most suitable and effective processes. For our lunar base, two processes were chosen as the favorites:

1. Hydrogen Reduction of Ilmenite
2. Carbothermal Reduction with Methane

11.6 Hydrogen Reduction of Ilmenite

Ilmenite is a type of rock composed of iron, titanium and oxygen and has the chemical formula $FeTiO_3$. The reaction with hydrogen will yield water which can be electrolysed and thus oxygen can be won:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$
$$2H_2O \rightarrow 2H_2 + O_2$$

One kilogram of ilmenite will yield up to 105 g of oxygen [76] – during the process a certain part of oxygen will certainly be lost. The conditions for this chemical process to take place are temperatures around 900 °C. The hydrogen can be won by electrolysing the water from the Moon thus no hydrogen has to be brought from the Earth. The hydrogen resulting from the last step of this oxygen winning process can be reused [21], [16].

11.7 Carbothermal Reduction with Methane

Another interesting method uses methane to extract the oxygen from the regolith. It is applicable to different types of metal oxides ($FeTiO_3$, $MgSiO_3$, $CaSiO_3$). The first step is the reaction of methane with the metal oxide:

$$MgSiO_3 + 2CH_4 \rightarrow MgO + Si + 4H_2 + 2CO$$
$$CaSiO_3 + 2CH_4 \rightarrow CaO + Si + 4H_2 + 2CO$$
$$FeTiO_3 + CH_4 \rightarrow Fe + TiO_3 + 2H_2 + CO$$

Then the resulting carbon monoxide is reacting with hydrogen which yields water that can be electrolysed.

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$
$$2H_2O \rightarrow 2H_2 + O_2$$

One kilogram of source material will yield up to 105 g ($FeTiO_3$), 319 g ($MgSiO_3$) or 275 g ($CaSiO_3$) of oxygen. The required temperature

for this process is around 1,600 °C. An advantage of this process is that the methane for the reaction does not have to be brought from the Earth since the Sabatier process from the life support system has methane as its end product [21], [104].

11.8 Drawbacks of Oxygen Extraction Processes

Unfortunately, both processes mentioned above share some problems which make them unusable for now:

- Since these extraction processes are still in their development phases, it is not easy to find detailed information about the required energy for the apparatuses. Assuming a feedstock of 50 %wt of ilmenite, 210,000 t of regolith have to be mined for each process to have enough ilmenite to produce 1,000 t of oxygen in one year. The energy needed for such a process would be around 3 MWy (hydrogen) to 3.5 MWy (carbothermal) in one year [104]. This is much more than the planned energy plant can produce.
- The apparatuses have to be tested in a low gravity environment similar to that on the Moon.
- Mining the regolith is not easy since it is predominantly consisting of very small particles and is comparable to dust. These fine grains should not find its way into the lunar base so the equipment for the processes must be outsourced.
- It is not known yet what type of regolith is found at the location of our lunar base – an exploration rover needs to determine the chemical composition of the rock nearby.

11.9 Oxygen Production for MOON BASE 2030

All the oxygen extraction processes have one thing in common: as a final step they use water electrolysis to extract oxygen. In order to supply our lunar base with the daily amount of necessary oxygen, it was chosen to use a part of the water extracted from the regolith to be electrolysed. Nevertheless, the base building has to be filled with an initial amount of oxygen. Per cubic meter, 1.42 kg of oxygen are needed. In total, the base has a usable volume of about 1,000 m^3 which results in 1,420 kg for one building complex. Generating such a huge amount of oxygen from water electrolysis would take too much time and require much energy. The energy system will only take up its work when the first astronauts arrive but at this point the base

should already be filled initially. Therefore the initial oxygen for filling the base will be brought from the Earth to the Moon. Calculations showed that it is best to bring the inital amount of oxygen for each new building complex from the Earth and only the daily amount will be generated in situ.

11.10 Helium-3

One major interest in going back to the Moon is the search for helium-3. It can be used as an energy generator by fusioning either two helium-3 atoms or one helium-3 and one Deuterium atom. The reaction produces low residual radioactivity which makes this fuel very clean. The Moon's regolith contains in total about one million ton of helium-3 which originates from solar flares and solar wind. Only exposed surfaces of regolith contain it and it is implanted in a few tens of nanometers. It was found out that ilmenite retains helium-3 better than other minerals [96]. So a high deposit of titanium points to a higher probability of finding helium-3. The highest titanium concentrations on the Moon are found around the equator region on the side facing the Earth [118]. Unfortunately, no helium-3 can be found at the lunar poles where our base is located which renders plans for mining it there redundant [21].

11.11 Water Consumption

To make a good calculation about the water consumption of the base, the different producers and consumers must be known. In case of the MOON BASE 2030, the only producer of water until the colonization phase is the MISWE Rover. The list of consumers comprises astronauts and greenhouses.

	Astronaut	Greenhouse
Inital Amount of Water (kg)	3.8	6.5
Daily Amount of Water (kg)	1.5	6.5
Inital Amount of Oxygen ($\frac{km}{m^3}$)	0.3	0.3
Daily Amount of Oxygen(kg)	0.3	–

Table 11.2: Water needed by astronauts (i.e. potable, hygiene) and greenhouses.

When one kilogram of water is electrolysed completely, 0.888 kg of oxygen can be won. Assuming that MISWE can extract two kilogram of water per hour, detailed calculations about how much water is won can be conducted. From Table 11.2 one can calculate the inital and daily consumption of water for the base. Table 11.3 shows the

calculations for the Preparation and the Supplied base phase.

Phase	p3	s
Begin of Mining Period	2027	2030
Numbers of MISWE Rovers	1	2
Rate ($\frac{kg}{h}$)	2	2
Working hours per day	12	12
Working days per week	5	6
Working weeks per year	50	50
Duration of phase (y)	3	5
Number of astronauts	0	4
Daily water consumption of base (kg)	0.00	32.00
Water consumption of base in phase (kg)	0.00	58,240
Water mined in phase (kg)	18,000	72,000
Water reservoir after phase (kg)	18,000	26,550

Table 11.3: Water consumption and calculations for Preparation and Supplied base phase.

At the beginning of the **Preparation** phase (**p3**) one MISWE is sent up and works for three years until the Supplied base phase begins. With a production rate of two kilograms per hour and a working time of twelve hours per day, five days per week and 50 weeks per year one MISWE Rover can extract 18,000 kg of water in three years. When the first astronauts arrive in the **Supplied base** phase (**s**), the water consumption begins and every day 32.00 kg of water need to be provided for the base. In order to not use the reservoir and with the idea of having it extended after this phase, a second MISWE Rover is brought to the Moon. In the Supplied base phase, 72,000 kg of water are extracted by the rovers whereas 58,240 kg are consumed. The water reservoir will comprise about 26,550 kg at the end of the Supplied base phase.

In the **Extended** phase (**x1**) the working time for the rovers barely changes. In order to keep the reservoir at a constant volume, the MISWEs have to work five to six days a week. The reservoir will comprise at least 24,319 kg at the beginning of the next phase. In the **Extended** phase (**x2**), eight astronauts and eight greenhouses have to be supplied with water. In Table 11.4 one can see that the base needs 64.00 kg of water per day in the Extended phase. Now, two additional MISWE rovers have to be brought to the Moon in order to provide enough water for the base. Calculations showed that the rovers will have to work six instead of five days a week such that more water is won than is used. With the adapted working time, the reservoir will be extended to 38,069 kg of water.

Twelve astronauts and twelve greenhouses have to be supplied in

Phase	x1	x2
Begin of Mining Period	2035	2037.5
Numbers of MISWE Rovers	2	4
Rate ($\frac{kg}{h}$)	2	2
Working hours per day	12	12
Working days per week	5	6
Working weeks per year	50	50
Duration of phase (y)	2.5	2.5
Number of astronauts	4	8
Daily water consumption of base (kg)	32.00	64.00
Water consumption of base in phase (kg)	29,120	58,240
Water mined in phase (kg)	30,000	72,000
Water reservoir after phase (kg)	24,319	38,069

Table 11.4: Water consumption and calculations for Extended and Operational phase.

the **Operational** phase. This results in 96.00 kg of water needed every day and after ten years, about 349,440 kg will be consumed. If the reservoir wants to be extended, a fifth rover has to be brought to the Moon while the working time is the same as in the previous phase (see Table 11.5). These calculations show that it is possible to use in-situ resources to supply the manned base with oxygen and water for at least 20 years.

Phase	o
Begin of Mining Period	2040
Numbers of MISWE Rovers	5
Rate ($\frac{kg}{h}$)	2
Working hours per day	12
Working days per week	6
Working weeks per year	50
Duration of phase (y)	10
Number of astronauts	12
Daily water consumption of base (kg)	96.00
Water consumption of base in phase (kg)	349,440
Water mined in phase (kg)	360,000
Water reservoir after phase (kg)	45,818

Table 11.5: Water consumption and calculations for Extended and Operational phase.

11.12 Production Problems or Failure

In case the water production experiences some problems (e.g. MISWE failure) it is useful to know the consequences and especially how long

the astronauts can survive without help from the Earth.

- If MISWE can not extract water in the Preparation phase at all, the mission will either have to be aborted or water has to be brought from the Earth which results in a very costly business.
- If MISWE has problems during the Preparation phase and can not fulfill the planned schedule, the water reservoir will turn out smaller. In the worst case, the MISWE rover can not solve the problem remotely and has to be fixed by an astronaut (in the Supplied base phase at the latest). Depending on how much water has already been extracted, new calculations will have to be made.
- During the Supplied base phase two MISWEs are working.
  - In case one of them fails or has a problem, there is still one rover left. In the worst case, only one rover has to supply the whole base. Then it is useful to increase the working time from six to seven days a week and from 12 to thirteen hours a day to be sure that the reservoir is not completely spent after this phase. The second MISWE should be repaired or replaced latest by the end of this phase.
  - If both MISWEs fail at the beginning of this phase, a reservoir of 18,000 kg can supply the base for about 560 days.
- Supposing that the planned schedule was achieved, about 26,500 kg of water reservoir are provided for the Extended phase x1.
  - If one MISWE fails, the base can be supplied with in-situ water until the end of this phase with only one MISWE working. The second MISWE should be repaired or replaced latest by the end of this phase.
  - In case both MISWEs fail at the beginning, the base can be supplied for about 820 days with the help of the reservoir.
- If no problems occur, the reservoir has a capacity of about 24,300 kg of water at the beginning of the Extended phase x2. Now four MISWEs are in operation.
  - If up to two MISWEs fail, the base can still be supplied with in-situ water until the end of the phase without changing the working time. But it is strongly recommended to repair the broken MISWEs.
  - If three MISWEs fail, the base can not be supplied with in-situ water until the end of this phase. It is necessary to fix them as soon as possible or to send new ones from the Earth.

  - If all MISWEs fail, the reservoir can supply the base for about 379 days.

- At the beginning of the Operational phase, the reservoir ideally comprises 38,000 kg.
  - In case one MISWE fails, the base can be supplied with in-situ water if the working time for the remaining four MISWEs is increases from twelve to fourteen hours a day.
  - In case two MISWEs fail, the working time needs to be increased from twelve to fifteen hours a day and from six to seven days a week in order to supply the base with in-situ water. It is strongly recommended to fix at least one of the broken MISWEs.
  - If more than two MISWEs fail, the base can not be supplied with in-situ water until the end of the phase. It is necessary to fix them as soon as possible or to send new ones from the Earth.
  - If all MISWEs fail, the base can be supplied with in-situ water for about 395 days.

11.13 Outlook

After the Operational phase, the water consumption will increase again and the number of MISWEs will have to be increased. The aformentioned microwave technology could be installed in the Whipple crater to extract the water deeper in the ground where MISWE's drill can not reach. After the Operational phase, 336,000 kg of water will be mined by the MISWEs. The Whipple Crater contains at least around 98,000 t, so there is enough left for many more years. Nevertheless other permanently shadowed craters near the base can be explored, like the Hermite A crater or subcraters of the Peary crater since these are thought to contain water ice, too [97].

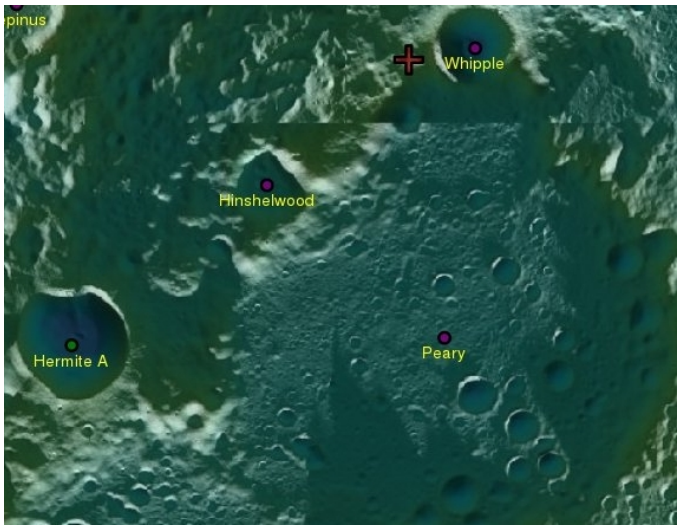


Figure 11.13: Map of the North Pole of the Moon. Red cross marks the location of the base compared to Peary and Whipple Crater. [75]

12
Surface Transport

by Florian Gillmann and Helge Lauterbach

12.1 Transportation Needs

The main task of the Surface Transportation System is, to carry different goods from one place of the lunar base to another area, as well as enabling mobility of the crew. The following list displays all jobs that have to be done, in accordance with all other work packages, and describes them in a short way:

Solar plants Help setting up the solar plants, replace panels if defective and bring crew members to the solar plants site for the purpose of maintenance.

Landing zone Transport all incoming cargo and new crew members from landing zone to the lunar base. Also plane the landing zone, with a radius of 100 m, prior using it the first time.

Water mining Water mining is done by MISWE rovers beginning in 2025, featured in the resources working package. The mined water is brought from the Whipple crater to the lunar base by the surface transportation.

Regolith mining For the shelter / radiation shielding of the lunar base, the surface transportation's assignment is to mine the regolith with a suitable device and carry the needed mass amount to the construction area on time. In total 3 module shelters have to be created.

Base construction A vehicle has to be provided, that is able to carry a 3D-printer, which sinters regolith and prints the base modules shelter with it.

Phase	Mass [t/year]
Preparation (p)	6
Supplied base (s)	14.4
Extension (x1)	12
Extension (x2)	28.8
Operational (o)	36

Table 12.1: Produced water per year

Module	Total mass [t]	Year finished
1	2046	2030
2	4092	2037
3	6138	2040

Table 12.2: Crew modules to be build

Excursions and exploration One of the first tasks, which has to be done by rovers, is exploration of the bases location, to discover a suitable area for the main bases buildings and to find or verify driveable paths towards the other base parts, e.g. solar plants and water mining area. For scientific reasons, near (range up to 20 km) and far (range up to 100 km) base explorations and excursions (see Section 2.4) of the lunar terrain and environment are done during different phases by crew members. Surface transport provides the necessary vehicles, extra-vehicular activity (EVA) suits and tools for these jobs.

Waste disposal Like on Earth, on the lunar base also different types of liquid and solid waste come up, that have to be recycled or disposed. Surface transportation has to deal with parts of this, in finding an acceptable solution to dispose all solid non-recyclable waste.

Workload analysis outlook As a short outlook to the workload analysis done in Section 12.6, suitable vehicles have to be able to carry in total 6138 t regolith in cargo containers, approximately 550 t water in water tanks and more than 800 t material from the lander to different locations over bases lifetime. Also depending on the crew growth over the phases, an increasing size of people have to be transported, and shielded from radiation and sun events during driving and excursions.

Therefore a flexible surface transportation system, capable of all tasks, is needed.

12.2 *Material-Transportation*

Requirements Based on the jobs targeting non-crew transportation, further research and different work packages inputs, the following requirements for material transportation originated.

- Transport: various material from landing zone to basis, solar panels to solar plant locations, empty water tank to water mining crater, filled water tank to basis, empty cargo box to regolith mining, filled cargo box to construction site.
- Driving: autonomously or remote controlled, manage slope up to 35 degrees, because it's the maximal slope on the way to water mining in Whipple crater (see Section 11.1)
- Payload: small capacity (2.5 t) needed for material transportation, medium capacity (15 t) needed for unload cargo from Lunar Lift

- Range: minimal range to be covered with a vehicle, based on its purpose, is generally twice the maximal range to be driven. Overall, the maximal distance to be driven is 200 km (see Section 2.4).

