HAVEN

Lunar Port and Base

Design of a Lunar Arrival Port

with a Long-Term Habitat for Versatile Crew Occupations

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HAVEN Lunar Port and Base

Design of a Lunar Arrival Port
with a Long-Term Habitat for Versatile Crew Occupations

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des akademischen Grades eines Diplom-Ingenieurs
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von
Sabrina Kerber
1004901

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Kurzbeschreibung

Mit dem 50. Jubiläum der Mondlandung im Juli 2019 erlebt der Mond einen neuen Aufschwung. Raumfahrtbehörden, internationale Organisationen und sogar der privatwirtschaftliche Sektor zeigen verstärktes Interesse an der Planung von Mondmissionen.

Dieses Mal jedoch ist das Ziel nicht nur die Landung eines Menschens auf dem nächsten Nachbar der Erde, sondern die Etablierung einer langfristigen Forschungsstation. Während sich erste Missionen auf kurze sogenannte Sorties beschränken werden, durchgeführt wie schon zu Apollo Zeiten direkt von den Mondlandefahrzeugen aus, benötigen die angestrebten Langzeitmissionen permanentere Stützpunkte mit einem höheren Anspruch an Habitabilität.

HAVEN Lunar Port and Base ist ein Entwurf für einen Stützpunkt am Südpol des Mondes, basierend auf der nachhaltigen Wiederverwendung von ausrangierten Teilen von Mondlandefähren. Das HAVEN Areal besteht aus mehreren Komponenten, unter anderem aus einem Lande- und Startplatz zur Koordinierung der ankommenden Missionen am Südpol, einem Hangar zur Zwischenlagerung von Mondlandefahrzeugen und deren ausrangierten Komponenten, sowie einem Langzeithabitat.

Das Habitat bietet Platz für eine permanente Crew aus vier Astronauten, welche den Stützpunkt und die Start- und Landetätigkeiten koordinieren, sowie Forschung im Bereich der Habitabilität am Mond betreiben. Zusätzlich werden in HAVEN vierköpfige Kurzzeit-Crews für Akklimatisierung- und Instruktions-Aufenthalte von bis zu zehn Tagen aufgenommen, bevor diese zu respektiven Forschungsstützpunkten am Südpol transportiert werden. Ein Fokus des HAVEN Designs liegt auf dieser vielschichtigen und schnell-wechselnden Besatzungssituation; die Architektur des Habitats untersützt die unterschiedlichen Ansprüche an Privatsphäre der zwei Crews, fördert jedoch gleichzeitig einen Austausch von Erfahrungen und Expertisen, sowie das Entstehen einer Community, in gemeinschaftlich genutzen Bereichen.

Eine zentrale rigide Komponente und eine mehrschichtige aufblasbare Membran bilden die Struktur des Habitats, welches sämtliche Wohnansprüche von Arbeits- und Kommunikationsbereichen, über private Crewquartiere und Freizeiträume, bis hin zu technischen Supportsystemen und einem Gewächshaus beinhaltet. Leere Treibstofftanks der Abstiegsstufe von Mondlandefähren werden im Strahlungsschutz des Habitats verwendet, um eine ökologisch und ökonomisch nachhaltige Konstruktion zu garantieren.

In einem ganzheitlichen Ansatz beinhaltet die Diplomarbeit zum HAVEN Entwurf eine Analyse der Bedingungen am Mond, sowie der strukturellen, technischen und wohnlichen Ansprüche, die Auswahl und Koordinierung von Supportsystemen, welche die Grundvoraussetzung zum erfolgreichen Bau und Betrieb eines Mondhabitats bilden, sowie alle notwendigen architektonischen Überlegungen, Pläne und Details.

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Abstract

With the 50th anniversary of the Moon landing in July 2019, the Moon is experiencing a new boom. Space agencies, international organisation, and even the private sector are competing in what might be described as a new race to the Moon.

This time, however, the goal is not only to set foot on Earth's nearest neighbour, but to establish a base for long-term research. While initial missions will focus on short sorties, conducted directly from a lunar lander as it was done during Apollo, long-term missions will make use of a more permanent outpost with increased habitability levels.

The HAVEN Lunar Port and Base is an integral design for an arrival port at the Moon's South Pole, based on the sustainable reuse of discarded lander components. The main elements of the compound are a launch and landing area for incoming and leaving crews, a hangar to place landers and lander components into interim storage, and a long-term habitat.

The habitat provides room for a permanent crew of four, which runs the arrival port and conducts research in the area of lunar habitability. In addition, HAVEN will house short-term crews of another four astronauts for an acclimatisation and instruction period of up to ten days, before their distribution to their respective research outposts at the lunar South Pole. The HAVEN design pays special attention to this versatile and fast-changing crew; the architecture aims to cater to the different privacy needs of the two seperate sub-crews, while simultaneously encouraging an exchange of experience and expertise, as well as the formation of a larger community, in shared areas.

The habitat consists of a rigid centre component and a multilayer inflatable and accommodates all habitation needs from dedicated work and communication spaces, over private crew quarters, as well as leisure time areas, to technical support systems and a greenhouse. Empty propulsion tanks of discarded lander descent stages are used in the construction of the habitat's radiation shielding, in order to achieve both, a more sustainable and more economic construction process.

In a holistic approach, the thesis design HAVEN includes an analysis of the lunar environmental conditions, as well as structural, technical, and habitability needs, the selection of mission support equipment needed to construct and maintain the base, and the necessary architectural deliberations, plans and details.

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Preface

With space missions being launched into orbit on an almost daily basis, the final frontier is being pushed continuously outwards. While humanity - or rather the technology humanity has devised - continues to penetrate new deep space destinations, the objective of an extra-terrestrial outpost with a permanent human presence gains the centre stage. The Moon, as Earth's nearest neighbour, and the only other planetary body humans have ever set foot on, is an obvious choice for such an endeavour.

Designing for any kind of space exploration or habitation requires an architect to define a new connection between technical requirements and spatial demands. It both forces and enables a change of perspective.
Rules and guidelines of terrestrial architecture have to be adapted with the change of the environment; new physical parameters demand a different strategy for spatial layouts.
While technical aspects, such as structural decisions, radiation shielding and the integration of life support systems, seem to take prevalence in the challenging task of enabling humans to survive in an extra-terrestrial setting like the Moon, it is just as important for a successful lunar habitat to ensure a livable environment. Smart interior solutions need to be leveraged to answer to the demands of multi-functionality, privacy and flexibility in a very confined setting. The possiblity of dynamic crew variations poses a particular challenge to the design.
Only by following an interdisciplinary approach can space architecture fulfill all its diverse tasks; only by sharing resources and experience can space exploration achieve goals like a sustainable long-term presence on another planetary body.
The design for the HAVEN Lunar Port and Base was developed with such collaborative aspects in mind, both in the design process, which entailed considerations not only from the architectural discipline, but also considers aspects from the fields of robotics, aerospace engineering, biology, sociology and psychology, as well as in HAVEN's intended function as an arrival hub for international crews and a focal point for the exchange of knowledge and experience.

Fig. 0.1 | "Earthrise", the first picture taken by a human of the Earth rising over the lunar horizon during Apollo 8

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Abbreviations

AS	Ascent Stage (of a lander)
ATHLETE	All-Terrain Hex-Limbed Extra-Terrestrial Explorer
CapCom	Capsule Communicator (modern: spacecraft communicator)
CNSA	Chinese National Space Administration
CMC	Chariot Crew Mobility Chassis
CSM	Command Service Module, Apollo Programme
DS	Descent Stage (of a lander)
ECLSS	Environmental Control Life Support System
ESA	European Space Agency
FAST	Masten in-Flight Alumina Spray Technique
GCR	Galactic Cosmic Radiation
HAVEN	**H**abitable **A**rrival Port, **V**antage Point, and **E**xploration Base for a **N**etwork of Lunar Explorers | *haven*: syn. "port"; a place of safety
HMS	Human Mobility System
ILEWG	International Lunar Exploration Working Group
ISRU	In Situ Resource Utilisation
JAXA	Japan Aerospace Exploration Agency
LM	Lunar Module, Apollo Programme
LRO	Lunar Roving Vehicle
LRV	Lunar Reconnaissance Orbiter
LSMS	Lunar Surface Manipulation System
NASA	National Aeronautics and Space Administration
UPR	Unpressurized Rover
PLSS	Portable Life Support System
PSR	Permanently Shadowed Region
RSWT	Radiation Shield Water Tank
SCR	Solar Cosmic Rays
SLS	Space Launch System
SPE	Solar Particle Event
SPR	Small Pressurized Rover
SMART-1	Small Missions for Advanced Research in Technology (no. 1)
TLI	Trans Lunar Injection