Material Transportation-Concepts During the research, the following possible concepts of material transportation emerged and were evaluated based on the requirements and some assumptions.

Magnetic Levitation Also known as MagLev, this mass driving method utilizes magnetic levitation to move and speed up objects along a kilometers long track. Depending on the underlying technology, the magnetic force is either applied only to let the object hover or also used to thrust the object forward. The technology can be used to transport people or objects at high speeds over long distances. On Earth, this technology is used for some high speed trains.(see [24])

Pro	Contra
• high velocity possible • known solution on Earth • high payload capacity • moderate maintenance effort	• complex, long, heavy structure • tracks too heavy to bring to Moon • inefficient for small workload • no flexibility in destination • high energy consumption

Railgun Basically a railgun also uses magnetic force to speed up objects, which are residing on a to be accelerated sledge above two parallel running rails, providing the necessary current to create wandering magnetic fields. It is much shorter than a MagLev track and is not intended for transportation of most living organisms, as the applied g-forces are too high. It could be used on the Moon to shoot cargo in a parabolic arc to a specific selected destination, or to overcome escape velocity and launch something into space. The possible payload mass varies depending on the size, length and energy consumption and is generally much lower than the one on a MagLev, ropeway or rover. (see [34])

Ropeway In principal, ropeways are capable of transporting large amounts of material. The simplest variant of a ropeway connects two locations by a single rope, called circulating monocable ropeway. In specific distances masts have to be built up to hold the cable. Electric engines on one or both ends of the ropeway providing the necessary force to drive the rope. Attached to the rope,

Pro	Contra
• destination adjustable prior launch	• quite new solution, mostly for military tasks on Earth • high energy storage capacitors needed

carriers hold the cargo. Depending on the dimensioning on the ropeway, a very large amount of material can easily be processed. Despite many advantages of a ropeway transport system as shown below, there is one crucial disadvantage. Assuming a ropeway from base down to Whipple crater with ten kilometer length, according to [61] the needed rope with a diameter of 30 mm and a specific weight of around 7.4 $\frac{\text{kg}}{\text{m}}$ would have a total mass of approximately 150 t. This is too heavy for just a rope, bringing it from Earth to the Moon.

Pro	Contra
• generally easy to construct • high payload capacity possible • more flexible to be re/build than MagLev • low maintenance effort • relatively independent from ground • relatively energy efficient • well known solution on Earth • can easily be automated	• rope too heavy • inefficient for small workload

Rover A rover is a vehicle created to move along and across unknown terrain on different astronomical bodies, like Mars or Moon, and conduct various scientific tasks with its attached tools. It can be remotely controlled from a place far away or work and function autonomously. Depending on the size and type, it is even able to even carry material, resources or astronaut crew members around. For rover comparison, the NASA Chariot rover was used, as it seems to be a promising concept.

Chosen Concept On the first look, the masses to be transported look quite enormous. But breaking the numbers down, like described in the workload section, the mass transportation per day isn't very high. In fact, it's too low to invest into building a ropeway or a MagLev, which would also just connect predefined, stationary locations and

Pro	Contra
• high mobility, flexibility • easy scaleable • small-medium payload capacity • low maintenance • comparable known solution on Earth • supposedly more efficient than MagLev or railgun	• limited range due to energy storage • relatively low speed • less efficient than ropeway

would have to be rebuild, e.g. if under certain conditions water or regolith mining site would have to be changed. Railguns seem quite interesting and could be a future option for some scenarios, e.g. if resources from or satellites build on the Moon need to be launched into space. So in the end the chosen concept is "Rover".

12.3 Crew-Transportation

Requirements The following requirements for crew transportation resulted after further research, based on the jobs targeting crew transportation form the first surface transportation Section, and different work packages inputs.

- Transport: crew size of two people from landing zone to basis and back, evacuate (fast) four people to landing zone, two people for maintenance to solar plants.
- Excursion: near base (up to 20 km), later far base (up to 100 km)
- Independence: excursion near base up to 48 h, far base up to 14 days (see Section 2.4)

Crew Transportation-Concepts The next possible concepts of crew transportation emerged during research and were evaluated based on the requirements and based on previous concepts for material transportation already chosen.

Ropeway As ropeways used for resource transportation have already been briefly described, it is of course possible, instead of attaching wagons, to utilize person cabins on the rope for crew transportation.

Rover For material transportation rovers have already been briefly reviewed and are the chosen concept for the lunar base. Adding a

Pro	Contra
• large amount of crew transportable	• inefficient for small workload • no excursion possible

pressurized cabin on the Chariot rover, in this setup named NASA MMSEV, makes it a possible device for crew transportation and manned exploration.

Pro	Contra
• additional radiation shielding • base independent crew housing • additional lifesupport • usable for exploration	• relatively low speed • limited range

Chosen Concept Connecting different parts of the lunar base with ropeways, if the rope could be created on site, would be a possible option for crew transport, especially if ropeways would also be used for material transportation. But, as different explorations on the Moon shall be conducted, a concept enabling high mobility in unknown terrain is mandatory. Ropeways aren't suitable for that task. So the remaining concept is Rover, which is a good fit, as the previous chosen concept for material transportation is also "Rover".

12.4 Entire Concept

For each phase of the mission (see Chapter 3), different types and quantities of rovers are needed. They are listed the subsequently paragraphs and described in Section 12.5 in more detail.

Phase p Two rovers are necessary for material transport. They mainly transport regolith for base construction and water from Whipple crater to base.

For unloading incoming landers one special rover is needed, as well as one rover for carrying a 3D-Printer for base construction as mentioned in Section 5.

As the the power generation system has still to be setup, the rovers batteries are charged by two mobile solar panels, which provide 5 kW of power each. They are positioned at the later position of the solar plant because the illumination is expected to be higher there than

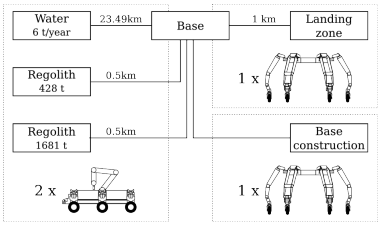


Figure 12.1: Surface transportation concept in phase p

at the base location (see Section 13.4). Assuming an effective solar constant of 0.41 $\frac{kW}{m^2}$, each solar panel has an area of 12.2 m^2.

Phase s In Addition to the rovers from phase p, two pressurized MMSEV rovers serve as crew transportation vehicle.

Phase x and o In phase x, the rover pool is enlarged by two unpressurized rovers, as soon as the crew is extended. Additionally one portable utility pallet for each pressurized rover extend their range. Therefore long range excursions with pressurized rover over several days are possible.

Phase o differs from phase x in that way, that base construction is finished and the printing rover is not needed anymore.

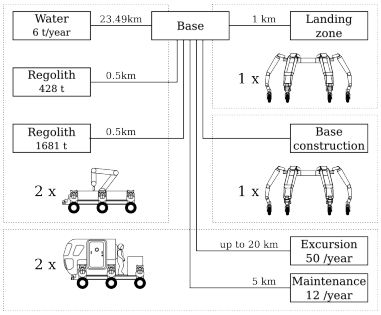


Figure 12.2: Surface transportation concept in phase s

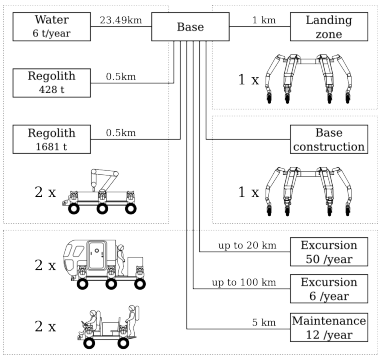


Figure 12.3: Surface transportation concept in phase x and o

12.5 Rover & Tools Specification

Rover for Material-Transportation The chosen rovers are based on the NASA Chariot, which is more specific the NASA MMSEV's chassis without pressure cabin.

Chariot is the base for all rovers, except ATHLETE rover, why most technical specifications are the same for the other rover types explained later in this Section. For remote or autonomous driving trough the lunar terrain or interacting with certain objects, all rovers shall provide stereo cameras and LIDAR sensors. For sending a live video feed of one rover stereo camera to the lunar base or to Earth, including an up- and downlink for remote operations respectively telecommands and voice communication, a bandwidth of 4 Mbit is estimated (see Section 10.3). To reduce bandwidth usage, generally only one stereo camera video feed per rover is transmitted.

Chariot has twelve wheels, grouped to pairs of two. Each group is able to pivot of 360°, allowing to drive in any direction [72] and providing a turning radius of zero. They are driven by an 15 kW electrical engine. [55]

Because it was very difficult to get valid information about the MMSEV's energy storage system, some assumptions were made for this report. According to an early concept of NASA [33], the battery has a capacity of 20 kW h to provide a maximum range of 100 km in lunar gravity, whereas in existing chariot prototype batteries provide only a capacity of 17.28 kW h [55]. In later facts sheets [72], [71], LER and SEV provide a maximum range of 200 km, which either means that battery has a higher capacity or the average energy consumption is much lower. For this report, the battery was chosen to provide 20 kW h of energy. Furthermore the average energy consumption was

MMSEV stands for Multi Mission Space Exploration Vehicle. As part of NASA's canceled constellation program, it was also called LER (Lunar Electrical Rover), SEV (Space Exploration Vehicle) or small pressurized Rover before

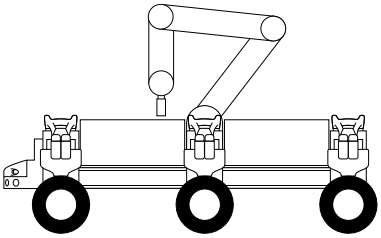


Figure 12.4: Chariot with attached robot arm and loaded cargo boxes

estimated by 0.2 $\frac{\text{kW h}}{\text{km}}$ and the maximum range was reduced from 200 km [71] down to 100 km. By using lithium ion batteries, which fulfill NASA's requirement for a specific energy density of 0.2 $\frac{\text{kW h}}{\text{kg}}$, they have a total weight of 100 kg. They are not available yet, but under development. (see [73])

Table 12.3 shows further rover details, based on [71] and [72].

Attribute	Transport material
Setup	Chariot chassis
Dimensions	4.5 x 4 x 1.3 m
Weight	1 t
Payload	3 t
Energy	20 kW h
Range	100 km
Speed	10 $\frac{\text{km}}{\text{h}}$
Crew	0 to 1

Table 12.3: Chariot data [72][71]

Additional rover tools In addition to NASA's design of Chariot, a proposition to extend the rover by the following different additional tools was made.

Robotic arm It is attached like shown in Figure 12.4. It is used for loading up cargo, like water tanks and cargo boxes. Therefore it shall have a maximum payload of 1.5 t in lunar gravity. Its proposed dimensions are shown in Figure 12.5, but a separate workspace analysis is required to proof its functionality. For transport it should be able to fold the robot arm in such way between Chariots wheels, that Chariots volume is not extended. The mass of the robot arm was estimated to 0.5 t, but has to be proved. Moreover, the robot arm shall have a connector, which serves to pick up cargo like water tanks and cargo boxes or to attach tools like a shovel. Secondly the connector and the arm itself should have the ability to be used autonomous or tele-operated and to be compatible to ATHLETE.

As the robot arm is attached to the rover permanently, the effective maximum payload of material transportation rovers is reduced to 2.5 t.

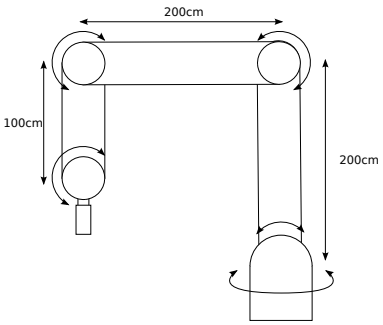


Figure 12.5: Dimensions of proposed robot arm

Bulldozer blade A bulldozer blade is used to plane different areas, like the landing zone, and is attachable in front of the rover.

Shovel A shovel can be attached to the robot arm, for example enabling it to dig into the regolith and to fill it into cargo boxes next to the rover, or into already loaded ones.

Water tank One water tank has the capacity of 1.25 t, and is filled during the water mining process by a MISWE rover (see Section **??**). When it's full, it is transported from the Whipple crater with a Chariot rover to the base. Because of economical reasons and because of this rover's maximum payload, water transportation is only done, when two water tanks are completely filled. The water tanks are equal to these, proposed in Chapter 11.

Cargo box One cargo box, in dimensions of 1.5 m x 1.5 m x 0.7 m, is capable of containing 1.25 t regolith with a density of 1.5 $\frac{\text{g}}{\text{cm}^3}$. Two

of these boxes are used for transporting mined regolith to the construction area, they are filled with Chariot's robot arm and an attached shovel.

ATHLETE rover for heavy lifting Athlete stands for All-Terrain, Hex Limbed, Extra-Terrestrial Explorer. (see [69])

> [It is] a new approach to unloading, transporting and handling cargo on the Moon. It has six limbs, each with a wheel and a quick-disconnect tool adapter next to it for the use of various tools. The limbs can also be used as arms for complex manipulations. The wheels are relatively small, providing power-efficient rolling mobility over most lunar terrain. When traversing deep soil, steep grades or other navigation impediments, the wheels lock and are used as feet while the limbs walk over the more difficult terrain. [69]

ATHLETE has the ability to separate itself into two Tri-ATHLETE [57], so heavy cargo can be lifted by docking from two sides. Each wheel of ATHLETE is equipped with a 1.4 kW electrical motor and each joint of the limbs uses a 0.12 kW brushless dc motor. [111] By NASA, the battery's capacity was specified to 6.5 kW h and the maximum range to 5 km with maximum payload [33]. Although ATHLETE's main task is to unload cargo, wherefore 5 km maximum range might be enough, ATHLETE was proposed to have an 13 kW h battery for a maximum range of 10 km with maximal payload and a 60 km range with 2.5 t payload within this report.

Table 12.4 summarizes some important technical information of ATHLETE.

Although ATHLETE might also be useful for other tasks, it is primarily required to unload cargo from incoming lander. ATHLETE was designed to be compatible with NASA Altair lander. As Lunar Lift (see Section **??**) was derived from NASA Altair lander, NASA ATHLETE should be compatible with Lunar Lift too. Due to the possibility to use one or two limbs as arms, while standing on four limbs, one of two ATHLETE helps continuously on base construction by carrying a 3D-Printer, which uses regolith to do its print jobs (see Section 5.6).

Pressurized-Rover for Crew-Transportation Rovers with pressurized cabins have the advantage of extended mission duration due to the independence of EVA suits. The chosen pressurized Rover is based on the NASA MMSEV. The chassis of the MMSEV is identical to the Chariot rover, which was described before.

It has an pressurized cabin attached to the chassis. This cabin allows crew members to travel without their EVA suit. It can hold

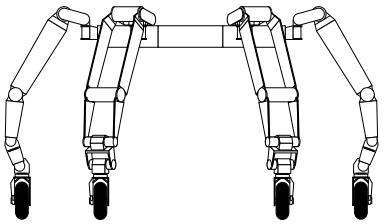


Figure 12.6: Sideview of NASA ATHLETE

Attribute	unload Lunar Lift
Height	1.1 m up to 6.4 m
Length	8.4 m
Weight	2.3 t
Max reach	15.5 m
Payload	14.5 t
Energy	13 kW h
Speed	5 $\frac{km}{h}$

Table 12.4: ATHLETE data [69]

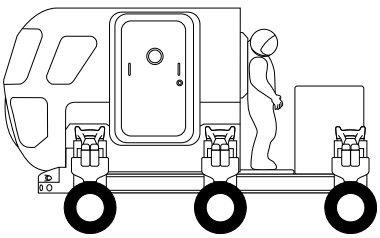


Figure 12.7: Pressurized Rover based on MMSEV



a crew of two in normal case. In case of an emergency it also can support a crew of four. (see [72])

In contrast to unpressurized rovers, NASA MMSEV provides radiation protection up to 72 h against solar particle events by a 2.5 cm water ice shield, which is also used as fusible heat sink. (see [72])

On the backside of the cabin are two so called suit ports. Crew Members can get into their suits and start an EVA without the need of an airlock. This reduces preparing time for EVAs to approximately ten minutes.

Moreover, one rover can dock to the base or another Rover. Thus, crew members can easily get into the rover without the need of an EVA suit and with a minimum loss of atmosphere.