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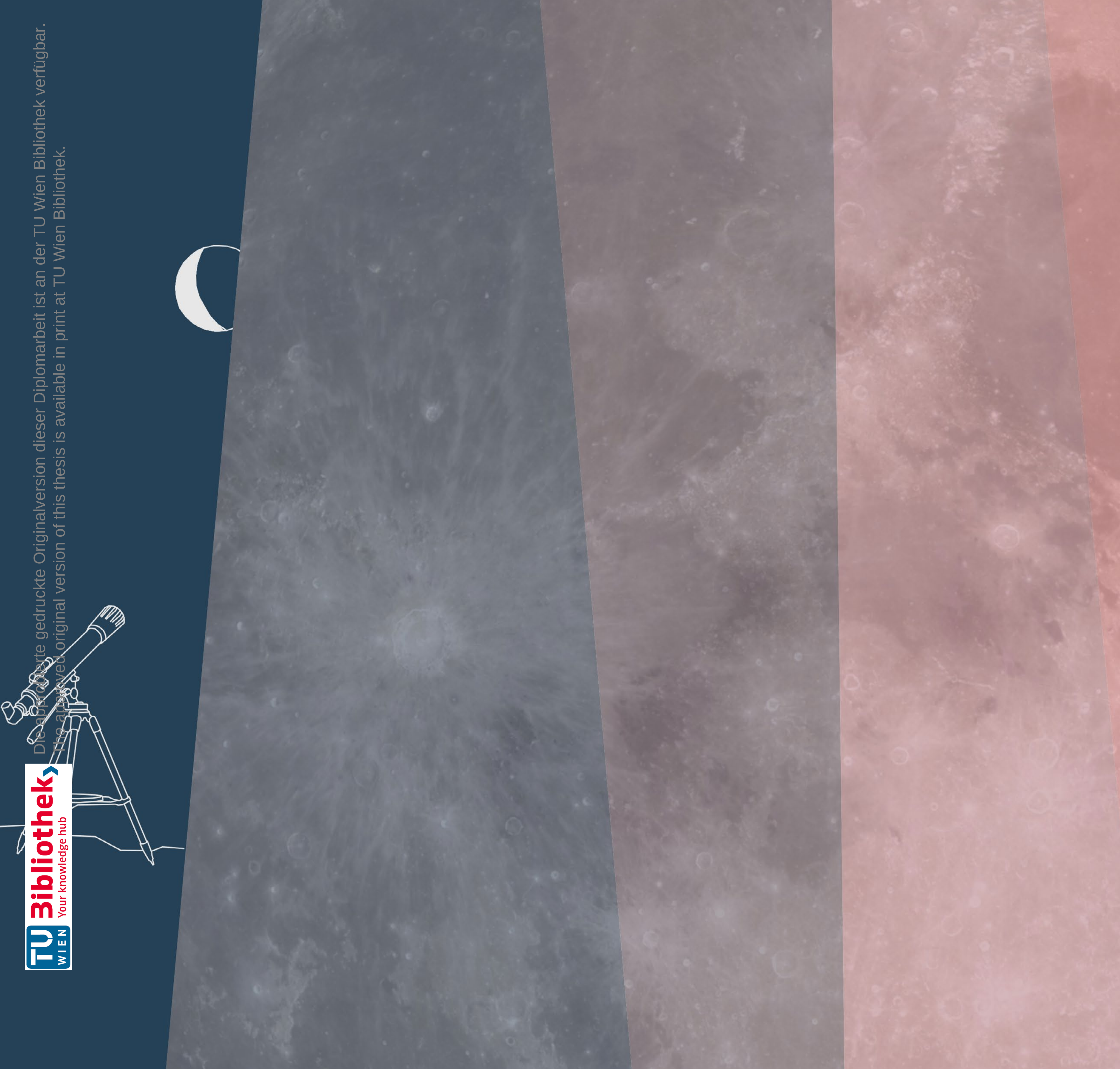
Terminology

direct handover	crew rotation schedule in which the old crew departs after the new crew's arrival; direct contact between the crews (contrary: indirect handover)
lunar staircase	stairs with different dimensions than conventional terrestrial stairs, due to the lower lunar gravity; typically with a rise of 50 cm
microsociety	small circle of social interaction with little diversity and conform social roles; community (contrary: macrosociety)
multi-team	mission team consisting of the core crew and all additional support personell on and off site
percussive excavation	excavation system based on the utilization of high-frequency and low-energy impacts
periselene	periapsis of a lunar orbit; the point in a lunar orbit closest to the Moon (contrary: aposelene)
pneumatic mining	excavation system based on harnessing gas momentum to move particles into a bin
sortie mission	a crewed mission with short duration where the crew performs tasks on the surface of a moon or planetary body (contrary: outpost mission)
suitport	rear-entry spacesuit, attached to and sealed against the hull of a pressurized space module: Suitport Extravehicular Access Facility by M. Cohen;
regolith	a layer of unconsolidated solid material covering the bedrock of a planet or moon
Connecting Ridge C1-0	area on the ridge between Shakelton and De Gerlache craters with favourable illumination conditions; HAVEN site



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CHAPTER 1

Exploring the Moon

The Moon provides anything but a friendly living environment and establishing an outpost on Earth's nearest neighbour will pose significant challenges. An almost non-existent atmosphere, severe danger from radiation and micrometeoroid bombardment, stark temperature fluctuations, and a rough terrain impede any manned activity on the lunar surface. And yet, the Moon has always been a focal point of human interest and exploration. If implemented correctly, a human presence on the Moon offers a multitude of incentives, from various resources over extensive progress in countless scientific disciplines, to deep space access. As a first step towards achieving secure lunar habitation, and thus gaining its many possible benefits, the lunar environment, history, and potential resources have to be understood.

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1.1 Choosing the Moon

In order to achieve secure long-term lunar habitation we need a great deal of supporting technology and knowledge. The disciplines involved in this endeavour reach from technical engineering and advanced manufacturing over medical sciences to sociology and human factors and address applications in autonomous robotic support tools, advanced sensing systems, tele-control, life support systems, and material technology, to name only a few. While both hardware and software innovations in these fields are progressing at high speed, there is still a great deal of research and development to be achieved. (Benaroya 2018, p.14f)

However, despite the undeniable challenges there may be no question whether the goal of a lunar outpost is an objective worth pursuing.

The momentous development of science and engineering alone is a clear argument for further space exploration, as terrestrial applications will benefit greatly from the progress in all disciplines. Furthermore, industrial activity and economic growth will be driven by the continuous challenges and later the availability of lunar resources. (Benaroya 2018, p.14f)

While Mars has gained more and more attention over the last decade, setting up a first long-term outpost on the Moon is the logical choice. As our closest planetary neighbour, the Moon is in a highly advantageous position to Earth. The close proximity and tidal locking allows near real-time communications and remote control of almost constant, worldwide availability. This supports the rapid assembly of habitation facilities and support structures. The small distance between Earth and the Moon will furthermore enable quick assistance in emergency situations. (Schrunk et al 2008, p.xl) A trip to the Moon takes around three days with current propulsion systems, while a journey to Mars would last several months, increasing technological and psychological challenges many times over. (Benaroya 2018, p.12)

The available resources are another argument for a lunar outpost. An abundant variety of elements applicable for construction, life support, and refueling can be found in the lunar regolith; it is highly likely that there is water to be found in the Moon's polar regions; solar energy could be harnessed to power an outpost.

The gravity on the Moon, even if much lower than that on Earth, provides human settlers with the possibility to move in bipedal postures. Furthermore it allows the use of terrestrial technology, like wheeled vehicles, with only little adaptations necessary. (Schrunk et al 2008, p.xl)

From the scientific point of view, the Moon is likewise a most beneficial site for a first settlement. A better understanding of not only the Moon's origin but the evolution of our solar system can be gained by on site research in various geological and geophysical disciplines. Furthermore, the lunar surface provides a much superior base for space telescopes than Earth's orbit. The Moon's far side, which is completely shielded from Earthen radio interference, offers perfect conditions to set up radio telescopes.

Altogether, the most important argument for choosing the Moon as a location over other planetary bodies is the Moon's perfect conditions to serve as a test-bed and gateway for extra-terrestrial exploration and habitation. A base for research, development and production of space-faring requirements on the Moon will enable humanity to use the Moon as a stepping-stone towards far more distant destinations in our solar system. (Schrunk et al 2008, p.xlif)

In an interview with the author, Professor Bernard Foing, ESA Senior Scientist and Executive Director of the International Lunar Exploration Working Group (ILEWG), summarized the objectives of a permanent lunar settlement: *"The Moon is the next continent where we shall expand knowledge, life, humans, and culture. It will be also a place to learn to live off the cradle, before settling at other destinations: asteroids, orbital space, Mars, and planetary Moons."*

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1.2 Lunar Exploration through the Ages

1.2.1 Past

Since the dawn of civilization, the Moon has been an anchor point of human interest; cultures, mythologies and religions were shaped by the study of the Moon. Different iconography, reaching from imagery of prosperity and fertility to dark foreboding and myths, has been allocated to the Moon over the centuries. In many cultures the Moon was even worshiped as a deity. The Greek philosopher Plutarch, convinced that the Moon was inhabited, was confident to see oceans in the dark areas of the Moon - an error that nevertheless came to influence the contemporary denomination of the Moon's 'maria' and 'terrae'. (Jaumann, Köhler 2009, p.14ff)

Fact is, the scientific interest in the Moon goes back many millennia. A remarkable artifact from prehistoric times, the bronze Nebra Sky Disk (fig.1.1), which shows different phases of the Moon, is the first depiction with purely astronomical content and proof of just how far the astronomical interest in the Moon dates back.