Attribute	Transport crew
Setup	Pressure cabin
Dimensions	4.5 x 4 x 1.3 m
Weight	3 t
Payload	1 t
Energy	20 kW h
Range	100 km
Speed	10 $\frac{km}{h}$
Crew	2 to 4

Table 12.5: MMSEV data [72]

Portable utility pallet (PUP) To extend the independence of the MMSEV from base, a portable utility pallet (PUP) can be a part of the rovers payload. This device contains additional water, oxygen and waste water capabilities and increases the life support from three days for two crew members up to 14 days. Also a solar array providing roughly 4.5 kW and an additional 10 kW h battery are included. With the help of the last two objects, the rovers range increases up to 200 km. The PUP's dry mass was previously estimated to 300 kg, whereas 100 kg come from the battery's mass and the rest from the solar array and the PUP's structure. Recently older literature [33] was discovered, describing the PUP to be quite more heavy than expected, with a dry mass of approximately 700 kg.

Extra vehicular activity (EVA) suit A suitable EVA suit has to be developed for lunar environment and gravity. They have to be durable but must have low mass. Moreover sufficient mobility and flexibility for crew members must be provided to ensure maximum flexibility. (see [91]) They have to feature an adequate pressure, making oxygen prebreathing needless. Thus the risk of decompression sickness, which could occur when astronauts switch between different atmospheres, is eliminated. [91]

Candidates for this are the NASA Mark III from 1990's or the NASA Constellation Space Suit in Configuration Two, which both are compatible to the MMSEVs suitports. Unfortunately the development of Constellation Spacesuit was stopped with the end of the Constellation program. [62]

> The Mark III rear entry hatch space suit is a technology demonstrator. It was originally designed as a zero-pre-breath suit [..]. The suit weighs approximately 120 lbs [54.4 kg] and has an operating pressure range

up to 8.3 psi. The hard upper torso (HUT) may be constructed of cast aluminum, heavy composite material, or lightweight composite [20]

Unpressurized Rover for Crew-Transportation Based on the original Chariot chassis, a lighter, smaller and faster rover was designed, for providing crew mobility if both pressurized rovers are not available, because they are outside the base for long range excursions. This small rover is unpressurized, wherefore crew members have to use EVA suits.

The Chassis length was reduced to around two third of the original length of Chariot and one axis was removed. In normal case this rover holds a crew of two. The drivers seat is located between the front wheels. Behind it a second seat is placed and next to it a box for payload. Two additional crew members can stand side by side on a backwards attached platform. The facts on table 12.6 were estimated.

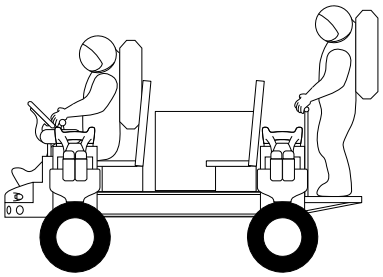


Figure 12.8: Unpressurized rover side-view

Attribute	Transport crew
Setup	Small Rover
Dimensions	3.3 x 4 x 1.3 m
Weight	0.7 t
Payload	1.5 t
Energy	25 kW h
Range	50 km
Speed	35 $\frac{km}{h}$
Crew	1 to 4 in EVA suits

Table 12.6: Small rover data

12.6 Analysis of rover workload

This section shows the workload of the rovers in more detail. To calculate the average workload of the rover the following methods were used:

It is assumed, that all trips were done by traveling with half speed, namely 5 $\frac{km}{h}$ if not explicitly mentioned otherwise. Moreover an average energy consumption of 0.2 $\frac{kW\,h}{km}$ is used, like already mentioned in Section 12.5. With this, the consumed energy from the total driven distance was calculated. The yearly average charging duty was derived by adding the time needed to charge batteries with the estimated consumed energy per trip and 5 kW power. The total charging time averaged over one year leaded to the average charging duty. By estimating the time needed to fulfill one task, charging time inclusive, and adding up all tasks, the yearly average workload for one rover was calculated.

Regolith The main base consists of three modules. For the shelter, 2046 t of regolith are required per module, whereas 428 t of regolith is sintered and 1618 t is bulked across the sintered shelter (see Section 5.6). Hence, 6138 t of regolith have to be mined and brought to the construction area by rovers in total.

The needed mass of regolith for each module corresponds to a volume of approximately 1400 m^3 of bulked regolith. Therefore an area of approximately 55 m times 55 m has to be excavated to a depth of half a meter per module.

year	mass [t]	workload
p3	428	0.86 %
p4	1618	3.25 %
s1	428	0.86 %
s2	1618	3.25 %
x1	428	0.86 %
x2	1618	3.25 %

Table 12.7: Regolith transportation for base construction

The excavation is done by a shovel attached to the rovers robotic arm. The regolith is transported in two cargo boxes with a payload capacity of 1.25 t each. Due to the rovers maximum payload capacity, one rover has to travel about 820 times between the digging place and the construction area, to transport the needed regolith for one module.

To estimate the workload, it is assumed that the digging place is located within a distance of maximal 500 m to the main base area. The duration of one trip is estimated by 0.4 hours, due to traveling time and the time to dig 2.5 t of regolith. Working twelve hours a day, one rover has to work six days to transport 428 t of regolith for the sintered shelter of one module. This leads to a workload of 55 % on working days, time to charge inclusive, and an average workload of 0.86 % per year for one rover. Working in the same way, one rover needs to work 22 days to bulk up the remaining 1618 t of regolith as soon as the sintering of one modules shelter is finished. This leads to an average workload of 3.25 % per year.

The first module has to be finished in 2030, before the first crew arrives. For the construction of one building, a duration of five years as estimated. Therefore one rover starts to mine 428 t of regolith in the end of 2024. The rest is mined in 2029. Regolith for both other modules is mined in 2030 and 2035 and accordingly in 2035 and 2039 in the same way as the first module.

Batteries for Printing Rover Since in sub phase p4 the main power supply is not yet available, the required power for base construction has to be generated in a different way. As already mentioned in Section 5.6, this is done by transporting batteries with mass of one metric tonne between one solar panel and construction area. Over five years construction time for the first module, 605 trips are necessary, which leads to 121 trips per year. Each trip was estimated to take two hours due to a distance of 5 km between base and solar array. Therefore an average workload of 3.32 % results.

Water As mentioned in Section 11.1 water is produced in the Whipple crater, beginning three years before the first crew arrives. According to Section **??** the path from lunar base to MISWE has a length of 23.29 km. So one trip contributes 0.13 % to the average yearly workload and 0.02 % to the average charging duty.

In Phase p, 18 t water is produced, respectively 6 t per year, which have to be transported to the main base (see Table 12.8). This is done by one rover, whenever two water tanks with a capacity of 1.25 t each were filled up by MISWE. Three trips have to be done during phase p

phase	water [$t/year$]	trips /year	workload /year
p4	6	3	0.4 %
s	14.4	6	0.80 %
x1	12	5	0.67 %
x2	28.8	12	1.60 %
o	36	15	2.00 %

Table 12.8: Transport of water

per year. This leads to an average working load of 0.4 % per year.

In phase s, two MISWE work, so that 14.4 t water have to be transported per year which leads to six trips per year and an average workload of 0.80 % per year for one rover.

In phase x1, 12 t water lead to five trips per year and an average workload of 0.67 % per year for one rover, while in phase x2, 28.8 t water from 4 MISWE lead to twelve trips per year and an average workload of 1.60 %. During phase o, five MISWE produce 36 t water which implies 15 trips and an average workload of 2.00 % per year for one rover.

Waste Disposal As mentioned in Section 12.7, the total mass of waste is estimated to five percent of the total mass brought to the Moon. This leads to 40 t solid waste in total, assuming approximately 800 t of material brought from Earth. As the waste disposal begins in phase s, 2 t of solid waste per year have to be transported on average. So with respect to to the rovers maximum payload capacity of 2.5 t, one trip is necessary per year. The waste is brought to a crater approximately 10 km away of the main base area. Therefore one trips duration is estimated to 4 h. This leads to an average workload of 0.06 % per year.

Prepare Landing Zone The landing zone is an area with radius 100 m. It has once to be planed in phase p. To estimate the time needed to plane this area a square with a side of 200 m was assumed. To plane it, a rover moves across this area in stripes with the bulldozers width (see Section 12.5). Further assumptions are, that the area has to be planed twice and a half, to over estimate the effort to deal with unforeseen eventualities. The entire driven distance including the path from and to the base was estimated to 30 km which leads to twelve working hours.

Unload Cargo from Lunar Lift This task is done by one ATHLETE rover. Time needed to unload cargo from Lunar Lift and transporting it to the main base is estimated to two hours. In case of trips to the solar plant 3.6 h are assumed, due to the longer distance. Within this workload analysis, it is not distinguished between different payloads, because for each flight of Lunar Lift, there is one trip necessary. To estimate the workload for ATHLETE, all flights of Lunar Lift (see Section 8.4) were counted with respect to phase and destination and averaged for each phase. An overview of the resulting workload for ATHLETE is shown in Table 12.10.

Printing the base The second ATHLETE carries the 3D printer as already mentioned in Section 12.4. With respect to the general assumption, if one entity has a workload of 80 % then a second entity is needed, the printing ATHLETE is granted an average workload of 50 %, without the time for driving or charging, for a duration of 15 years until the base construction is finished.

Entire Workload Material Transport Merging the workload of all jobs together results to an average workload with respect to the rover type as shown in Table 12.9 and Figure 12.9 for Chariot, Table 12.10 for ATHLETE.

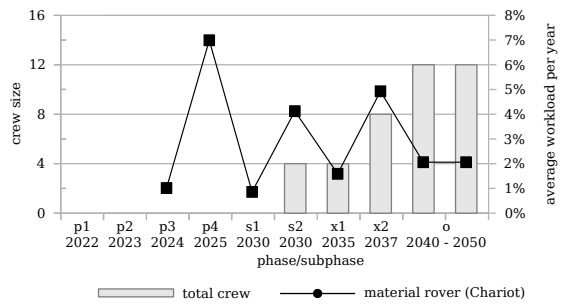


Figure 12.9: Overview of material rovers average workload

With the results of this workload analysis, the concept for material transportation can be validated. Firstly, the yearly average workload is not higher than 7 %. Without battery and regolith transportation, which are the reason for the peeks in Figure 12.9, the workload is less than 2.5 %. Secondly, all jobs are not time critical, despite transporting the batteries in phase p4. So one Chariot might be enough to do all jobs. However, it is better to provide two Chariot rover for redundancy issues. Due to the high workload of 50 % for the printing ATHLETE, as well as its attached 3D printer, there might be no possibility for unloading cargo, although its required effort is low. So the second ATHLETE is necessary anyway.

Crew arrival Although the landing zone is less than one kilometer away from the base and new crew members could easily walk, they are picked up by rovers. Since the distance to the base is low, one rover trip takes less than half an hour. As already mentioned in Section 3 four crew members stay six months in the base in phases s and x1. Therefore crew changes twice a year, so two rover trips are necessary. In phase x2 the crew is extended to eight people, so that four crew changes and four trips arise. Also in phase o four crew changes take place, although the crew strength is twelve in that phase.

Task	mass [t/year]	trips /year	distance [km]	Chargingduty /year	workload /year
Phase p3					
Regolith	428	172	1	0.08 %	0.86 %
Landingzone Prep.	0	1	30	0.01 %	0.16 %
Total/year	428	1	202	0.09 %	1.02 %
Phase p4					
Water	6	3	46.58	0.06 %	0.40 %
Regolith	1618	648	1	0.30 %	3.25 %
Batteries	121	121	10	0.55 %	3.32 %
Total/year	1745	772	1997.75	0.91 %	6.97 %
Phase s1 (2 weeks)					
Regolith	428	172	1	0.08 %	0.86 %
Total/year	428	172	1	0.08 %	0.86 %
Phase s2					
Water	14.4	6	46.58	0.13 %	0.80 %
Regolith	1618	648	1	0.30 %	3.25 %
Waste	2	1	20	0.01 %	0.06 %
Total/year	1634.4	655	947.48	0.43 %	4.12 %
Phase x1					
Water	12	5	46.58	0.11 %	0.67 %
Regolith	428	172	1	0.08 %	0.86 %
Waste	2	1	20	0.01 %	0.06 %
Total/year	442	178	424.9	0.19 %	1.59 %
Phase x2					
Water	28.8	12	46.58	0.26 %	1.6 %
Regolith	1681	648	1	0.30 %	3.25 %
Waste	2	1	20	0.01 %	0.06 %
Total/year	1648.8	661	1226.96	0.56 %	4.92 %
Phase o					
Water	36	15	46.58	0.32 %	2.00 %
Waste	2	1	20	0.01 %	0.06 %
Total/year	38	16	718.7	0.33 %	2.06 %

Table 12.9: Workload analysis for material transportation rovers

Table 12.10: Workload analysis for unloading cargo from Lunar Lift by ATHLETE

destination	trips /phase	Distance [km]	chargingduty /day	workload /day	chargingduty /year	workload /year
phase p2 (1 year)						
base	1	2	2.2 %	10.5 %	0.006 %	0.029 %
total	1	2			0.006 %	0.029 %
phase p4 (5 years)						
base	1	2	2.2 %	10.5 %	0.001 %	0.006 %
solar plant	2	10	10.8 %	25.8 %	0.012 %	0.028 %
total	3	22			0.013 %	0.034 %
phase s1 (2 weeks)						
base	6	2	2.2 %	10.5 %	0.929 %	4.500 %
solar plant	1	10	10.8 %	25.8 %	0.774 %	1.845 %
total	7	22			1.702 %	6.345 %
phase s2 (5 years)						
base	31	2	2.2 %	10.5 %	0.037 %	0.178 %
total	31	62			0.037 %	0.178 %
phase x1 (2.5 years)						
base	19	2	2.2 %	10.5 %	0.045 %	0.219 %
total	19	38			0.045 %	0.219 %
phase x2 (2.5 years)						
base	22	2	2.2 %	10.5 %	0.052 %	0.253 %
solar plant	1	10	10.8 %	25.8 %	0.012 %	0.028 %
total	23	54			0.064 %	0.281 %
phase 0 (10 years)						
base	62	2	2.2 %	10.5 %	0.037 %	0.178 %
total	62	124			0.037 %	0.178 %

This is because crew members stay one year on Moon (see Section 3.4). Table 12.11 shows the resulting average workload per year with respect to the mission phase.

Phase	Trips /year	average workload /year
s, x1	2	0.01 %
x2	4	0.01 %
o	4	0.01 %

Table 12.11: Workload crew arrival

Maintenance of solar plants The Solar plant should be maintained by crew members once a month (see Section 9.4). Maintenance tasks start in phase s. The resulting workload is identical for all phases since phase s. One maintenance job is done by two crew members using one pressurized rover for driving to the plant and using EVA suits for working on the solar panels. EVA suits can be used at most six hours, for which reason the duration of one maintenance job is restricted to six hours plus traveling time. Table 12.12 shows the yearly effort of solar plant maintenance. Assuming, that twelve trips are done per year, maintaining solar plant contributes 1.01 % to the average yearly workload and 0.05 % to the average charging duty.

distance one way	5 km
duration	7 h
chargingduty	0.05 %
workload (12 trips/year)	1.08 %

Table 12.12: Workload for solar plant maintenance

Human exploration As already mentioned, it has to be distinguished between near base and far base crewed exploration and excursions.

Short range excursions is done beginning in Phase s, as early as the first crew arrives. As already mentioned in Section 2.4 up to one near base excursion per week is conducted in all crewed phases. One of these excursions was estimated to take at most six hours. Therefore a maximum total distance of 60 km can be covered within a range of 20 km towards the base. One trip contributes 0.1 % to the average workload and 0.03 % to the average charging duty. Added up, 50 short range excursions contributes 4.79 % to the average workload and 1.37 % to the average charging duty.

Additionally, long range exploration is possible as soon as the crew size is extended in phase x2. With regard to the constraint from Section 2.4, six long range excursions are performed in phase x2 and o per year. Each excursion takes 14 days which is equal to 336 h with two pressurized rovers and a crew of four. The PUPs are be used. The total driven distance was assumed to be 200 km within a range of 100 km from the base, although it can be much higher, due to the possibility of recharging batteries during excursion with PUPs solar panel. Each of both rover has to be charged with 30 kW h (battery and PUP). Thus an average workload of 23.22 % and an average charging duty of 0.41 % results per rover.

Entire Workload Crew Transport Merging the workload of crew transportation results to an average workload as shown in Table 12.13 and Figure 12.10 for one rover. For redundancy issues two pressurized rovers are necessary during phase s and x1. Due to the far base

excursions in phase x2 and o, the secondary pressurized rover has a workload of 23.22 %. To provide mobility during far base excursions for those crew members which remain in the base, both additional unpressurized rovers are needed, although their workload is very small.

Table 12.13: Workload analysis for crew transportation

task	trips /year	crew	rover	driven distance [km]	duration [h]	Chargingduty /year	workload /year
Phase s and x1							
Crewchange	2	4	1	2	0.2	0.002 %	0.01 %
Exkursion	50	2	1	60	6	1.37 %	4.79 %
Maintenance	12	2	1	10	7	0.05 %	1.01 %
Total/year	64			3124	384.4	1.43 %	5.81 %
Phase x2 and o							
Crewchange	4	4	1	2	0.2	0.002 %	0.01 %
Exkursion (near)	50	2	1	60	6	1.37 %	4.79 %
Excursion (far)	6	4	2	200	336	0.41 %	23.22 %
Maintenance	12	2	1	10	7	0.05 %	1.01 %
Total/year	72			5528	4416.8	1.84 %	29.03 %

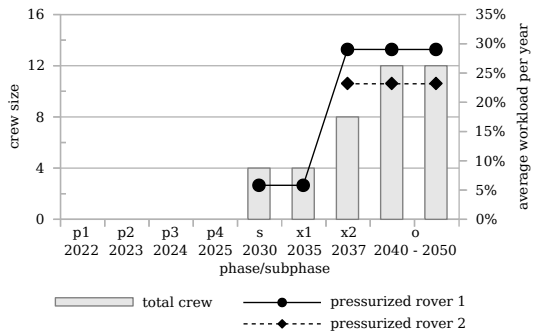


Figure 12.10: Overview of crew rovers average workload

12.7 *Waste disposal*

Generally, when speaking of waste management, it has initially to be distinguished between two different types of waste. There is recyclable, mostly biologic waste, which can be solid like e.g. unusable parts of crops, or fluid like e.g. waste water. Non-recyclable fluid or solid waste would be the second type. It should nearly always be possible to transform the fluid form into a solid state for easier handling. In accordance with the other work packages, the surface

transportation work package deals only with non-recyclable solid waste.

Existing Concepts The next concepts for the disposal of non-recyclable solid waste were brought up during the research and were evaluated based on the requirements and additionally needed resources.

Burn Burn all non-recyclable solid waste to ashes in a special reactor / incinerator building, with high temperature and under the use of oxygen.

Pro	Contra
• reduces waste volume drastically • known solution on Earth	• needs special reactor building to burn waste • needs oxygen to support the burn process • maybe needs device to compact remaining waste • needs place to store the remaining ashes • needs transportation to storage place

Bury Bury all waste of the mentioned type in a near base crater, using it as landfill, like it its done on Earth.

Pro	Contra
• no reactor building needed • no further reduction of waste volume • no additional oxygen needed • known solution on Earth	• maybe needs device to compact waste • needs bigger place to store the waste than "burn" • needs transportation to storage place

Blast Blast / shoot the prior packaged waste away from Moon into space, for example into the direction of the Sun, with the help of technical solutions.

Chosen Concept After comparing all advantages and disadvantages, the chosen concept is the one previously named "bury". No additional buildings or technical solutions are required and no resources are wasted. For this concept a material rover regularly carries the waste to a crater next to the base and dump it in. A suitable crater, or

Pro	Contra
• no reactor building needed • no additional oxygen needed • no place to store waste needed	• not a known / common solution on Earth • device to compact the waste is needed • waste needs to be packaged accordingly to technical solution used • technical solution like MagLev / Railgun needed, to speed up packages over escape velocity

depending on the size more craters, will have to be found during the autonomous exploration of the rovers during phase p.

12.8 Further work

The needed power for rover recharging was highly overestimated. As Table 9.1 in Chapter 9 shows, the previous assumed charging duty of the rovers for material transportation and the pressurized crew rovers was 13 %. The workload analysis results in an average charging duty of 0.23 % up to 0.4 % for material transportation rover and 1.43 % up to 1.84 % for pressurized crew rover. The overestimation has several reasons:

- the rovers workload was much lower than previously estimated and therefore the rovers charging duty as well.
- the rovers battery and their average energy consumption turned out to be much lower than assumed.

Since both reasons turned out very late, recalculation and resimulation of the bases total power demand (see Chapter 9) was not possible anymore before report's deadline.

Batteries as energy storage do have some disadvantages. Their energy density is low for which reason their mass has to be big if an adequate capacity is needed. Even though new technology like lithium ion batteries got rid of the memory effect, their charging cycles are restricted. Alternatively, fuel cell could be used to produce electric power for the rovers.

The additional proposed tools for the Chariot rovers (12.5) need more research. Especially the robot arm has to be designed in more detail, as well as the proposed connector, which shall enable autonomous and tele-operated work with cargo and tools.

The mission scenario for MOON BASE 2030 also provides a phase colonization, which was not further evaluated within this report. Although the workload for rovers is low and the proposed transportation concept can easily be scaled, other concepts might be more efficient, if crew and base grow big. Instead of transporting water with rovers from Whipple crater to the base, a ropeway, using the direct path down to Whipple crater, could be a proper alternative.



13 Simulation

by Tobias Wenzel

A system like a moon base model is very complex and time-dependent. Simulation of such systems is essential because of the high dependency of different, time-dependent parameters. The simulation is one of the few views on the whole system and the interaction of different subsystems. Simulation supports the dimension of values and in serious cases it can save life.

The simulation concept is roughly based on ideas from a dissertation [41]. Further investigation in simulation is needed due to time constraints.

13.1 Simulation Tools

From some of the examined tools, libraries and frameworks, following are used in this simulation approach.

- **Python** version 2.7 is used for implementing the simulation core [1]
- **matplotlib** used for plotting of diagrams and images [2]
- **pint** handles physical quantities [3]
- **Python Imaging Library (PIL)** provides image processing capabilities [4]
- **NumPy** is a array-processing package designed to efficiently manipulate large multi-dimensional arrays of arbitrary records [5]
- **SciPy** provides user-friendly and efficient numerical routines such as routines for numerical integration and optimization [6]
- **OWSLib** is a Python package for client programming with Open Geospatial Consortium (OGC) web service (hence OWS) interface standards [7]
- **pyproj** performs cartographic transformations and geodetic computations [8]

[1] http://www.python.org/

[2] http://matplotlib.org/

[3] https://pypi.python.org/pypi/Pint/

[4] http://www.pythonware.com/products/pil/

[5] http://www.numpy.org/

[6] http://www.scipy.org/

[7] http://geopython.github.io/OWSLib/

[8] https://pypi.python.org/pypi/pyproj

13.2 Simulation Model

A system model defines a relationship of the different subsystems and work packages respectively. The model can be used by a simulation approach.

In the first step a rough view on the lunar base system is derived Figure 13.1 on page 186. The most important information is the (time-dependent) flow of resources and masses respectively $\dot{m}(t)$. In this model resources are water, energy, food, atmosphere (oxygen, nitrogen and carbon dioxide), waste, communication data, resupply, spares, crew etc. Resources are represented in the graph as directed edge labels.

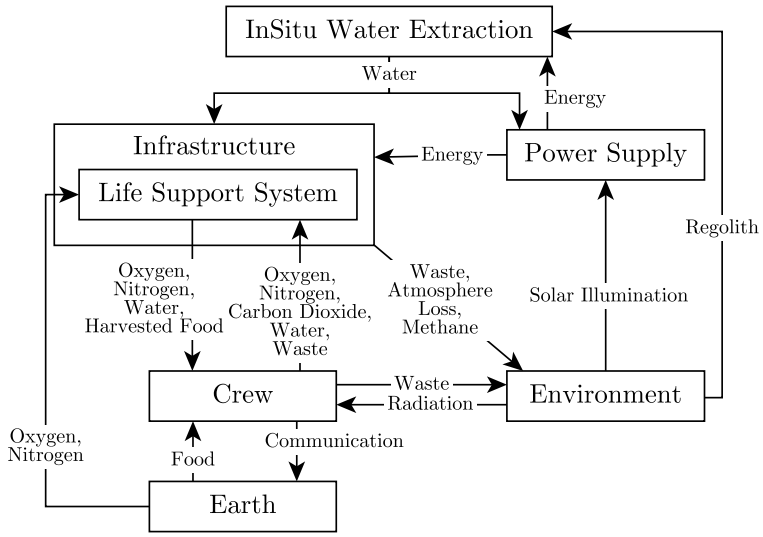


Figure 13.1: Simulation model overview

Some resources are not covered by this simulation. For lack of time and imprecise data, resources like thermal, waste, communication and food are not considered. These resources are only roughly covered in each subsystem.

The Logistic Scenario in Section 8 covers the resources resupply and spares. An overview of these mass flows is given in Figure 13.2 on page 186.

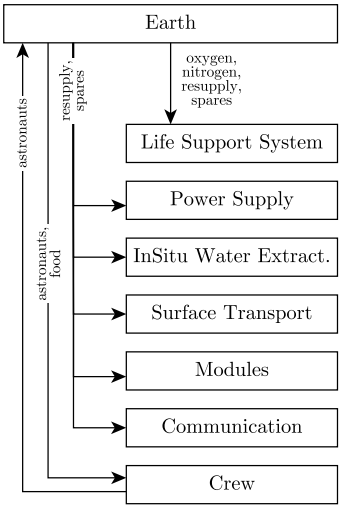


Figure 13.2: Logistic Scenario model overview

13.3 Lunar Base Location

For simulation matter detailed information about the lunar base location is needed. The lunar base is placed near the lunar north pole. The north pole has a geodetic distance of 15.17km to the main base.

In the following table the most important data is given. The last two columns are related to the geodetic and cartographic distance to main base.

Site	Lon.	Lat.	Geodetic	Cartographic
Main Base	135.250°	89.487°	-	-
Solar A	−46.278°	89.623°	4.30*km*	4.67*km*
Solar B	126.552°	89.374°	26.70*km*	27.72*km*

Table 13.1: Lunar site coordinates and distances

The data from Table 13.1 on page 187 is illustrated in Figure 13.3 on page 187. The map layer used was "LROC WAC color shaded relief".

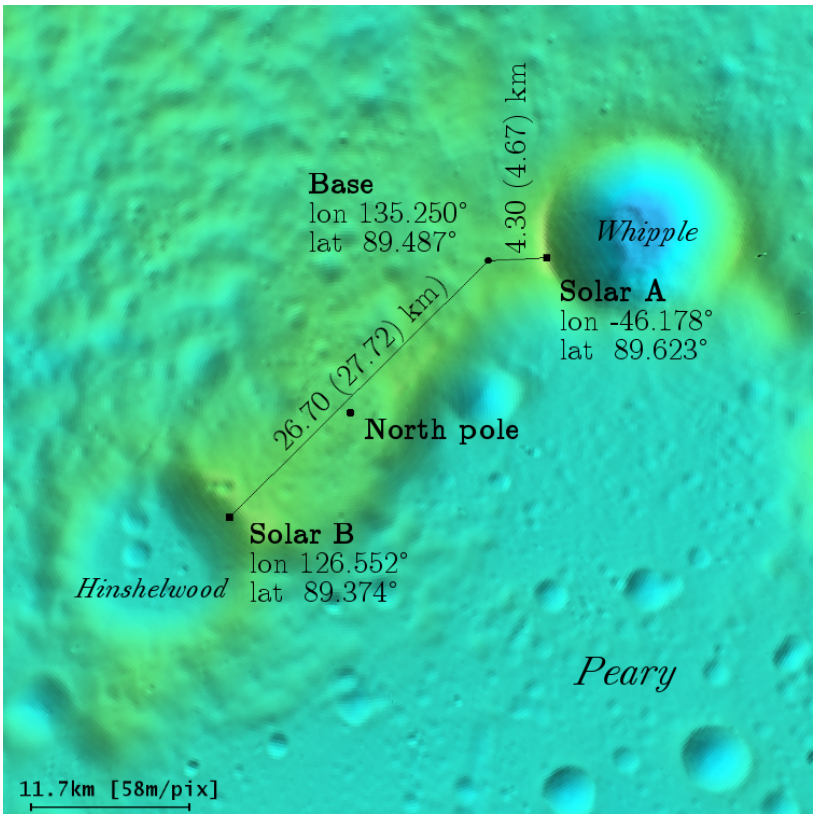


Figure 13.3: Site overview with base, possible solar sites A and B and distances. Source: `http://webmap.lroc.asu.edu/`

The Arizona State University provides cartographic data gained by Lunar Reconnaissance Orbiter (LRO) mission (`http://webmap.lroc.asu.edu/`). The Lunar Reconnaissance Orbiter Camera (LROC) addresses measurement requirements of landing site certification and polar illumination. LROC comprises a pair of narrow-angle imaging cameras (NAC) and a single wide-angle camera (WAC).[9] A

[9] `http://lroc.sese.asu.edu/`

near-global lunar 100 meter raster (GLD100) Digital Terrain Model (DTM) was extracted from the LROC WAC stereo image data. A DTM or rather a Digital Elevation Model (DEM) holds elevation data for discrete locations. The colors of Figure 13.3 on page 187 corresponds to elevation data.

Elevation data for a path can be gathered by a LRO/LROC Target Observation Request[10]. In Figure 13.4 on page 188 are the elevation profiles given to sites Solar A and B. Solar A seems to be almost 500 meters over the base elevation. The ascent up to 30% could be a problem for rovers driving the direct route (Section 11). The cartographic distances are used as an input for cable length and rover tours.

[10] http://target.lroc.asu.edu/

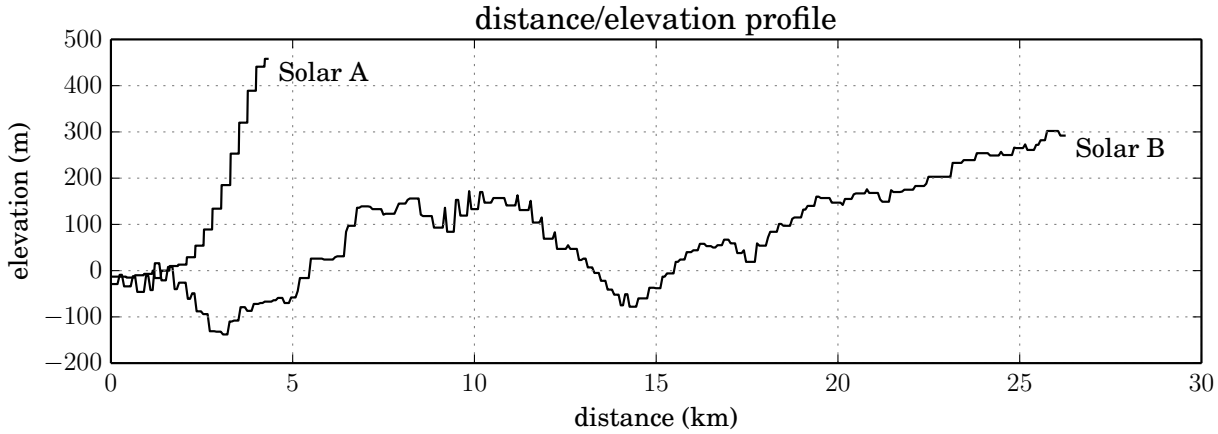


Figure 13.4: Distance/elevation diagram from base to possible solar sites A and B.

13.4 Solar illumination

In the article DEM-based Illumination Simulation [54] it is described how to calculate shadows based on a DEM. This service the Arizona State University offers as a map layer "luna_illumination" on their web-based map called "Lunaserv". Unfortunately, the calculation is rather slow because for each pixel vector calculations have to be done. So viewing tiles of this layer takes at least several seconds up to minutes to appear.

Figure 13.5 on page 190 shows a time series of the lunar region like in Section 13.3 with virtual calculated shadows. The series starts at midnight on 1st January 2030 with a time step of two days, so it ends on January 29, 2030. The regions of illumination and shadows varying over a lunar day and secondary a year depending on orientation of

the rotational axis of moon. If the rotational axis, which has an angle of ca. 1.5° to ecliptic [41], regarding the lunar north pole points away from sun, there are only a few regions illuminated. If not so, the illumination is very well and has only short gaps. Shadows can become very long in pole regions depending on the elevation of mountains and crater rims respectively up to hundreds of kilometers.

The image data is a good data base to determine the illumination distribution for the corresponding sites of this project. As source data hourly images during one whole year are used. Figure 13.6 on page 191 is a merged image of this data. Red areas represent high illumination intensity whereas a blue area indicates no illumination. This image was also used to place solar arrays reasonably in several iterations.