Over the centuries, scholars from ancient civilizations, such as Egypt, Babylon, and China, engaged in the study of the Moon; renown Greek philosophers and astronomers expanded humanity's knowledge and worked on calculating the Moon's shape, size, and distance to Earth. While these were still experiments of natural philosophy and shaped by a geocentric view of the solar system, scientists like Tycho de Brahe, Kepler, and Galileo (fig. 1.2) took astronomy and the study of the Moon to a new level in the modern era. The invention of telescopes caused an unprecedented progress in astronomy and especially our knowledge about the Moon. Telescopes quickly grew in size and range; maps of the Moon in accuracy and detail. (Kuphal 2013, p.1ff)

Only one other event is comparable with the boost in science and exploration caused by the telescope – the beginning of

Fig. 1.1 | Nebra Sky Disk, c.1600 BC

Fig. 1.2 | Drawing of the Moon by Galileo based on telescopic observations for his Sidereus Nunicus

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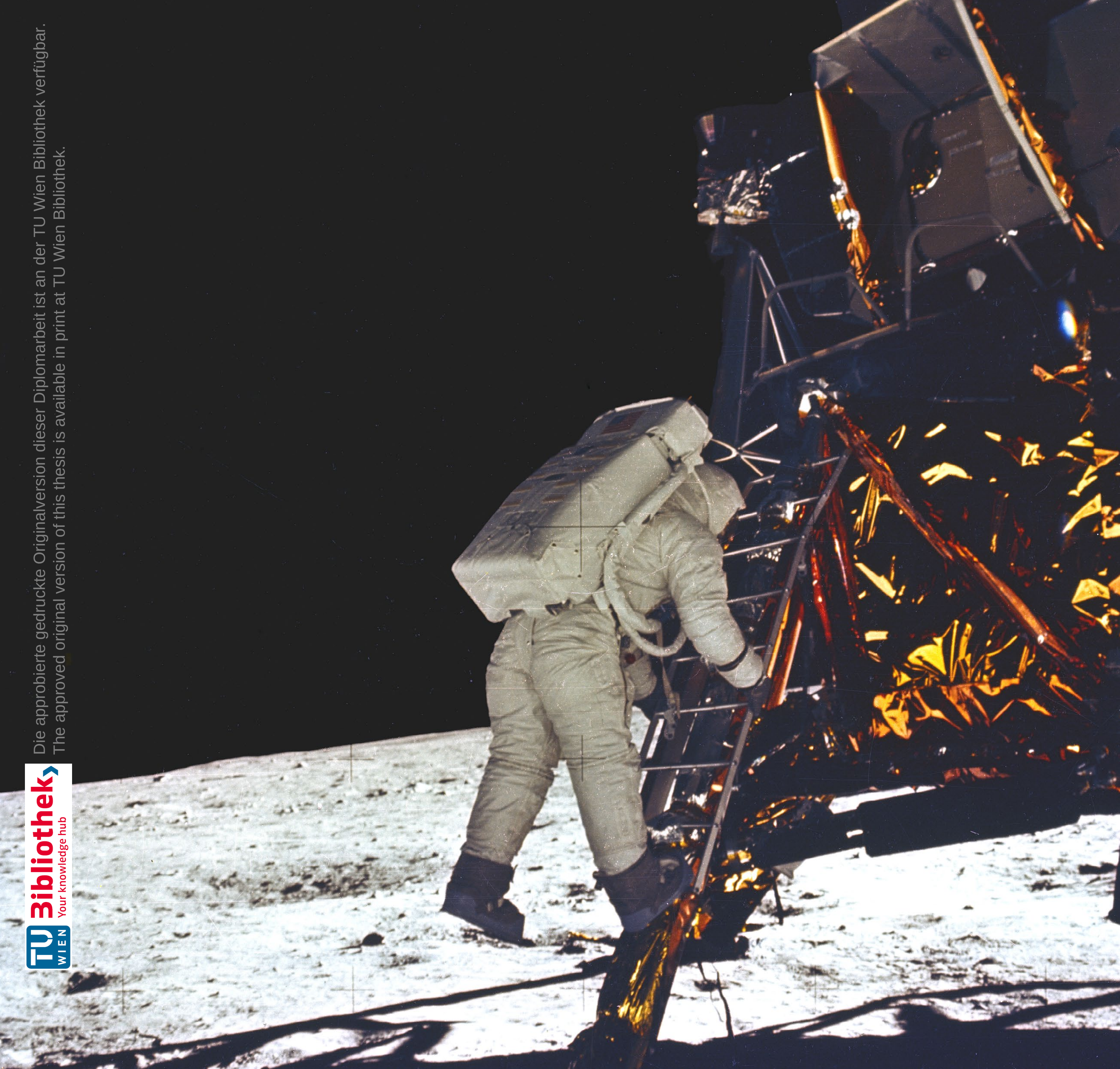
spaceflight in the 1950s.
With the launch of the Soviet satellite Sputnik the race for technological dominance of the space field, and thus the race to the Moon, begun. While Lunik 1, the first probe sent to the Moon, missed its goal by almost 6000 kilometers, Lunik 3 delivered the first images of the far side of the Moon in 1959 and with them a spectacular achievement for the Soviet side. Two years, later the USA officially announced their goal of a human moon landing, which was followed by frantic activity on both sides. NASA launched several successful programs in preparation of the moon landing, namely the Ranger project, five Lunar Orbiters and the Surveyor program to collect data of the Moon's surface and conditions. In combination with the intel collected through the Soviet Lunik Program, which achieved the first soft landing in 1966, humanity's astronomical knowledge expanded manifold and the Moon suddenly seemed much closer. (Jaumann, Köhler 2009, p.30ff)

1.2.2 Present

With Neil Armstrong's 'small step' onto the lunar surface in 1969 a new area in the Moon's history begun (fig. 1.3). It was the end of the Moon race and at the same time the beginning of a more cooperative lunar exploration. 700 million people watched this to date biggest achievement in the Moon's history, accomplished by an incredible amount of research, development, and financial investment and contingent not least upon the invention of the Saturn V rocket through Wernher von Braun, who had led the German rocket program during the Second World War and later became vice president of NASA.
Twelve men walked the Moon in the process of the Apollo missions; 382 kilogram of moon rocks were brought back to Earth. Another 321 gram of lunar soil was brought retrieved by the Soviet Luna 16, 20, and 24. Even if the amount is almost negligible in comparison with the American quantity, this is still an incredible feat of engineering.
The exploration of the Moon didn't cease after the Apollo program. Countless probes and orbiters were sent to gather additional information. China, Japan, and India joined the effort with their Chang'e, Kaguya, and Chandrayaan lunar probes. In 2003 the European Space Agency (ESA) sent the first European probe, SMART-1. (Kuphal 2013, p.32ff)
As the first lunar mission of the new millennium, SMART-1 left Earth's orbit using only solar power and 60 liters of Xenon propulsion. Bernard Foing, ESA's Principal Project Scientist on SMART-1, states: *"SMART-1 contributed to ILEWG's goals of international collaboration in lunar and planetary missions and engaged the public, the youth, and the whole world towards the benefits of a Global Moon Village community."* (Interview with Bernard Foing by the author)

Since 2009, NASA's Lunar Reconnaissance Orbiter (LRO) is orbiting the Moon in a low altitude. The Gravity Recovery and Interior Laboratory (GRAIL) and the Lunar Crater Observation and Sensing Satellite (LCROSS) continue to provide vital new insights. (Kuphal 2013, p.32ff)
So far, three nations have managed a successful soft landing – the US achieved five robotic landings and six manned missions, the UdSSR landed seven probes, including three sample missions, and China achieved two landings, including the first landing on the far side in 2019, another important milestone in the Moon's history. (Xiao et al 2019) In 2019, the first attempt at a soft landing by a private actor was conducted by the non-profit organisation SpaceIL, which is dedicated to achieving the fist Israeli moon landing. Even though the Beerensheet lander eventually crashed into the lunar surface, it reached the Moon and the mission has to be acknowledged as a commendable outset to private lunar landings. (Shydkrot et al 2019)

Fig. 1.3 | Neil Armstrong's historic first step onto the Moon, Apollo 11



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1.2.3 Future

In recent years, lunar exploration has experienced a reinforced interest, not only though a boost by national space agencies and international space organisations, but also through the increasing participation of private companies from various sectors. Disciplines like architecture and design are continuously gaining importance in future plans for the Moon. ESA's concept of the Moon Village (fig. 1.4) has sprouted a multitude of designs for lunar settlements and new approaches to lunar habitability. The Moon Village idea, which calls for a permanent, international presence on the Moon, aims to *"create an environment where both international cooperation and the commercialisation of space can thrive"*. (ESA 2016, par.2)

Currently, the probably best published and most heeded endeavour is NASA's ambitious goal to return astronauts to the lunar surface by 2024. The Artemis program not only aims to return humans to the Moon, but also to achieve the long overdue first female moon landing. A Lunar Orbital Platform-Gateway, short Gateway, which is currently in development, is supposed to act as a command centre and aggregation point for the Artemis missions. While Artemis I and II are planned as respectively uncrewed and crewed test flights, Artemis III is set to achieve a soft landing and surface stay of a few days. Additional Artemis missions however work towards a more permanent presence on the Moon, by constructing a surface habitat for lunar exploration of up to two months. (NASA 2019)

Of increasing importance for both, the Artemis program and other planned lunar exploration missions, are collaborations be-

Fig. 1.4 | A vision of the Moon Village, Foster + Partners

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tween nations, organisations, and private companies. While the space sector remains a highly competitive field and it is not least this competition that drives innovation, the need for international and inter-organisational collaboration can and shall not be denied.

Fig. 1.5 | B. Foing

"We developed with ILEWG and ESA partners the concept of Moon Village with the goal of a sustainable human presence and multiple activities on the lunar surface for multiple users. The goals of the Moon Village include planetary science, life sciences, astronomy, fundamental research, resources utilisation, human spaceflight, peaceful cooperation, economical development, inspiration, training, and capacity building. We can prepare for it with robotic missions and terrestrial demos, as with the ILEWG EuroMoonMars programme."

(Interview with Bernard Foing by the author)

NASA and the Japan Aerospace Exploration Agency (JAXA) have agreed on a collaboration for the Artemis missions and the Gateway (SpaceNews 2019); ESA and the Chinese National Space Administration (CNSA) recently announced an intention of collaborating on future lunar exploration (ESA 2018); several industry actors have partnered up for the development of the Artemis lander (SpaceNews-I 2019). Especially when aiming for big-scaled projects like the construction of a lunar outpost, a cooperative approach will enhance the mission's feasibility. The concept of ESA's Moon Village aims for such an approach of international liaison and versatility in functions.
Jan Wörner, Director General of ESA, described his vision of the Moon Village by highlighting the collaborative aspect: *"Moon Village is not a single project, nor a fixed plan with a defined time table. It's a vision for an open architecture and an international community initiative."* (ESA 2016 par.6)

In 1969 humanity raced each other to the Moon to set foot on another planetary body for the first time in history. Now, in future endeavours, we need to pool our resources, share experience and knowledge, and work together, so we can not only return to the Moon, but achieve our common goal of long-term lunar habitation.

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1.3 Orbital, Physical, and Environmental Parameters and their Impact on Habitation Design

A thorough understanding of the conditions on the Moon is an essential foundation for the successful design of any lunar structure and, in particular, a lunar outpost. Both, structural aspects and habitability requirements of such an architecture, are influenced significantly by the harsh lunar environment. An adaption of conventional design parameters is required; a rethinking of terrestrial approaches is necessary.

1.3.1 Earth and the Moon - a comparison in facts and parameters

When analysing the correlation between Earth and the Moon - the Earth-Moon system - the significant relative size of the Moon in comparison to Earth has to be highlighted. Even though Earth is one of the smaller planets in our solar system, Earth's moon is the fourth largest of all moons.
While the distance between Earth and the Moon shifts with the Moon's travel around Earth, the mean value of the distance can be listed with 384.400 km. (Eckart 1999, p.109f) This results in a travel time of around three days and allows communications with almost no delay. (Benaroya 2018, p.12)
Adding a few centimeters each year to this distance, the Moon is continually moving away from Earth.
Caused by the synchronous orbit of the Moon around Earth, the Moon has a near side and a far side in conjunction with Earth. This means the Moon's rotation is locked to Earth; the near side, the one visible from Earth, is constantly turned toward Earth. The far side, which is eternally averted from Earth, is thus completely and steadily shielded from any electromagnetic interference from Earth. (Heiken 1991, p. 109f)
Despite the tidal locking and close proximity, there are stark differences in the lunar and terrestrial environments (see table 1.1, figure 1.7).

1.3.2 Lunar Gravity

The gravitational acceleration on the Moon measures 1.62 m/sec^2, which is around one-sixth of what humans are used to from Earth's 1 G. (Heiken et al 1991, p.28)
Lunar gravity severely affects both, human locomotion and the load bearing capacities of structures.

Structural Effects

In regard to habitat construction and other structures, 1/6 G means that on the Moon only a sixth of the load bearing strength required on Earth is needed to bear a certain payload. In other words, a result of lunar gravity is that a structure on the Moon can bear six times the weight of what the same structure could bear on Earth. Consequently, the design process for lunar architecture has to focus on mass rather than weight. Haym Benaroya explains this as follows: *"Mass-based rather than weight-based criteria will need to be developed for lunar structural design codes, because mass is invariant whereas weight depends on the gravitational acceleration, as per the equation: weight is mass times gravitational acceleration."* (Benaroya 2018, p.47f) Benaroya furthermore states that lunar gravity also results both in the possibility for much longer spanned structures, as well as in a lower relevance of gravity in the anchoring of structures on the Moon. (Ibidem)

Physiological Effects

In regard to effects on the crew, the reduced gravity raises several medical concerns that need to be addressed. Oxygen metabolism, the blood and cardiovascular system, neurophysiological aspects, and calcium turn-over are some of the fields that are affected by changes in gravity. Issues like these are being inves-

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tigated mainly through zero gravity experiments. (Benaroya 2018, p.47f) However, the exact medical impacts of lunar gravity are not sufficiently analysed as of today. While research has, for example, shown that a serious condition called space-anemia, caused by atrophy of the bone marrow and the immune system, is a result of microgravity, experts theorize that the partial gravity on the Moon might be enough to prevent this medical concern. (Eckart 1999, p.390)
Form an architectural angle of particular interest is the muscle degeneration that is caused by 1/6 G, similar to that faced by astronauts on the International Space Station (ISS). The posture, locomotion, and movements human bodies are used to in 1G would change severely under the influence of lunar gravity. (Häuplik-Meusburger 2011, p.18) On the ISS, astronauts complete a daily exercise of two hours at dedicated facilities in the various ISS modules. The training devices rage from treadmills and grip masters, over ergometers and gymnastic balls, to special applications like the Resistive Exercise Device (ARED), which targets the muscle structure, and the Flywheel device to prevent muscle atrophy and bone loss. Some of these applications can be stowed away when not in use. An integrated vibration isolation system in the facilities makes sure that nearby science experiments won't be disturbed. (Häuplik-Meusburger 2011, p.274)
A lunar outpost would require similar facilities to enable the crew to exercise daily and prevent any negative physiological effects caused by the lunar gravity, while not causing disturbances to work and rest areas in close spatial proximity.

Furthermore, Apollo astronauts mentioned that the low gravity on the Moon has differing effects on the skills learned on Earth. This does not only affect the locomotion ("loping gait") but also the handling of objects (Heiken et al 1991, p.28), and poses a significant challenge to astronaut training on Earth as the application of learned processes will be complicated. Additional training on the Moon upon arrival seems a logical solution to the author of this thesis.

Fig. 1.6 | Astronaut Mark Vande Hei on the treadmill aboard the ISS

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Property	**Moon**	**Earth**
Mass (kg)	7.353×10^{22}	5.976×10^{24}
Radius (spherical) (km)	1738	6371
Surface area (km²)	37.9 × 106	510.1× 106
Mean density (g/cm³)	3.34	5.517
Gravity at equator (m/s²)	1.62	9.81
Escape velocity at equator (km/s)	2.38	11.2
Sidereal rotation time (days/hours)	27.322 days	23.9345 hr
Inclination of equator/orbit	6°41'	23°28'
Mean surface temperature (°C)	107 (day) - 153 (night)	22
Atmosphere (molecules/cm³)	~104 (day) 2 × 105 (night)	2.5 × 1019
Heat flow (average) (mW/m²)	~29	63
Magnetic field (A/m)	0 (small paleofield)	24-56

Table 1.1 | Earth and Moon - a comparison of parameters

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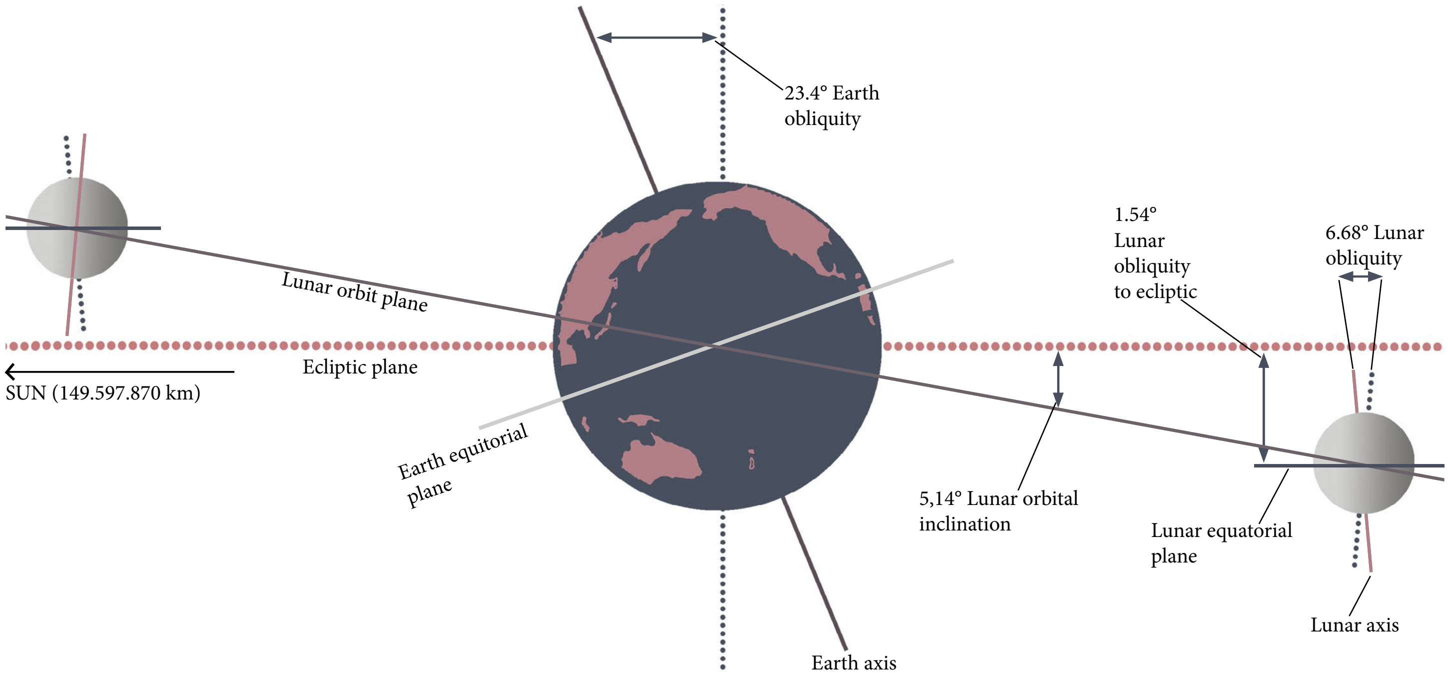
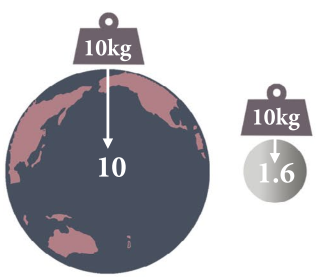
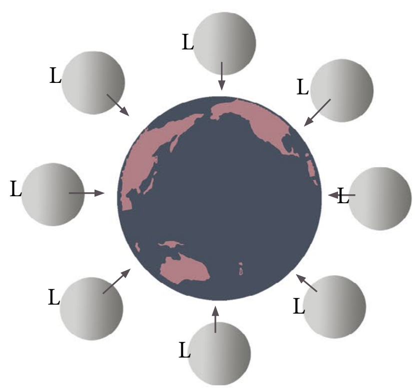
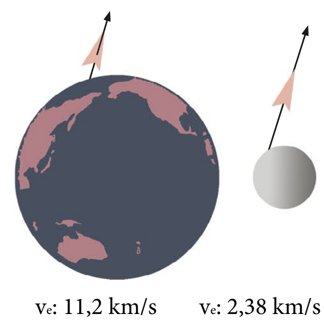




Impact of different gravities:
10 kg on Earth: 10 kg weight scale; 98 N
10 kg on Earth: 1.6 kg weight scale; 16 N



Visualization of the tidal locking between Earth and the Moon (near side, far side), in comparison with the lunar illumination (L)



Comparison of escape velocities

Fig. 1.7 | Earth and Moon - a visual comparison of parameters

note: Earth-Moon relative sizes are to scale;
Earth-Moon relative distances are not to scale. Earth-Moon distance: 384.400 km

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1.3.3 The Lunar Atmosphere

Contrary to common belief, the Moon does have an atmosphere, however, it is almost negligible from a terrestrial point of view, as the lunar atmosphere is extremely tenuous with only 2x105 molecules/cm^3 during the lunar night and even less during the day. In comparison, Earth's atmosphere shows about 14 orders of magnitude more molecules per cm^3. Consequently, the Moon's atmosphere is so thin, that there can be talk of a lack thereof. (Heiken et al 1991, p.40)

This "lack of atmosphere" results in serious challenges for the design of a lunar outpost, the most precarious maybe being radiation and micrometeoroids.