As a simulation input for power generation by solar arrays the illumination distribution has approximately a binary value domain. The distribution for Solar A is shown in Figure 13.7 on page 192. The considered image region of a solar site corresponds to an area of $\left(9pixel \times 58\frac{m}{pixel}\right)^2 \approx 272m^2$. The brightest pixel of this area is used and the pixel values are normalized to 1. The distribution is "high" if the illumination is higher than a threshold value of 0.1 else "low". Further investigation regarding the sun elevation angle and illumination-cap, because solar arrays are always orthogonal to the sun vector, is necessary.

13.5 Power Supply

In Figure 13.8 on page 193 the power generation subsystems are shown schematically. The solar arrays produce electrical energy which a cable routes the voltage to base. The power distribution unit may stores energy in a storage or distribute it to a consumer directly. The energy storage uses an electrolysis to store and vice versa a fuel cell to generate energy. Most of the subsystems can be represented in the simulation by efficiencies.

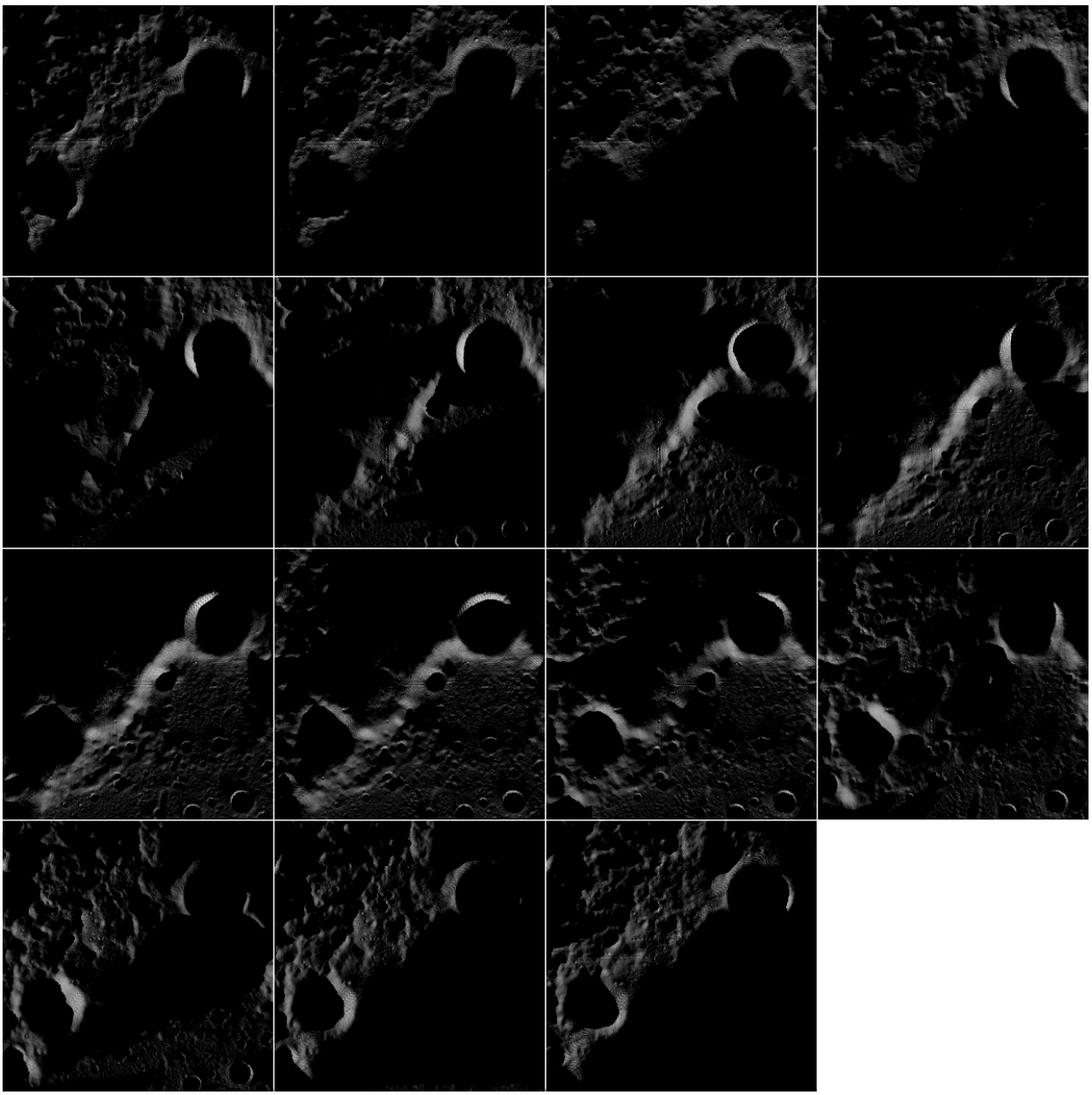


Figure 13.5: Shadow demonstration over four weeks in January 2030. This image area corresponds to Figure 13.3.

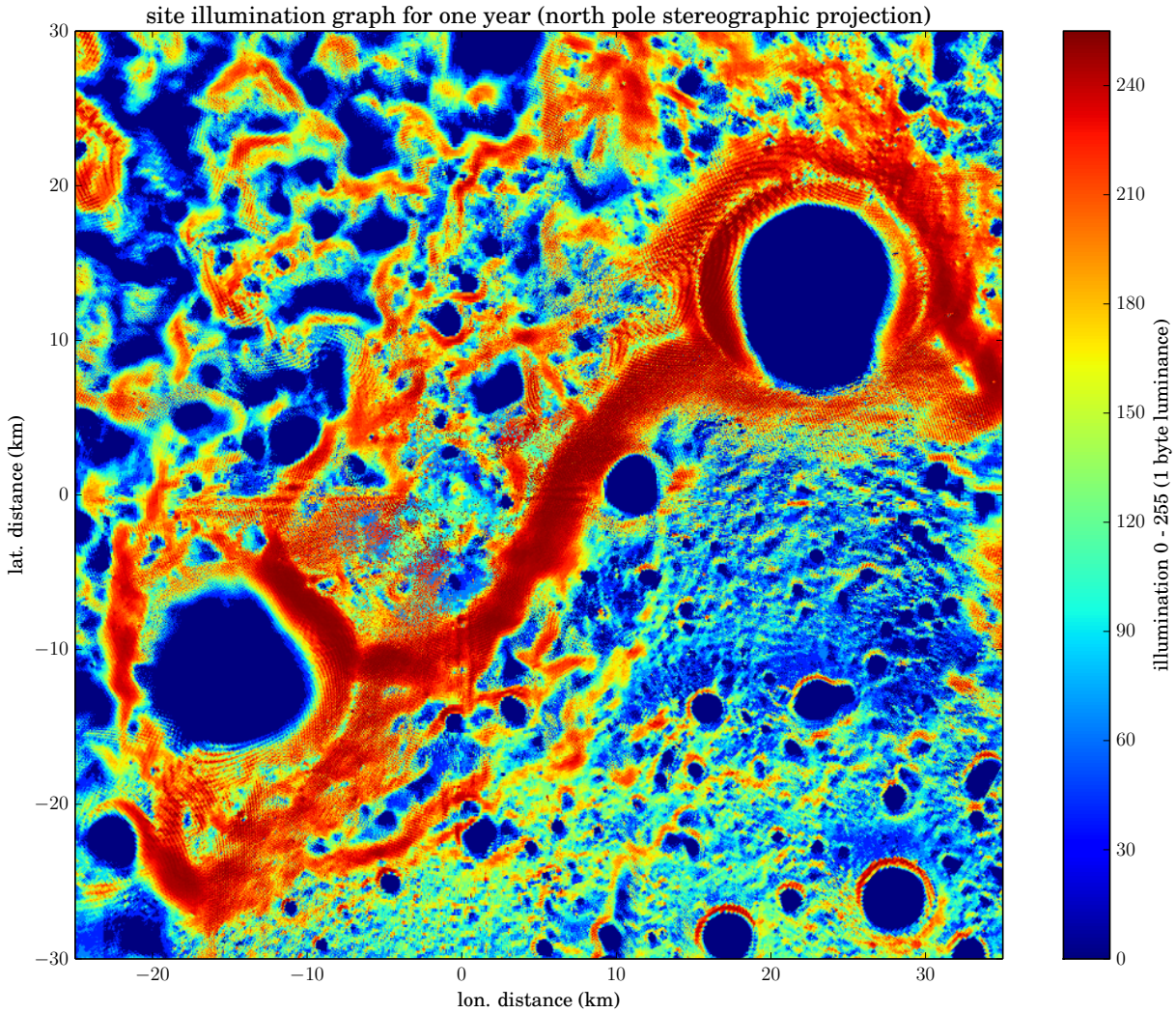


Figure 13.6: Solar illumination intensity over one year. Image area corresponds to Figure 13.3.

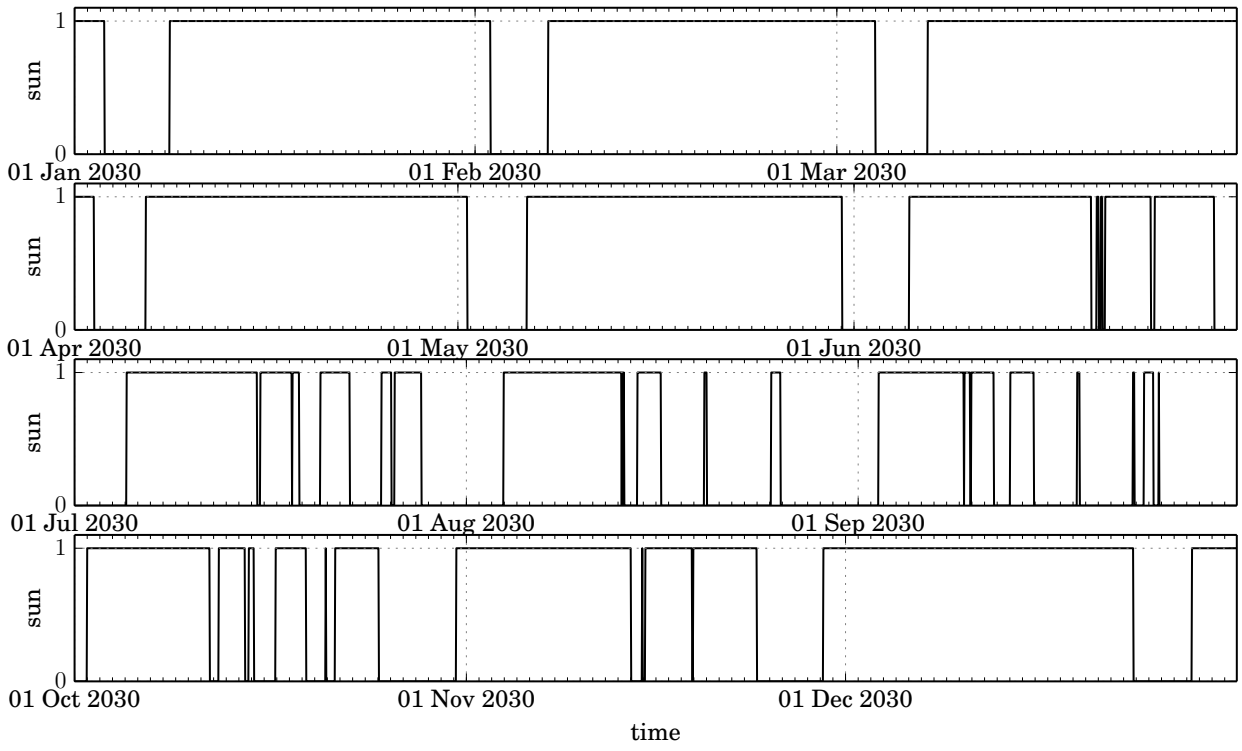


Figure 13.7: Approximated (binary) solar illumination at solar site A.

The most important time-independent derived values by simulation are given in Table 13.2 on page 193. All the time-dependent values are not listed here for sake of clarity. For details look also in Section 9.

	Value
Overall efficiency (without storing)	85.6%
Efficiency only battery:	46.2%
Overall efficiency (with storing):	39.5%
Power by solar cells (sun$\perp$)	$410.10\frac{W}{m^2}$
Power (without storing)	$350.90\frac{W}{m^2}$
Power (with storing)	$162.05\frac{W}{m^2}$

Table 13.2: Simulation power supply derived values

Based on the illumination distributions from Section 13.4 for Solar A and B, different solar array configurations are considered. In this document there is only one exemplary comparison for 2037 between Solar A and Solar A and B illustrated (Figure 13.10 on page 194 and Figure 13.11 on page 195). Solar A is the nearest solar array site to base, so this site is always included in the analysis. Another solar array site like Solar B is considered because the illumination depends on time while moon is rotating about the rotational axis through the near lunar north pole. It is a trade-off of mass for another solar site B plus mass of cables and increasing the battery size to survive the longer shadow time of only one solar site. The conclusion is, that the disadvantages for a more distant solar array site Solar B like mass of array, cables and rover tours do not outweigh the minimal advantage. For detailed information see Section 9.

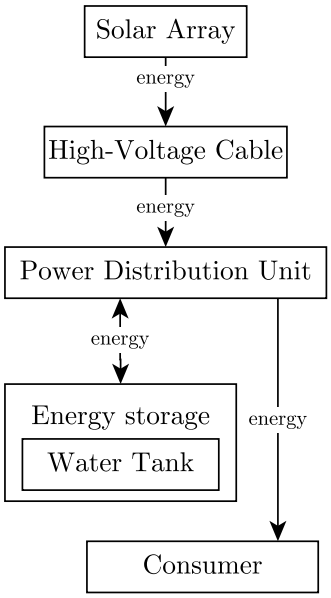


Figure 13.8: Simulation model of power supply

Figure 13.9 on page 194, Figure 13.10 on page 194, Figure 13.11 on page 195 and Figure 13.12 on page 195 shows the trend of energy storage and tank levels of water, oxygen and hydrogen depending on phases and solar configurations. The saw tooth functions is caused by the sun is visible or not. The large peaks September and October are caused by the bad constellation for the north pole of the lunar rotational axis pointing away from the sun. The maximum period without sunlight is barely 14 days. Beside increasing energy storage, a night reduction factor could be also achieved to get more safety margin during this time. There is one third as a margin while this bad axis orientation chosen.

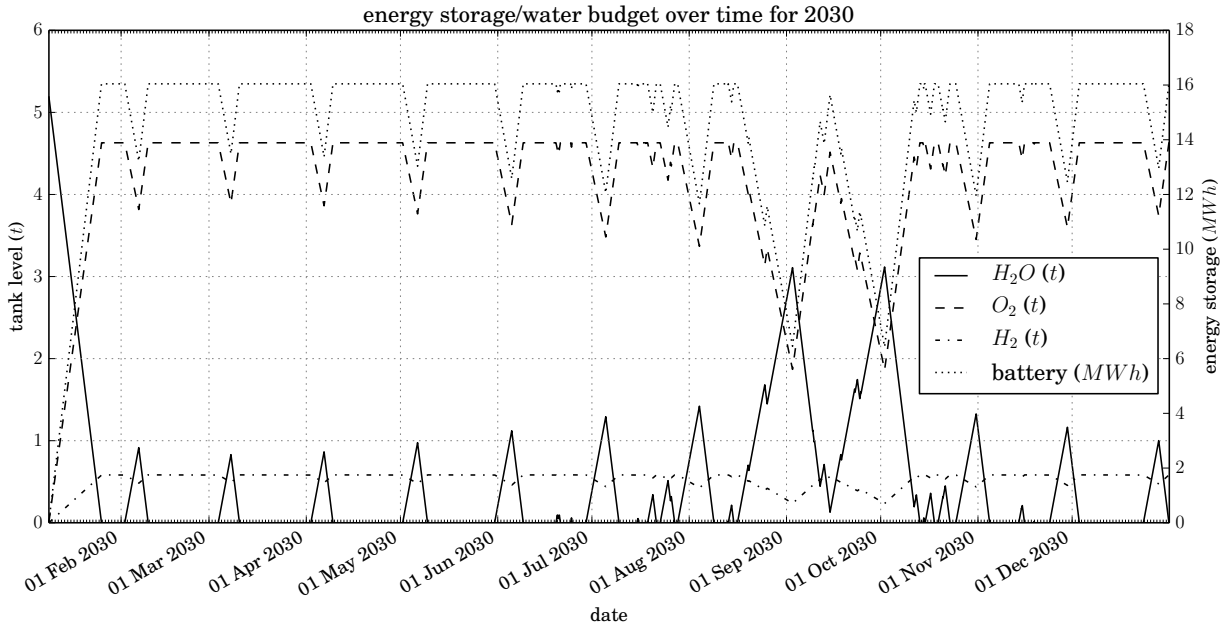


Figure 13.9: Energy storage/water budget over time for 2030 only with Solar A.

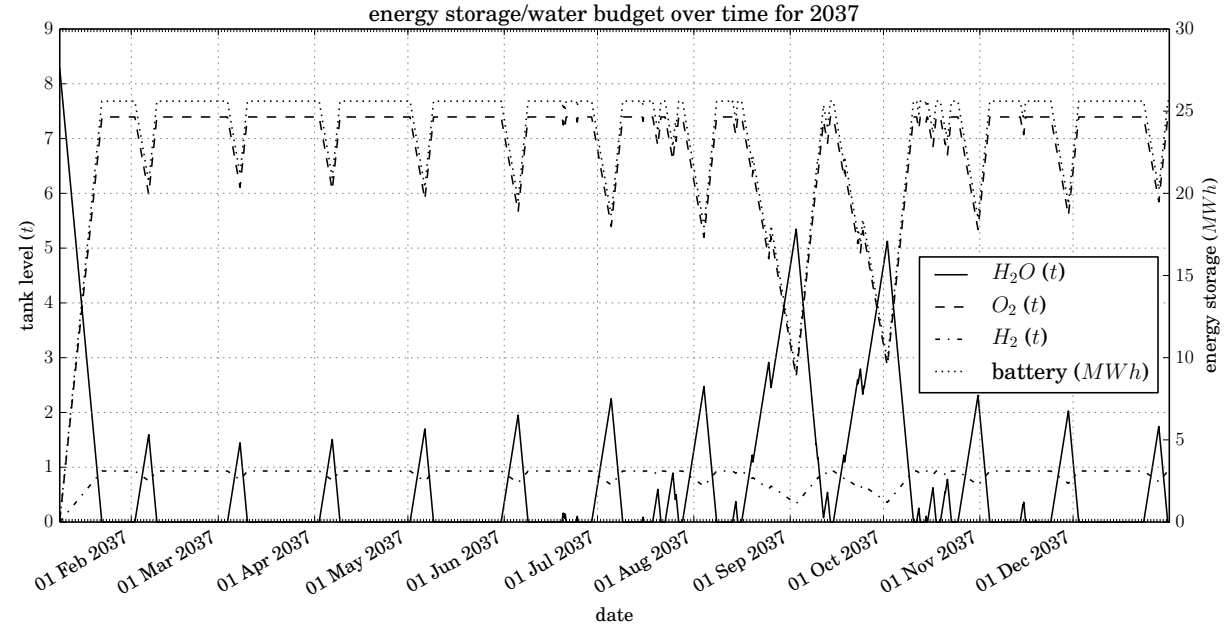


Figure 13.10: Energy storage/water budget over time for 2037 only with Solar A.

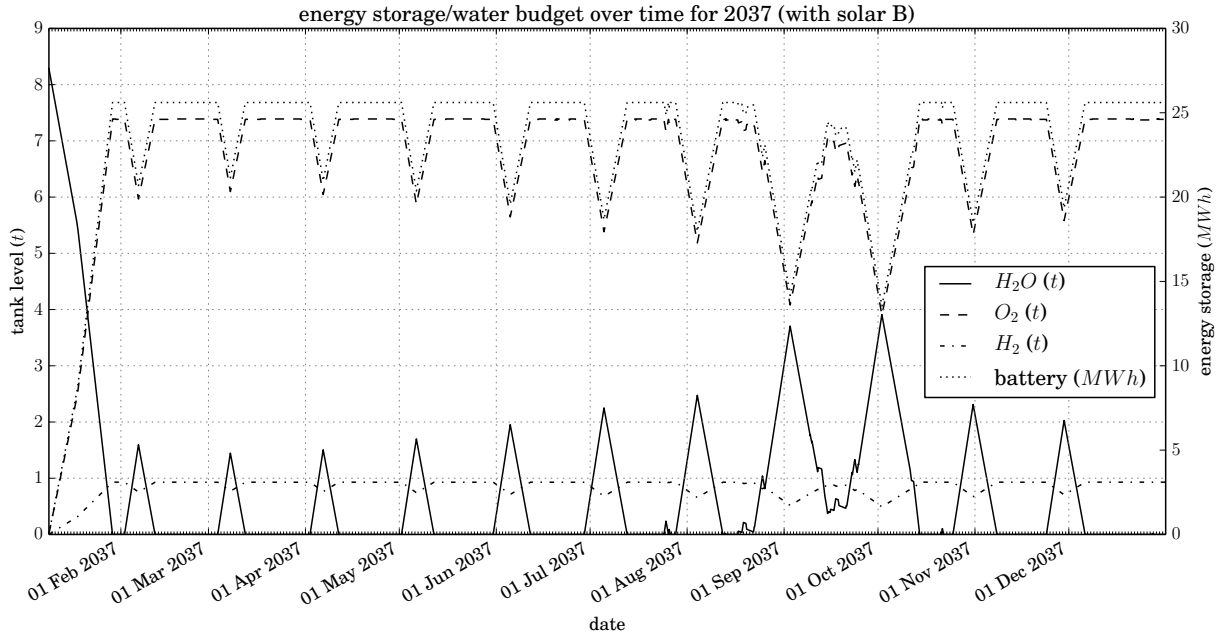


Figure 13.11: Energy storage/water budget over time for 2037 incl. Solar B.

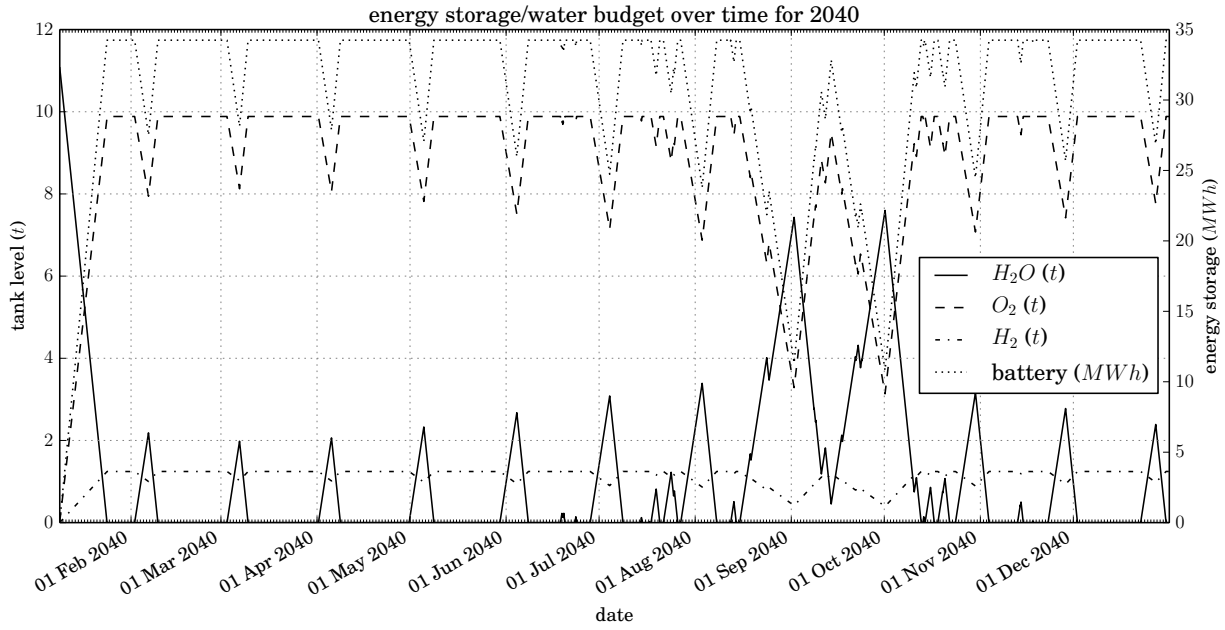


Figure 13.12: Energy storage/water budget over time for 2040 only Solar A.

13.6 Radiation

The radiation simulation includes a work day of an astronaut depending on different phases of the moon base . The simulation don't include special events like Coronal Mass Ejections.

There is a big difference in exposed radiation dose depending on whereabouts. For demonstrationFigure 13.13 on page 196 shows a comparison staying for example for one day in the Spacesuit, Rover or Base exclusively. Living just in base has almost no difference to earth surface except CME whereas wearing a space suit is significantly noticeable.

Based on the values from Section 7.7, Section 12 and Section 6 the following work day (Table 13.3 on page 196) can be derived. The acceptable dose for a mission is $100mSv$.

Habitation	**Phase**			**Exposed Radiation**
	≥S	≥X2	≥O	
Spacesuit	$0.51\frac{h}{d}$	$0.6\frac{h}{d}$	$0.4\frac{h}{d}$	$1.4\frac{mSv}{d}$
Rover	$0.43\frac{h}{d}$	$2.42\frac{h}{d}$	$1.62\frac{h}{d}$	$0.2\frac{mSv}{d}$
Base	$23.06\frac{h}{d}$	$20.98\frac{h}{d}$	$21.98\frac{h}{d}$	$2.5\frac{mSv}{y}$
Total	$24\frac{h}{d}$	$24\frac{h}{d}$	$24\frac{h}{d}$	

Table 13.3: Simulation work day exposed radiation during phases

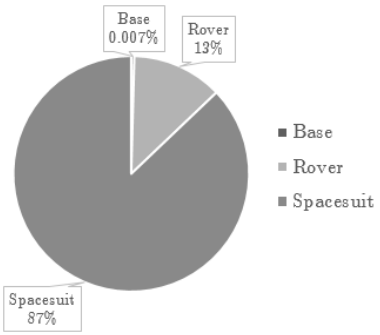


Figure 13.13: Radiation dose values in different whereabouts in comparison

The simulation of a work day depending on the phase is given in Figure 13.14 on page 197. Over a year of mission duration a dose of ca. $23mSv$ is reached in phase X2. The acceptable dose of $100mSv$ is never reached in this consideration. Further specific investigation of for example Coronal Mass Ejections their intensity and frequency is needed. Preliminary reconnaissance probes will also provide more details in the preparation phase.

13.7 In Situ Water Extraction

Water extraction in situ is described in Section 11and is done by rovers. The count of rovers decreases depending on time. The extraction rate of water of one rover depending on work days of the rovers in different phases. Both are shown in Figure 13.15 on page 197. The extraction rate changes because it depends on the workload needed to extract enough water. The overall water tank level depending on these values is considered in Section 6.

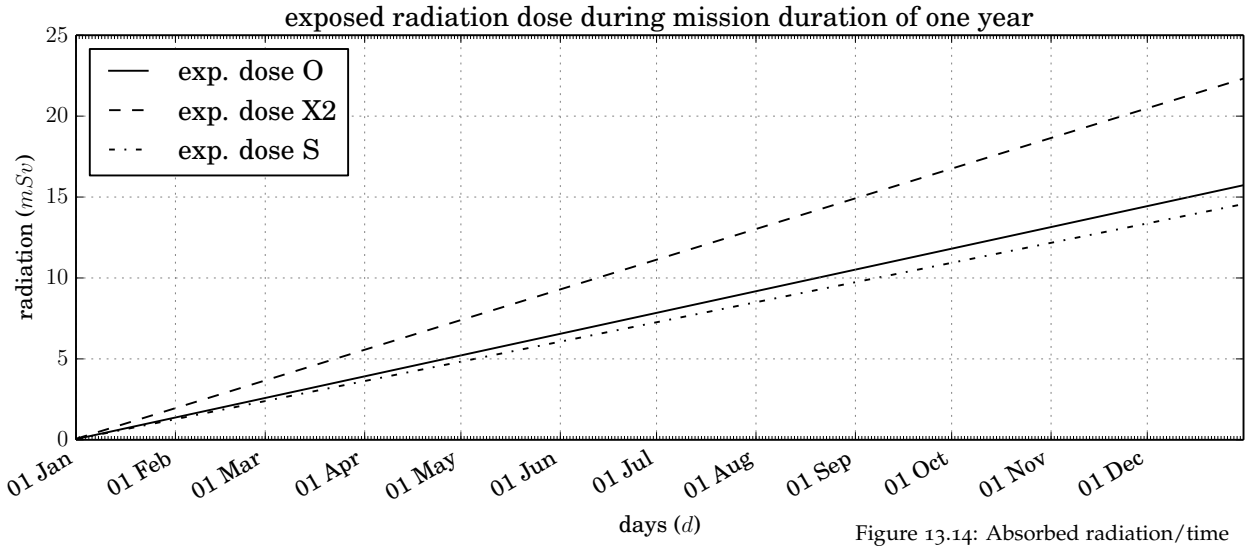


Figure 13.14: Absorbed radiation/time diagram of an astronaut within a mission duration of one year. This diagram doesn't include CME etc.

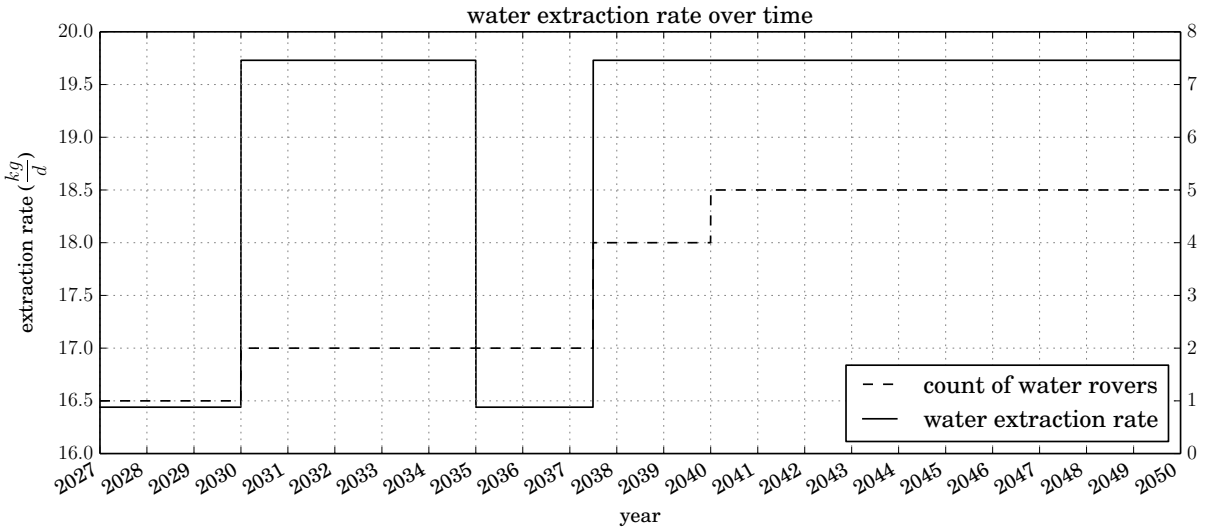


Figure 13.15: In situ water extraction rate of one rover and count of rovers over time

13.8 Life Support System

The Life Support System shall guarantee the life of the crew. So many values are combined in this system. Some important figures are listed in the following.

- Nitrogen in atmosphere: $0.982 \frac{kg}{m^3}$
- Oxygen in atmosphere: $0.307 \frac{kg}{m^3}$
- Atmosphere density: $1.289 \frac{kg}{m^3}$
- Oxygen consumed: $0.879 \frac{kg}{d \cdot person}$
- Carbon dioxide produced: $0.933 \frac{kg}{d \cdot person}$
- Hydrogen required by Sabatier: $0.085 \frac{kg}{d \cdot person}$
- Water recovered by Sabatier: $0.764 \frac{kg}{d \cdot person}$
- Water (potable) consumed: $3.8 \frac{kg}{d \cdot person}$
- Water (hygienic) consumed: $48.2 \frac{kg}{d \cdot person}$
- Water (potable) recovered: $1.674 \frac{kg}{d \cdot person}$
- Water (hygienic) recovered: $42.1 \frac{kg}{d \cdot person}$
- Water budget: $-7.462 \frac{kg}{d \cdot person}$

The most important value is the water budget of $-7.462 kg$ per day and person. This value depending on the crew size have to be overbid by the in situ water extraction per day in order to avoid a decreasing water tank.

Derived from the base model there is a extended model for the Life Support System inFigure 13.16 on page 199. The Sabatier process is converting carbon dioxide and hydrogen to water.

Figure 13.17 on page 199 shows the increasing water tank size during the phases. The near drawn graph represents the water tank level. The hydrogen graph describes the amount of hydrogen which is needed to compensate exhaled carbon dioxide via Sabatier process.