Radiation

Lunar structures need to be designed to protect its inhabitants against various forms of radiation, originating both from deep space and the Sun. In particular, any habitat has to be shielded against Solar Cosmic Rays (SCR), Galactic Cosmic Radiation (GCR), and Solar Wind, which are all types of ionizing radiation. (Eckart 1999, p.144f)

While on Earth, which is protected by its atmosphere, the surface radiation dosages lie between 0.001-0.002 Sv per year, the annual dosages on the Moon can reach up to 0.3 Sv. This is a result of the galactic cosmic radiation, which the lunar surface is not shielded against. The high-energy GCRs are composed of heavy nuclei, protons, and alpha particles. The short-term effects of GCR are only a low risk to humans, however the long-term effects, which are important to be considered in a lunar outpost, can be lethal. To lower this amount to a terrestrial standard of 0.002 Sv, considerable shielding is necessary.

In addition, a lunar habitat design also has to allow for the danger of solar particle events (SPE), which are a row of high-energy protons emitted by solar eruptions. Usually, inhabitants of the Moon aren't in any immediate danger of SPE, however, exposure during solar storms would be fatal and thus extra protection is necessary. Such events can be predicted by systems on Earth or in orbit, which would enable the crew to seek shelter in time.

However, not only the human inhabitants are in danger of radiation, but also the plant life on a lunar outpost, although plants are much more resistant than mammals. (Benaroya 2018, p.46ff)

Furthermore, material degradation and technological failure through radiation is a factor that needs to be calculated for.

In comparison to spaceflight, the radiation dosage on the Moon is considerably lower, as the planet provides shielding against half the environment. But despite this factor, radiation is one of the most severe implications to lunar habitation. Secure radiation shielding is certainly amongst the most important aspects of a lunar outpost design. (Ibidem)

Micrometeoroids

In the Lunar Sourcebook, Grant Heiken et al explain the terminology of micrometeoroids: "*The term "meteoroid" is used for a naturally occurring solid body, traveling through space, that is too small to be called an asteroid or a comet.*[1] *Meteoroids with diameters less than about 1 mm (…) are commonly classified as micrometeoroids.*" (Heiken et al 1991, p.45)

Such meteoroids hit the Moon with considerable velocities. The Moon's side facing into the direction of Earth's motion around the Sun, which changes with the movement of the celestial bodies, is exposed to larger and more hazardous meteoroids. (Eckart 1999, p.148) On Earth, micrometeoroids pose no threat, as such small particle simply burn up in the atmosphere. Merely the occasional larger meteorite manages to reach the ground and cause damage. However, on the Moon, with no mentionable atmosphere to stop them, even the small micrometeoroids can be highly hazardous to surface structures. Consequently, shielding against these impacts is vital. Both direct impacts, which would do immediate damage to the structure, and near-by impacts, which would transfer kinetic energy into the ground as seismic energy, have to be considered in the lunar outpost design. (Benaroya 2018, p.276ff)

1 - This is not to be confused with the term "meteorite"; the suffix "ite" refers to recovered meteoroids, which fell through an atmosphere.

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1.3.4 Lunar Diurnal Cycles and Illumination Conditions

A lunar diurnal cycle lasts 29.53 Earth days, meaning that a full lunar day equals around one month on Earth. Daylight and nighttime are almost evenly split in this cycle. Accordingly, the Moon experiences around 14 Earth days of sunlight, followed by the same duration of darkness. Exceptions to this rule are the poles, where much longer daytime-nighttime periods can be found. (Schrunk et al 2008, p.114) Caused by a 1.54 rotational obliquity, the Sun elevation at the poles is only ±1°32', which leads to radically different illumination conditions than in regions with lower latitudes. Some areas in these regions, such as certain craters, are cast into permanent shadow while other parts of the landscape experience almost constant sunlight. (Gläser et al 2017)

Temperature

The lunar surface is subject to extreme temperature fluctuations during the diurnal cycle. Temperatures from 111°C to -171°C have been measured at the Apollo landing sites. These temperature changes happen rapidly between daylight and nighttime with a speed of about 5°C per hour.
The result of such fluctuations – and another important implication for habitat design – are noticeable thermal expansions and contractions in materials. Any structure on the Moon must thus be designed with these temperature changes in mind; materials have to be selected and combined carefully to withstand the challenges of thermal cycling. (Benaroya 2018, p.42)
Especially extreme temperatures can be measured at the Permanenty Shadowed Regions and Peaks of Light. (Gläser et al 2017)

1.3.5 Resources

Despite the harsh environment, the Moon offers up a broad variety of resources that could be used to support a lunar base. These in-situ resources can be found both on the lunar surface and in the lunar environment.
As every kilogram that has to be brought to the Moon adds significantly to the mission costs, using local materials for construction and life support highly increases the feasibility of a lunar outpost. At large, all elements that can be found on Earth are also available on the Moon, thus enabling a global infrastructure to support both, the Moon and outward directed endeavours. (Eckart 1999, p.607f)

Sunlight

Given the right location, the Moon offers an almost never-ending supply of sunlight. Schrunk et al describe this resource as *"constant, intense and virtually inexhaustible"*. (Schrunk et al 2008, p.52) With 1.365 W/m^2 of energy output when the Sun is in its optimal position, orthogonal to the surface, sunlight is a sufficient source to power any lunar outpost. This could even be accomplished by using only in-situ resources, as photo voltaic solar cells with a conversion factor of at least 20% can be manufactured from the elements compiling lunar regolith. Furthermore, sunlight could be concentrated with mirrors to create high temperatures for material processing. (Ibidem)
From an architectural point of view, sunlight brings the additional merit of increasing habitability by providing natural light.

Regolith

On the one hand, the lunar regolith contains an abundance of elements (fig. 1.8) that can be processed for life support and material production; on the other hand, regolith itself is a building material. It can be placed on top of habitats as shielding or used as a berm to support other structures or create shade. When sintered, regolith can be used to create bricks or similar construc-

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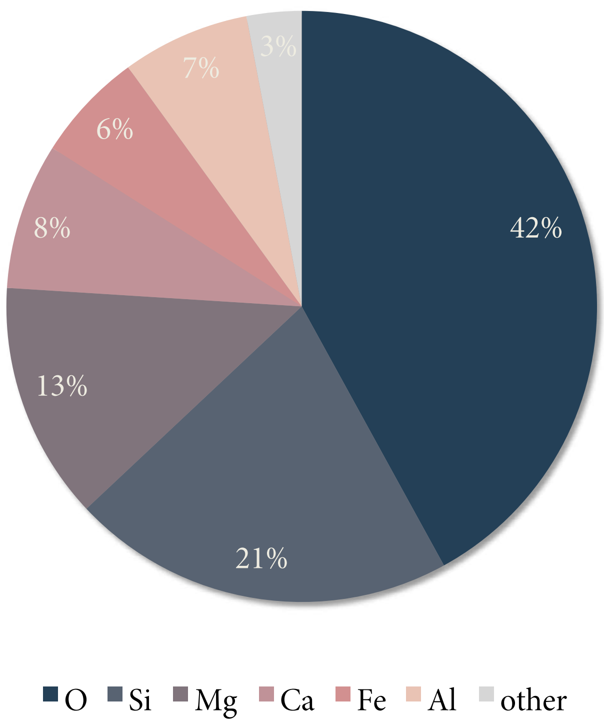

Fig. 1.8 | Lunar regolith composition

Fig. 1.9 (following page)| Peaks of light and PRSs at the lunar South Pole, SMART-1

tion materials. (Schrunk et al 2008, p.51)

In addition, regolith contains small amounts of sodium (Na) and titanium (Ti), as well as following trace elements, which can be used to produce fatty acids, amino acids, vitamins and sugars for life support systems and plastics: sulphur (S), phosphorous (P), carbon (C), hydrogen (H), nitrogen (N), helium (He), neon (Ne), argon (Ar), krypton (Kr), and xenon (Xe). (Schrunk et al 2008, p.50)

Water

The presence of water on the Moon has been long postulated. First suggested by Watson et al in 1961, the search for proof has since engaged scientists around the world.

While water could be created by combining hydrogen and oxygen, both abundantly present in the lunar regolith, it would be far more economic to mine ice-water or hydrated minerals. (Schrunk et al 2008, p.51)

The presence of such ice-water concentrations and water-rich permafrost has recently been confirmed. Especially the polar cold traps show deposits of these volatiles. (Miller et al 2014; Spudis et al 2013)

While useful during robotic missions, for example as a solvent, the precedent purpose of water is to enable life support systems and agriculture during manned missions. Extracted hydrogen and oxygen could additionally serve as propellant. (Schrunk et al 2008, p.51)

1.3.6 Geological Features

Selenodesy, the science of mapping the Moon, nowadays works with highly sophisticated technology, such as data from the LRO. Consequently, it is possible to create highly detailed maps of the lunar surface and its geological features.