Figure 13.18 on page 200 shows the air required by habitations and crew and resupply of the lunar base over time. Losses of atmosphere of $10 \frac{\%}{y}$ is also included. The three big steps in this graph represents the increase of the habitations depending on crew size and project phase respectively. Air resupply is provided from earth by Logistic Scenario. The smaller steps in the overlying graph represent resupply flights in regular periods.

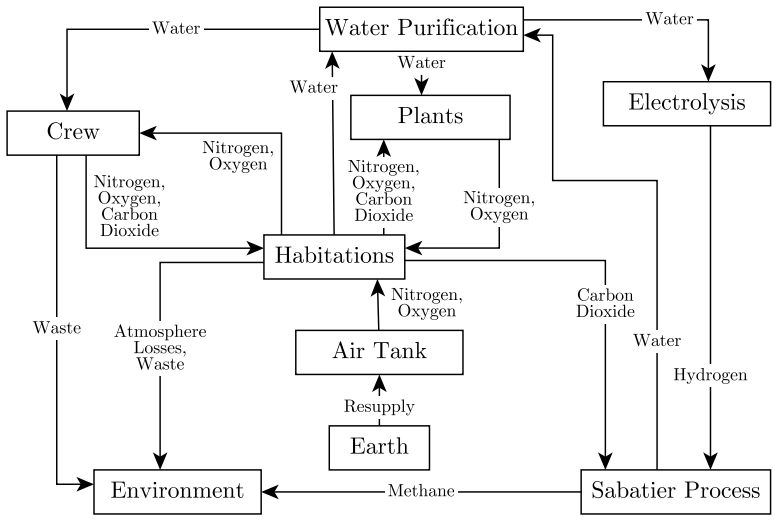


Figure 13.16: Extended Simulation model for Life Support

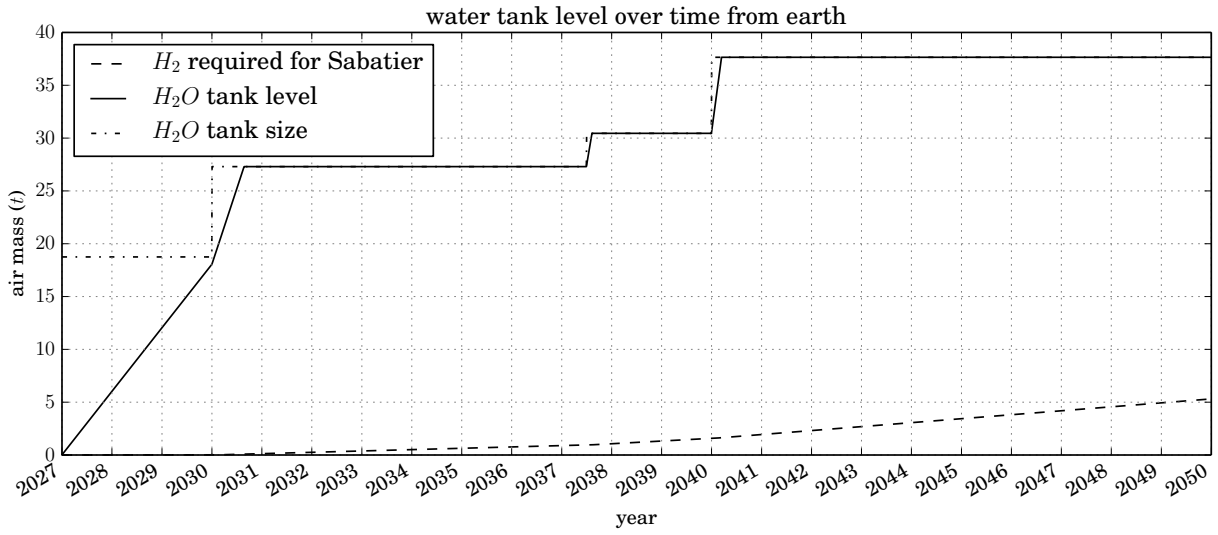


Figure 13.17: Simulation of water tank level, water tank size and hydrogen requirement considering Life Support System

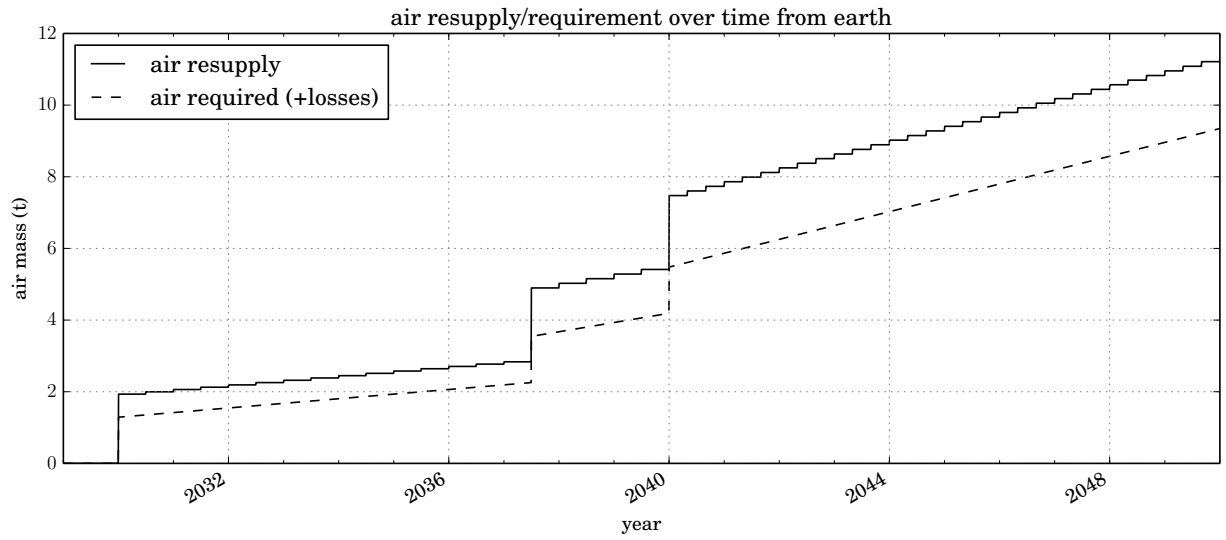


Figure 13.18: Air resupply and requirement by habitation/crew over time

13.9 Outlook

So far everything which is analyzed looks feasible.

The used Simulation Tools (Section 13.1) has proved to be extremely practical. This has work made a bit more comfortable.

It turns out that the overall water budget is the most important value for simulation because almost every parameter depends on availability of water. In the future there should be more attention turned on redundancy of water extraction rovers and confirmation of extraction rate values. Other factors like an acceptable night reduction rate in energy consumption could also be used to reduce power storage or to increase survival time of the base without sunlight. So there are a lot of optimization potential and trade-offs left.

The sun illumination is analyzed in detail and quite adequate. Only minor inaccuracies have to be investigated in more detail.

The collaboration with Power Supply, Resources, Life Support and Radiation work packages works well and shall be expand on the remaining work packages. The simulation provides important input parameters and validates assumptions for other work packages often iteratively. There is more data for example module area distribution needed.

A even closer relation of the subsystems and more time is needed to achieve a even more well-rounded view on the whole system model.

14
Accomplished Goals

by Frederik König

New concepts and technologies for a lunar base have been regarded like 3d-Printing with regolith, combined usage of existing energy technologies, advanced robotics and automation, etc. The scientific research in the different sub packages has shown that a lunar base is difficult but an achievable venture. But we have to consider, that technological ideas need to be tested in reality. Despite of all the planning there is still the possibility for unknown effects. A closed bioregenerative system as supposed in this study for example has never been tested under environmental conditions as on the moon.

The proof of concept will be provided at the time when the system is operational and stable for a longer period of time. This is caused by the fact, that not every system is fully observable. There is also the possibility for rediscussed and undiscovered problems because not every aspect could be regarded in detail in this study. So the goal of testing technology is fulfilled when the base is built and running.

This study has shown that the following sub goals are achievable with existing technology and therefore they are accomplished:

1. it is logistically possible to transport the required materials to the moon
2. it is possible to build-up a lunar base
3. it is logistically possible to supply a lunar base
4. it is technologically possible to run a closed environment if closed means that some supplies like nitrogen are allowed
5. it is technologically possible to gather the required resources for a human habitat, running the base and to do scientific research

Providing a science laboratory in a unique environment for experiments in physics, chemistry, biology, geology, physiology and



sociology which cannot be conducted on Earth is accomplished by the International Standard Payload Racks (ISPRs) and the Liquid-Mirror-Telescope. Providing possibilities for experiments in many scientific disciplines is fulfilled.

Building up a Lunar Base in multiple stages is fulfilled, so we establish the first extraterrestrial human settlement as an initial step for expanding human activities in the solar system.

Exploration of moon, earth, earth-moon is fulfilled, we improve our knowledge of the Moon and its resources with seismologic sensor stations and the fact of building a Lunar Base. The Lunar Base as self-sufficient as possible is also fulfilled with our concept.

Having accomplished all this goals, we also accomplish the goal for infrastructure for astronautics. With our concept, we establish a bridgehead for further missions.

Considering a bigger scope, our Lunar Base will help to achieve further going ideas in astronautics and science like mars colonization, asteroid-mining, independent bioregenerative life-support systems and more.

Conclusion: our base achieves its goals and is a first step to space colonization and more.

15
Outlook

by Kai Werner

As already reiterated in chapter 14, most of our objectives could be fulfilled. Some assumptions will have to be confirmed by further research.

The structure and composition of regolith will have to be further investigated to confirm the assumptions in how it will perform in sintering buildings. The structural engineering will have to detailed and confirmed. The development of an actual, working building structure with the corresponding effects on human inhabitants on the Moon will have to continue.

Energy Storage is still in development and should be monitored during the next years. We know that there is water on the Moon, and we can safely assume that there will be craters filled with it. The exact quantities and distribution in the craters will have to be cartographed and proper routes from base to mining site will have to be checked again as soon as better maps of the Moon Surface are available.

Most of the technologies used in Logistics or Surface Transport are still in development and may very well change specifics or even abandoned till 2030.

Many of the assumptions can only be proven on the Moon itself, and exploration will have to continue.

Altogether, this report presents a viable first step towards a lunar base and many more will follow.

Bibliography

[1] German potabel water regulation, trinkwv din2000.

[2] *International Standard Payload Rack (ISPR) Structural Integrator's Handbook*, . URL http://www.colorado.edu/ASEN/STAGE-1/ISPR_Structural_Integrators_Handbook.pdf.

[3] http://www.esa.int/Our_Activities/Human_Spaceflight/International_Space_Station/Columbus_laboratory, .

[4] *Formeln und Tabellen*. .

[5] http://hdr.undp.org/en/statistics/hdi, .

[6] International standard payload rack, . URL http://pdf.aiaa.org/preview/1998/PV1998_466.pdf.

[7] http://www.imbp.ru/Mars500/Mars500-e.html, .

[8] http://www.nbcnews.com/id/14505278/ns/technology_and_science-space/#.Ut84lrQwdaR, .

[9] http://www.nss.org/settlement/moon/NASAwhymoon.pdf, .

[10] http://www.bpb.de/wissen/I6T8RL, .

[11] http://www.weltbevoelkerung.de/oberes-menue/publikationen-downloads/zu-unseren-themen/grafiken/bevoelkerungsentwicklung/weltbevoelkerungsprojektionen-bis-2100.html, .

[12] . URL http://spaceflight.nasa.gov/gallery/images/station/hardware/hires/98_03644.jpg.

[13] The case for an international lunar base, 1990.

[14] Whipple (crater). http://en.wikipedia.org/wiki/Whipple_crater, 2014.

[15] David L. Akin. Mass estimation relations. In *University of Maryland - ENAE 483/788D - Principles of Space Systems Design*, 2009.

[16] Andrea Albalat. Assessment of oxygen production on the Moon through reduction of Ilmenite. Master's thesis, Unversitat Polytecnica de Catalunya, 2010.

[17] Wolfram Alpha. `http://www.wolframalpha.com`, 2014.

[18] Roger Angel, Dan Eisenstein, Suresh Sivanandam, Simon Worden, Jim Burge, Ermanno Borra, Clement Gosselin, Omar Seddiki, Paul Hickson, Ki Bui Ma, Bernard Foing, Jean-Luc Josset, Simon Thibault, and Paul Van Susante. A Lunar Liquid Mirror Telescope (LLMT) for deep-field infrared observations near the lunar pole. In *SPIE Conference*, 2006.

[19] Jodi Asbell-Clarke, Daniel Barstow, Teon Edwards, James Larsen, Jeffrey Lockwood, and Christopher Randall. Astrobiology – An Integrated Science Approach, 2005.

[20] Bill Atwell, Paul Boeder, and Amy Ross. Space radiation analysis for the mark iii spacesuit. In *43rd International Conference on Environmental Systems; Vail, CO; 14-18 Jul. 2013; United States*. NASA Johnson Space Center; Houston, TX, United States, 2013. URL `http://ntrs.nasa.gov/search.jsp?R=20130013366`.

[21] Viorel Badescu. *Moon: Prospective Energy and Material Resources*. Springer, 1st edition, 2012.

[22] BAuA. Baua; workplace environmental parameters. `www.gefaehrdungsbeurteilung.de`, 2014.

[23] Jan Behrends, Josef Bischofberger, and Rainer Deutzmann. *Duale Reihe Physiologie*. Georg Thieme Verlag, 2012.

[24] Maglev Board. The international maglev board e.v. Website, 1998. URL `http://magnetbahnforum.de/index.php?en_facts`. last visited 2014-02-10.

[25] BPB. Bpb; water consumption on earth. `http://www.bpb.de/nachschlagen/zahlen-und-fakten/globalisierung/52730/wasserverbrauch`, 2014.

[26] Calla, Mathur, and Jangid. Water Ice Detected at Secondary Craters on Peary Floor Using Mini-SAR & Mini-RF. In *Large Meteorite Impacts and Planetary Evolution V*, 2013.

[27] Angelo A Casaburri and Cathy A Gardner. Space food and nutrition: An educator's guide with activities in science and mathematics. 1999.

[28] F Ceccanti, E Dini, X De Kestelier, V Colla, and L Pambaguian. 3d printing technology for a moon outpost exploiting lunar soil. In *61st International Astronautical Congress, Prague, CZ, IAC-10-D3*, volume 3, 2010.

[29] Wu Chen, Alex Huang, Chushan Li, Gangyao Wang, and Wei Gu. Analysis and comparison of medium voltage high power dc/dc converters for offshore wind energy systems. *Power Electronics, IEEE Transactions on*, 28(4):2014–2023, April 2013.

[30] National Research Council Committee on the Evaluation of Radiation Shielding for Space Exploration. *Managing Space Radiation Risk in the New Era of Space Exploration*. The National Academies Press, 2008. ISBN 9780309113830. URL http://www.nap.edu/openbook.php?record_id=12045.

[31] A. P. S. Crotts. Lunar outgassing, transient phenomena, and the return to the moon. i. existing data. *The Astrophysical Journal*, 687(1):692 – 705, November 2008. URL http://iopscience.iop.org/0004-637X/687/1/692.

[32] F. A. Cucinotta and M. Durante. Cancer risk from exposure to galactic cosmic rays: implications for space exploration by human beings. *The Lancet Oncology*, 7(5):431 – 435, May 2006. URL http://www.ncbi.nlm.nih.gov/pubmed/16648048.

[33] Chris Culbert. Lunar surface systems project overview. Technical report, NASA, 2009.

[34] Wolfgang Demtroeder. Elektromagnetische beschleunigung von projektilen. Website, 1987. URL http://www.wissenschaft-und-frieden.de/seite.php?artikelID=0690. last visited 2014-02-10.

[35] N. Desai, E. Davie, and et al. Immunofluorescence detection of clustered g-h2ax foci induced by hze-particle radiation. *Radiation Research*, 164:518 – 522, 2005.

[36] The Tufte-Latex Developers. *A Tufte-Style Book*, 2013.

[37] *Germany on the ISS - COLUMBUS*. DLR. URL http://www.dlr.de/iss/Portaldata/19/Resources/dokumente/col_brosch_dlr_web.pdf.

[38] Ondrej Doule, Emmanouil Detsis, and Aliakbar Ebrahimi. A lunar base with astronomical observatory. In *41st International Conference on Environmental Systems (ICES), no. AIAA*, volume 5063, 2011.

[39] David R. Dr. Williams. Moon fact sheet. NASA Moon Fact Sheet, July 2013. URL `http://nssdc.gsfc.nasa.gov/planetary/factsheet/moonfact.html`.