Since 1961, such maps display north at the top in accordance with Earth convention. The prime meridian is referenced to a

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small crater named Mösting A. (Heiken 1991, p. 60)
The Moon's most prominent features are the highlands, maria, and craters, which are all distinguishable from Earth with the naked eye. The following list compiles the most important characteristics of lunar geography:

Highlands: The highlands, or terrae, are the Moon's primordial crust and date back about 4.6 billion years; they are visible as light-coloured patches and constitute over 83% of the lunar surface. In detail, they represent around 66% of the surface of the Moon's near side and almost all of the far side. The terrain of the highlands, which lies around 5 kilometers above the mean radius, is described as *rough* and *hummocky*. (Eckhart 1999, p.115ff)

Maria: The terrae's counterparts are the maria, also known as lowlands. These dark parts of the lunar surface, which were originally formed by massive lava flows, are the easiest to observe from Earth; they constitute 17% of the lunar surface and are almost completely located on the near side. The maria lie around 2-5 kilometers below the lunar globe's mean radius and display a relatively flat topography. (Eckhart 1999, p.116)

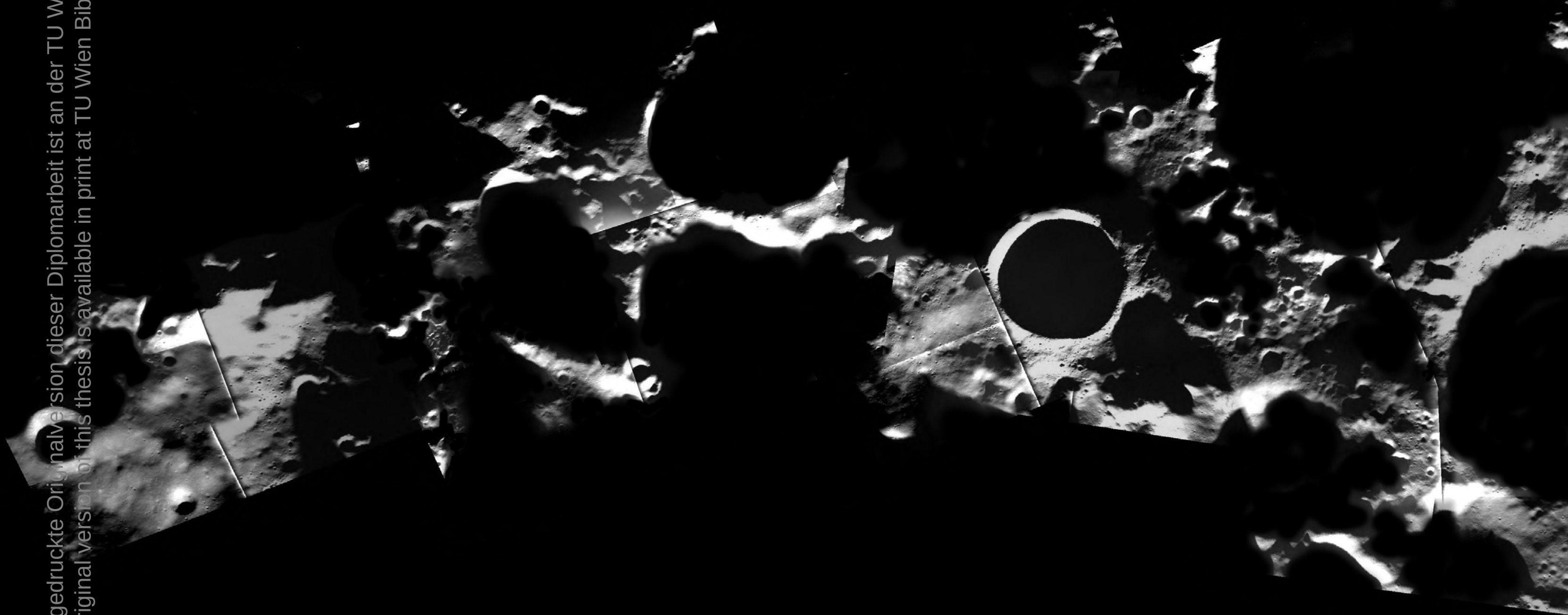
(Mare) domes: With basal diameters of 2.5-24 kilometers and heights of about 100-250 meters, these roughly circular, convex shapes are discernible as positive reliefs on the maria. Some of the domes exhibit summit craters. (Heiken 1991, p.101ff)

Craters: Lunar craters can be divided in two groups, namely impact craters and volcanic craters. Meteorite impacts are assumed to be the main cause for the formation of craters. Crater sizes range from less than a millimeter to thousands of kilometers. Structures with a diameter of less than 15 kilometers are classifies as simple craters; those with a diameter of up to 100 kilometers are called complex craters, as these show a more complex geography with rims and terraces; the largest form of craters are the basins, with the 2500 kilometers wide South Polar Aitken Basin being the vastest.
Craters can be found both in the highlands and maria, however while the highlands are densely cratered, a great deal less craters are to be found in the maria.
Most craters display a roughly circular shape with an elevated rim and a central peak located on the sunken floor. In comparison to their diameters, craters are relatively shallow; the slopes of the craters' walls are quite gentle. A crater filled with lava is classifies as a mare. (Eckhart 1999, p.117f)

Permanently Shadowed Regions (PSR): Permanently Shadowed Regions (PSR) are areas at the lunar poles that are cast into permanent darkness. The phenomenon is caused by the interaction of the very low angle of the sunlight and the hillocky topography. High concentration of volatiles are assumed to be found in the PSRs - amongst others, water in its frozen state, as the PSRs are believed to be some of the coldest areas on the Moon. This classifies PSRs as highly desirable locations for exploration and exploitation. (Gläser et al 2017)

Peaks of (eternal) Light: The counterpart of PSRs are so-called Peaks of Light, areas that experience elongated durations of uninterrupted sunlight. Likewise, caused by the Moon's axis of rotation and the variable terrain at the poles, these are locations on top of topographic heights, such as crater rims, ridges, or mountain tops where the Sun is visible for up to several months in the lunar summer. Such areas are highly coveted locations for lunar outposts, as the availability of almost uninterrupted - hence, *eternal* - sunlight for solar power allows long-duration missions. (De Rosa et al 2012)

Lava Tubes: Lava tubes, caused by drained lava flows, are cavernous systems that could be a highly favourable site for human habitation. Their inside could measure hundreds of meters with a roof thickness of more than 10 meters. Lava tubes would provide natural radiation and meteorite shielding, as well as benign



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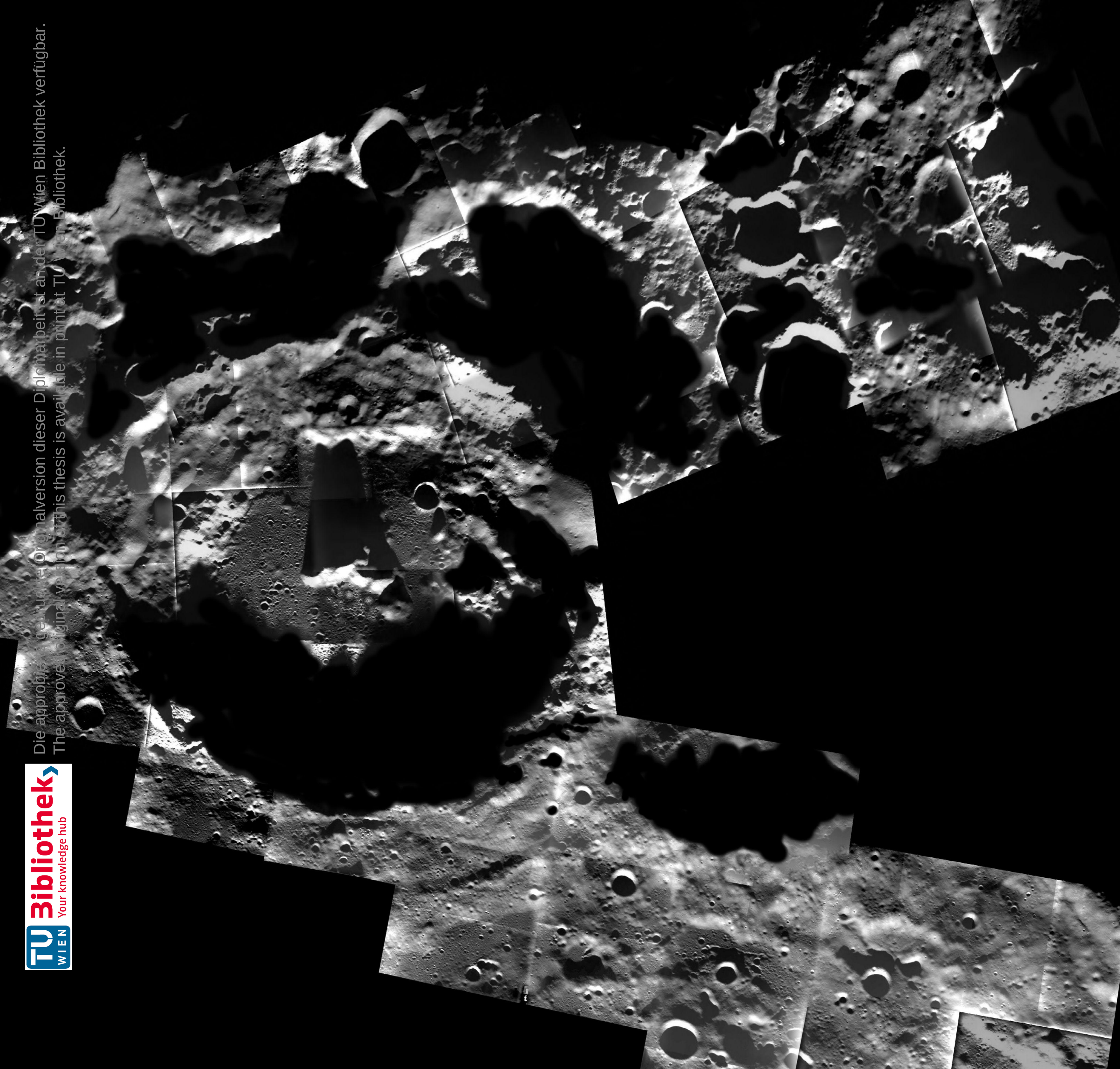

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and most stable temperatures of around -20 degrees. (Eckhart 1999, p.118) While suspected for many years, the existence of lava tubes has only recently been confirmed by scientific data. JAXA's Kaguya (SELENE) mission discovered a lunar skylight of around 60 meters diameter in the Marius Hills region of the Moon's near side. Such skylights are, in accordance with terrestrial lava tubes, assumed to be the entrance to the tubes. (Benaroya 2018, p.188) As of today, no lava tube has been accessed by humans or robotic systems, and almost all of the parameters associated with them are still subject of speculations.

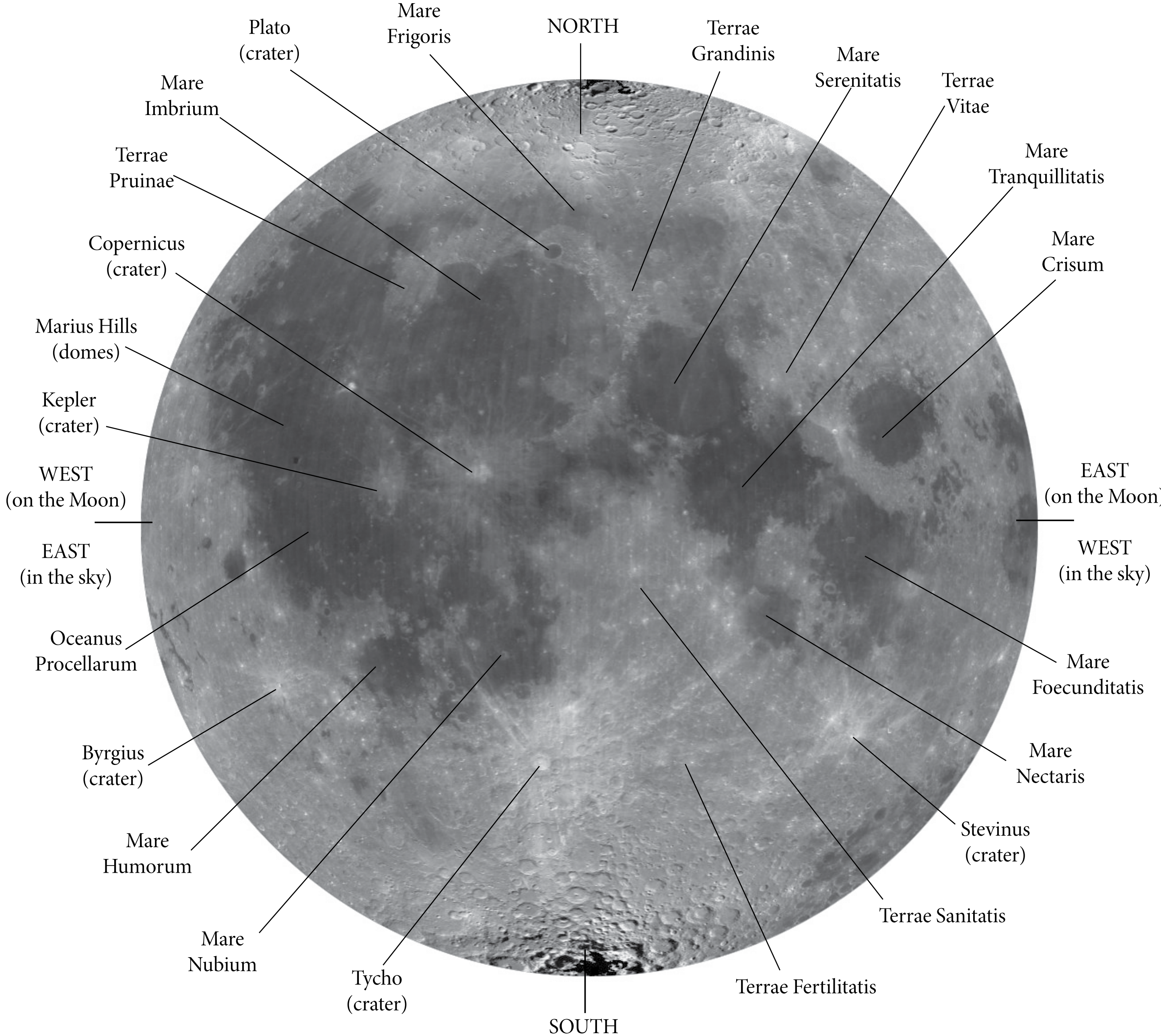
(Sinous) Rilles: Sinous rilles are U or V-shaped channels in the lunar surface that range from a few meters to 3 kilometers width with a length of up to 300 kilometers and a mean depth of about 100 meters. Usually rilles start at a crater or similar geographic feature and fall down into the smooth maria where they eventually fade. While in pre-Apollo times collapsed lava tubes had been theorized as the main cause of origin for rilles and dedicated research during Apollo 15 could indeed confirm a connection between basaltic lava flows and sinuous rilles, the exact formation process of rilles has yet to be understood. (Heiken 1991, p.99ff)

Nomenclature

Concerning the nomenclature of lunar geography, the International Astronomic Union (IAU) decided on a standardized system: (Heiken 1991, p.60)

(i) Craters and rings or walled plains are designated by the name of an astronomer or prominent scientist deceased, written in the Latin alphabet, and spelled according to the recommendation by the country of origin of the scientist named.
(ii) Mountain-like chains are designated in Latin by denominations allied with our terrestrial geography. Names are associated with the substantive Mons according to the Latin declension rules and spelling. (Three exceptions, Montes d'Alembert, Montes Harbinger, and Montes Leibnitz are preserved, due to former long use).
(iii) Large dark areas are designated in Latin denominations calling up psychic states of mind. These names are associated, according to the Latin declension rules and spellings, to one of the appropriate substantives Oceanus, Mare, Lacus, Palus, or Sinus. (The exceptions Mare Humboldtianum and Mare Smythii are preserved, due to former long use).
(iv) Isolated peaks are designated according to the same rules as for the craters, as well as promontories, the latter being preceded by the Latin substantive Promontorium.
(v) Rifts and valleys take the name of the nearest designated crater, preceded by the Latin substantives Rima and Vallis (The exception Vallis Schroter is preserved).
(vi) Undenominated features can be designated by their coordinates. They can equally be designated according to the former classical system, by taking the name of the nearest crater, followed by a block letter of the Latin alphabet for craters, depressions and valleys, by a minor letter of the Greek alphabet for hills, elevations and peaks, and by a Roman number followed by the letter r for the clefts.

Fig. 1.10 | The Moon's geological features explained (near side)



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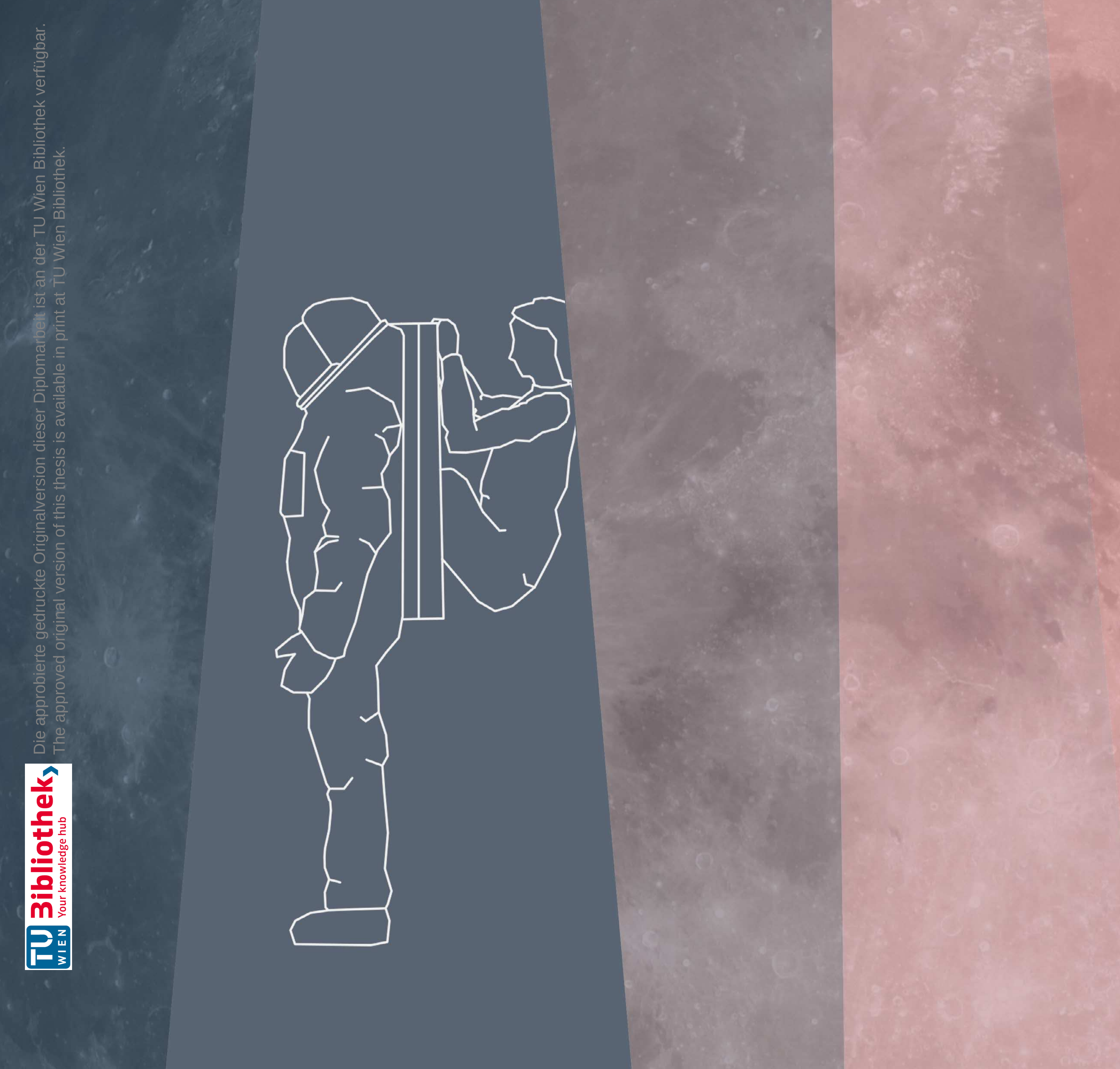