[40] M. J. Drake, J. P. Lowe, and et al. Uranium in the lunar crust: Implications for lunar origin and evolution. In *61st Annual Meteoritical Society Meeting*. Lunar and Planetary Laboratory, 2006. URL `http://www.lpi.usra.edu/meetings/metsoc98/pdf/5174.pdf`.

[41] Peter Eckart. *Parametric Model of a Lunar Base for Mass and Cost Estimates*. Herbert Utz Verlag, 1996. ISBN 3-9803925-1-1.

[42] Peter Eckart. *Spaceflight Life Support and Biospherics*. Space Technology Series. Kluwer Academic Publishers Group, P.O. Box 322, 3300 AA Dordrecht, The Netherlands, 1996.

[43] Peter Eckart. *Spaceflight Life Support and Biospherics*. Space Technology Series. Kluwer Academic Publishers Group, P.O. Box 322, 3300 AA Dordrecht, The Netherlands, 1996.

[44] Peter Eckart. *The Lunar Base Handbook*. Space Technology Series. Mcgraw Hill Book Co., second edition edition, 2006.

[45] Peter Eckart. *The Lunar Base Handbook*. Space Technology Series. Mcgraw Hill Book Co., second edition edition, 2006.

[46] EngineeringToolBox. `http://www.engineeringtoolbox.com/met-metabolic-rate-d_733.html`, 2014.

[47] Edwin Ethridge and William Kaukler. Extraction of Water from Polar Lunar Permafrost with Microwaves – Dielectric Property Measurement. In *American Institute of Aeronautics and Astronautics*, 2014.

[48] Edwin Ethridge, William Kaukler, and Frank Hepburn. Using Microwaves for Extracting Water from the Moon. In *COMSOL Conference*, 2009.

[49] W. M. Farrell, T. J. Stubbs, R. R. Vondrak, G. T. Delory, and J. S. Halekas. Complex electric fields near the lunar terminator: The near-surface wake and accelerated dust. *Geophysical Research Letters*, 34(14):n/a–n/a, 2007. ISSN 1944-

8007. DOI: 10.1029/2007GL029312. URL http://dx.doi.org/10.1029/2007GL029312.

[50] Georg Fuchs and Hans-Günter Schlegel. *Allgemeine Mikrobiologie: Begründet von Hans-Günter Schlegel*. Georg Thieme Verlag, 2006.

[51] Institut für Ernährungsinformation. Deutsches ernährungsberatungs- und informationsnetz. URL http://www.ernaehrung.de/tipps/allgemeine_infos/ernaehrung13.de.

[52] Daniel M Giel. http://www.energiekosten-unternehmen.de/energieverbrauch-von-aufzuegen.php/, 2014.

[53] AZUR SPACE Solar Power GmbH. 30Technical report, AZUR SPACE Solar Power GmbH, 2012.

[54] Caleb Hanger, Nick Estes, Mark Robinson, and Ernest Bowman-Cisneros. Dem-based illumination simulation in a web map service using lunaserv. 2013. URL http://lunarscience.nasa.gov/wp-content/uploads/LSF13P/Hanger_nlsf2013.pdf.

[55] Dan A. Harrison, Robert Ambrose, Bill Bluethmann, and Lucien Junkin. Next generation rover for lunar exploration. Technical report, NASA Johnson Space Center, 2007.

[56] G. H. Heiken, D. T. Vaniman, and B. M. French. *Lunar Sourcebook*. Cambridge University Press, Press Syndicate of the University of Cambridge The Pitt Building, Trumpington Street, Cambridge, CB2 1 RP 40 West 20th Street, New York, NY 10011, USA, 1 edition, 1991. URL http://www.lpi.usra.edu/publications/books/lunar_sourcebook/.

[57] Matt Heverly, Jaret Matthews, Matt Frost, and Chris McQuin. Development of the tri-athlete lunar vehicle prototype. Technical report, Jet Propulsion Laboratory California Institute of Technology, 2010.

[58] A. Scott Howe, Kriss J Kennedy, Tracy Gill, and NASA Deep Space Habitat subsystem leads4. Nasa habitat demonstration unit (hdu) deep space habitat analog. In *AIAA SPACE 2013 Conference and Exposition*, 2013.

[59] Richard A Zahoransky Prof Dr Ing, Elmar Bollin Prof Dipl Ing, Helmut Oehler Dipl Ing, Udo Schelling Prof Dipl Ing, Harald Schwarz Prof Dipl Ing, et al. Brennstoffzellen. In *Energietechnik*, pages 211–240. Springer, 2013.

[60] L. Jones, S. Jacques, J. C. Rask, E. Tranfield, L. Taylor, R. Kerschmann, and D. J. Loftus. Lunar dust biological effects. In *NLSI Lunar Science Conference*, 2008. URL http://www.lpi.usra.edu/meetings/nlsc2008/pdf/2100.pdf.

[61] Matthew Kaplan, Eric Carlson, Sherie Bradfute, Kent Allen, Francois Duvergne, Bert Hernandez, David Le, Quan Nguyen, and Brett Thornhill. The simpsons project: An integrated mars transportation system. Technical report, Texas Univ.; Dept. of Aerospace Engineering.; Austin, TX, United States, 1992.

[62] Amiko Kauderer and Brian Dunbar. Nasa awards contract for constellation spacesuit for the moon. Website, February 2009. URL http://www.nasa.gov/mission_pages/constellation/main/spacesuit.html. last visited: 2014-02-03.

[63] Takashi Kubota, Yoji Kuroda, Yasuharu Kunii, and Ichiro Nakatani. Small, light-weight rover micro5 for lunar exploration. *Acta Astronautica*, 52(2–6):447 – 453, 2003. ISSN 0094-5765. DOI: http://dx.doi.org/10.1016/S0094-5765(02)00187-X. URL http://www.sciencedirect.com/science/article/pii/S009457650200187X. <ce:title>Selected Proceedings of the 4th {IAA} International conference on L ow Cost Planetary Missions</ce:title>.

[64] D. J. Lawrence, W. C. Feldman, and et al. Thorium abundances on the lunar surface. *Journal of Geophysical Research*, 105(E8): 20,307 – 20,331, August 25 2000. URL http://onlinelibrary.wiley.com/doi/10.1029/1999JE001177/pdf.

[65] S. L. Lawson, W. C. Feldman, and et al. Maps of lunar radon-222 and polonium-210. *Lunar and Planetary Science*, 33:1 – 2, 2002. URL http://www.lpi.usra.edu/meetings/lpsc2002/pdf/1835.pdf.

[66] Lee S Mason and David Irvin Poston. *A Summary of NASA Architecture Studies Utilizing Fission Surface Power Technology*. National Aeronautics and Space Administration, Glenn Research Center, 2011.

[67] Maggie McKee. Sunny spot picked out for future lunar base. http://www.newscientist.com/article/dn7263-sunny-spot-picked-out-for-future-lunar-base.html#.Uvmh7YUz13A, April 2005.

[68] Cary A Mitchell. Bioregenerative life-support systems. *The American Journal of Clinical Nutrition*, 60(5):820S–824S, 1994.

[69] NASA. Athlete (all-terrain, hex-limbed, extra-terrestrial explorer).

[70] NASA. Lunar Reconnaissance Orbiter (LRO): Leading NASA's Way Back to the Moon
Lunar Crater Observation and Sensing Satellite (LCROSS): NASA's Mission to Search for Water on the Moon, 2009.

[71] NASA. Lunar electrical rover concept. 2010.

[72] NASA. Space exploration vehicle concept. 2011.

[73] NASA. Nasa's space exploration vehicle (sev). Website, 8 2012. URL http://www.nasa.gov/exploration/technology/space_exploration_vehicle/index.html. last checked 2014-01-27.

[74] NASA. Historic demonstration proves laser communication possible. NASA Website, 10 2013. URL http://www.nasa.gov/content/goddard/historic-demonstration-proves-laser-communication-possible/. 28.

[75] NASA. Map of the Moon. http://target.lroc.asu.edu/q3/#, 2014.

[76] Space Math NASA. Extracting Oxygen from Moon Rocks. http://spacemath.gsfc.nasa.gov, 2014.

[77] C. R. Neal. Using the New Views of the Moon Initiative to Define Future Missions: The Lunar Seismic Network. In *The Moon Beyond 2002: Next Steps in Lunar Science and Exploration*, page 40, January 2002.

[78] Holger Thiel Norbert Roewer. *Taschenatlas Anästhesie*. Thieme, 2013.

[79] Dagmar Oertel. Energiespeicher - stand und perspektiven. *Sachstandsbericht zum Monitoring »Nachhaltige Energieversorgung«*, page 59, 2008.

[80] U.S. Department of Agriculture Agricultural Research Service. Composition of foods raw, processed, prepared usda national nutrient database for standard reference, release 26.

[81] Scientific Committee on Food. Opinion of the scientific committee on food on the revision of reference values for nutrition labelling. Technical report, European Commission, March 2003.

[82] Ioannis Papagiannakis. Studying and improving the efficiency of water electrolysis using a proton exchane membrane electrolyser. Master's thesis, Strathclyde University, 2005.

[83] RL Patterson, R Furfaro, PD Sadler, G Boscheri, C Lobascio, M Lamantea, RM Wheeler, S Rossignoli, M Kacira, and GA Giacomelli. System dynamics and performance factors of a lunar greenhouse prototype bioregenerative life support system. In *International Symposium on Advanced Technologies and Management Towards Sustainable Greenhouse Ecosystems: Greensys2011 952*, pages 575–582, 2011.

[84] Angela Psoma and Gunter Sattler. Fuel cell systems for submarines: from the first idea to serial production. *Journal of power sources*, 106(1):381–383, 2002.

[85] Prof. Dr. Hans Quack. Die schlüsselrolle der kryotechnik in der wasserstoff-energiewirtschaft. *KI LUFT UND KAELTETECHNIK*, (3):157–161, 2002.

[86] J. White R.Bate, D. Mueller. *Fundamentals of Astrodynamic*. Dover, 1971.

[87] AA Rosielle and Kenneth J Frey. Estimates of selection parameters associated with harvest index in oat lines derived from a bulk population. *Euphytica*, 24(1):121–131, 1975.

[88] Gunter Sattler. Fuel cells going on-board. *Journal of power sources*, 86(1):61–67, 2000.

[89] Louis Schlapbach and Andreas Züttel. Hydrogen-storage materials for mobile applications. *Nature*, 414(6861):353–358, 2001.

[90] K.L. Schulte and V. Ermert. Meteorologie: ein lernskript für piloten nach europäischen richtlinien. Technical report, 2008. URL `http://books.google.de/books?id=jA9gRGeT3CMC`.

[91] Erik Seedhouse. *Lunar Outpost - The Challenges of Establishing a Human sttlement on the Moon*. Springer, 2009.

[92] Gedalia Shelef, William J Oswald, and PH McGauhey. Algal reactor for life support systems. *Journal of the Sanitary Engineering Division*, 96(1):91–110, 1970.

[93] SIEMENS. Sinavy-cis pem fuel cell for submarines. Technical report, Marine Solutions, 2009.

[94] Lisa C Simonsen, MJ DeBarro, and JT Farmer. Conceptual design of a lunar base thermal control system. In *NASA CONFERENCE PUBLICATION*, pages 579–579. NASA, 1992.

[95] Å.I. Skoog. Blss: A contribution to future life support. *Advances in Space Research*, 4(12):251 – 262, 1984. ISSN 0273-1177. DOI: http://dx.doi.org/10.1016/0273-1177(84)90569-6. URL http://www.sciencedirect.com/science/article/pii/0273117784905696.

[96] E. Slyuta, A. Abdrakhimov, and E. Galimov. The Estimation of Helium-3 Probable Reserves in Regolith. In *Lunar and Planetary Science XXXVIII*, 2007.

[97] Paul Spudis and Anthony Lavioe. Using the resources of the Moon to create a permanent, cislunar space faring system. In *AIAA SPACE 2011 Conference & Exposition*, 2011.

[98] SPACE.com Staff. http://www.space.com/14725-moon-temperature-lunar-days-night.html, February 2012.

[99] Kevin Steele. Prism - packaged liquefier system. Technical report, Air Products, 2002.

[100] T. J. Stubbs, R. R. Vondrak, and W. M. Farrell. Impact of dust on lunar exploration. Technical report, Solar System Exploration Division, NASA Goddard Space Flight Center, 2007. URL http://www.nasa.gov/centers/johnson/pdf/486014main_StubbsImpactOnExploration.4075.pdf.

[101] G Tamulaitis, P Duchovskis, Z Bliznikas, K Breive, R Ulinskaite, A Brazaityte, A Novičkovas, and A Žukauskas. High-power light-emitting diode based facility for plant cultivation. *Journal of Physics D: Applied Physics*, 38(17):3182, 2005.

[102] Karl Tate. How china's chang'e-3 moon rover yutu works (infographic), December 2013. URL http://www.space.com/23855-how-china-change3-moon-rover-works-infographic.html.

[103] G. Jeffrey Taylor, Stephen Mackwell, and James Garvin. Report of the space resources roundtable vii: Leag conference on lunar exploration. In *Report of the Space Resources Roundtable VII: LEAG conference on Lunar Exploration*, League City, Texas, October 2005. Lunar and Planetary Institute, Lunar and Planetary

Institute. URL http://www.lpi.usra.edu/lpi/contribution_docs/LPI-001318.pdf.

[104] Lawrence Taylor and W. David Carrier. Oxygen Production on the Moon: An Overview and Evaluation, 1993.

[105] Lawrence A Taylor and Thomas T Meek. Microwave sintering of lunar soil: properties, theory, and practice. *Journal of Aerospace Engineering*, 18(3):188–196, 2005.

[106] Peter Trechow. Kleiner reinigungsroboter für riesige solarfelder. *VDI nachrichten*, 49, 2013.

[107] vaisala. http://www.vaisala.com/humiditycalculator/vaisala_humidity_calculator.html?lang=de, 2014.

[108] W Van Ieperen and G Trouwborst. The application of leds as assimilation light source in greenhouse horticulture: a simulation study. In *International Symposium on High Technology for Greenhouse System Management: Greensys2007 801*, pages 1407–1414, 2007.

[109] Ketan Verma and Harish Garg. Step Towards the Development of Lunar Liquid Mirror Telescope. *International Journal on Emerging Technologies*, 1:110–112, 2010.

[110] Raymond M Wheeler. Carbon balance in bioregenerative life support systems:< i> some effects of system closure, waste management, and crop harvest index</i>. *Advances in Space Research*, 31(1):169–175, 2003.

[111] Brian H. Wilcox, Todd Litwin, Jeff Biesiadecki, Jaret Matthews, Matt Heverly, Jack Morrison, Julie Townsend, Norman Ahmad, Allen Sirota, and Brian Cooper. Athlete: A cargo handling and manipulation robot for the moon. *Journal of Field Robotics*, 24(5): 421–434, 2007. DOI: 10.1002/rob.20193.

[112] DONALD WISS. Smart-1: mit alternativer smart 1: Mit alternativer flugtechnik zum mond. *Sterne und Weltraum*, 2004.

[113] Klaus Wittmann. *Handbuch der Raumfahrttechnik*, chapter 4.2.2.3 Nukleare Energieversorgung, pages 252–253. Hanser Verlag, 2008.

[114] Inc. XCOR Aerospace. Xcor fluoropolymer composite materials. Technical report, January 2013. URL http://www.xcor.com/composites/.

[115] N. Yamashita, N. Hasebe, R. C. Reedy, S. Kobayashi, Y. Karouji, M. Hareyama, E. Shibamura, M.-N. Kobayashi, O. Okudaira, C. d'Uston, O. Gasnault, O. Forni, and K. J. Kim. Uranium on the moon: Global distribution and u/th ratio. *Geophysical Research Letters*, 37(10):n/a–n/a, 2010. ISSN 1944-8007. DOI: 10.1029/2010GL043061. URL http://dx.doi.org/10.1029/2010GL043061.

[116] K Zacny, G. Paulsen, J. Craft, L. Oryshchyn, J. Sanders, and R. Mueller. Mars In-Situ Water Extractor. In *Concepts and Approaches for Mars Exploration*, 2012.

[117] Kris Zacny. In Situ Water Extraction System for Asteroids and Comets. https://www.ippw10.com/index.php/component/content/article?id=230, 2014.

[118] Y. Zheng, Z. Ouyang, and D. Blewett. Implanted Helium-3 Abundance Distribution on the Moon. In *Lunar and Planetary Science XXXIX*, 2008.