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CHAPTER 2

Structural Concepts and Materials for a Lunar Outpost

In order to enable a safe and functional lunar habitation, an outpost on the Moon has to address numerous challenges posed by the lunar environmental parameters. Technical solutions like multilayer-shells provide shelter from radiation, temperature, and micrometeoroids; life support systems permit the control of environmental factors inside the habitat.
A careful selection of the structural composition, materials, and additional technical factors is vital for the design process.

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2.1 Lunar Outpost Structures

According to Haym Benaroya, structures on the Moon can be grouped into three different categories, namely:

- habitats
- storage facilities or shelters
- supporting infrastructure

A considerable overlap in the design of these structures causes an easier design and fabrication process, however the commonality also bears the threat that a single part defect could affect the whole system. It is thus recommendable to aim for a common strategy in regard to materials, systems, or parts, while ensuring that the systems maintain some individuality. (Benaroya 2018-I, p.18) Particular notice has to be paid to the spatial allocation of the different structures on a lunar outpost compound (fig. 2.1). Especially the habitation structures need to be at a safe distance to any potentially harmful elements.
In addition to the habitation structure, Kriss Kennedy et alius defined several other zones that all should be located at a safe distance from the inhabited area:

- the launch and landing zone
- the power generation zone
- the science and industry zone
- the ISRU zone

Kennedy et al explain the necessary balance of safe distance and close proximity between and within these structures: *"While the distance in location provides the capability to run the different zones as separate elements and protects the habitation zone from damage in case of failure at another zone, the different areas, especially the launch and landing zone, are closely tied together."* (Kennedy et al 2007, p.19f)

Habitation Structure

A list of requirements for extra-terrestrial habitats was defined by Benaroya. While all the items on the list influence habitability, most of them require a primary technical solution. However, the human factors should always be kept in mind, when deciding on the technological aspects of the design: (Benaroya 2018, p.87)

- pressure containment
- atmosphere composition/control
- thermal control (active/passive)
- acoustic control
- radiation protection
- meteoroid protection
- integrated/natural lighting
- local waste management/recycling
- dust control
- airlocks with scrub areas
- emergency systems
- psychological/social factors

In regard to the location, it has to be kept in mind that each element for the habitat, as well as each astronaut, has to travel the distance between the landing zone and the habitat, ergo these two zones must be integrable despite remaining at a safe distance. (Kennedy et al 2007, p.19f)

Launch and Landing Area

The exhaust plume from a lunar landing vehicle poses numerous risks to surrounding infrastructure. Dust particles and bigger sized rocks are ejected from the lunar surface and sent traveling great distances at high velocities. The landing of the Apollo 12 Lunar Module, for example, thoroughly sandblasted the surface of the Surveyor 3 spaceship, when it landed in relative close proximity of 160 meters. (CLASS 2020) Such high-velocity ejecta can cause serious damage to the lander and other nearby facilities, as well as spread dust into the lunar orbit. Blast protection

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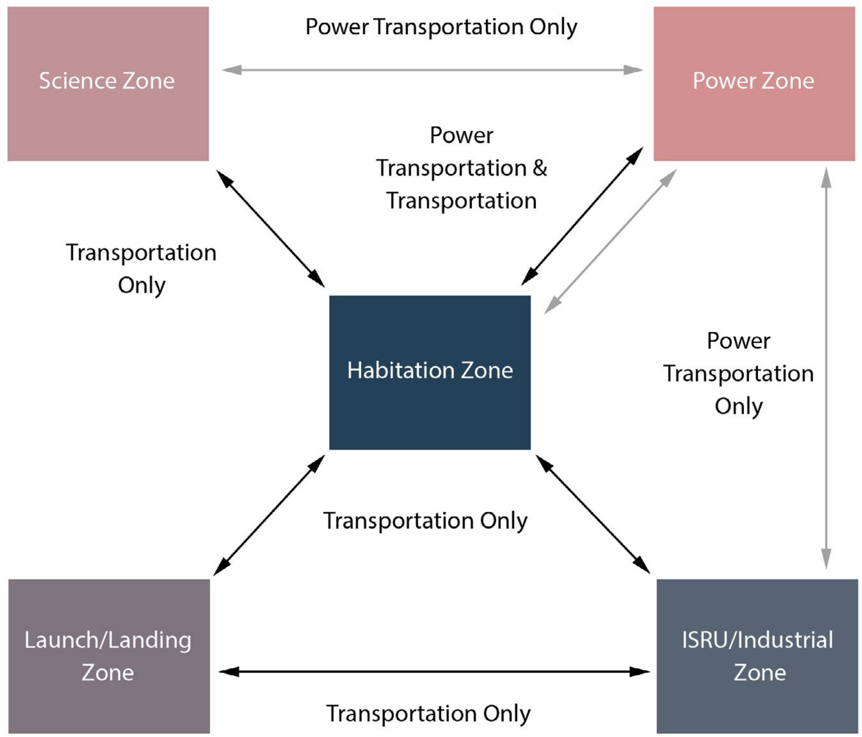

Fig. 2.1 | Schematics for surface outpost organisation by Kennedy et al

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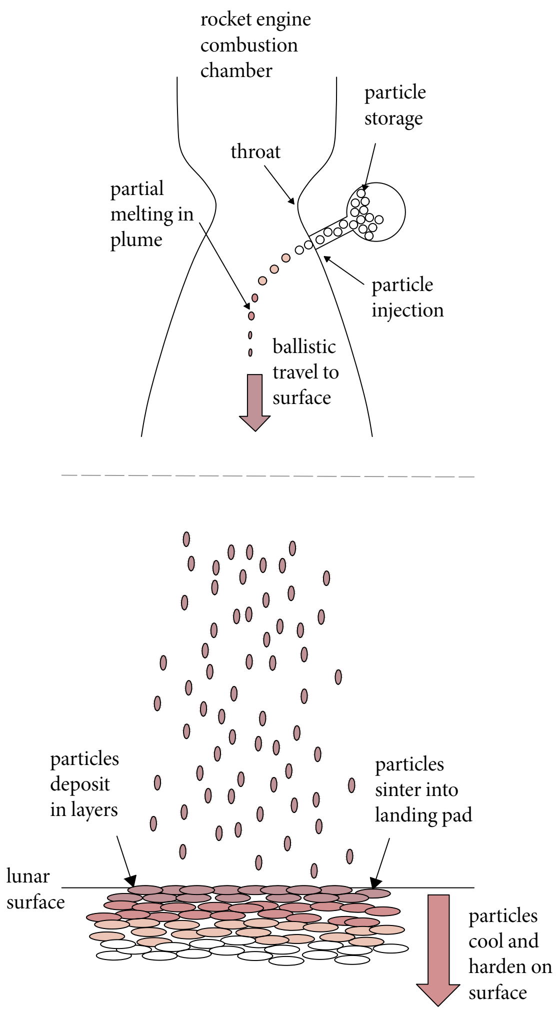

Fig. 2.2 | FAST particle injection in the lander engine (top) and deposition on the surface (bottom)

berms can reduce the ejecta damage but won't fully mitigate the danger, as they won't stop dust particles spreading in the lunar vacuum. The construction of a suitable landing pad, which can withstand multiple landings and additional activities, is necessary. (Nannen et al 2019, Van Susante 2012)

The positioning of the launch and landing pad has to ensure that neither launching nor landing vehicles cross over the habitation zone; other zones should be avoided in the flight path at best possibility. While early missions would allow a closer proximity of habitation zone and launch and landing pads, separate locations should be created for these zones as fast as possible and surely before allowing additional landings while the habitation zone is occupied. (Kennedy et al 2007, p.19f) Metzger et alius argue that any human landing should be preceded by the in-situ construction of a secure landing zone. (Metzger et alius 2009)

Early, Non-Reusable Pads

In the early stages of the base construction, unprepared, non-reusable pads could be used with a distance of 250-400 meters between the landing pad and the habitat. However, the habitat should always lie outside the landing ellipse of around 100 meters. (Phillips 1992, p.143f)
A novel approach for such unprepared pads for early mission stages is the Masten in-Flight Alumina Spray Technique (FAST) landing pad, which is currently under development by NASA. FAST creates an instant landing pad underneath the lander as it descends, by using particles injected into the rocket plume to create a coating over the landing area (fig. 2.2). (NASA 2020)

Permanent, Reusable Pads

The permanent, reusable landing zone for later phases should remain in maximum walking distance of the base, which enforces a proximity of at least 3-5 kilometers. The size of the pad is dependent on the margin of landing error and lander size. A suitable pad size would be around 100 meters across. (Phillips 1992, p.143f)

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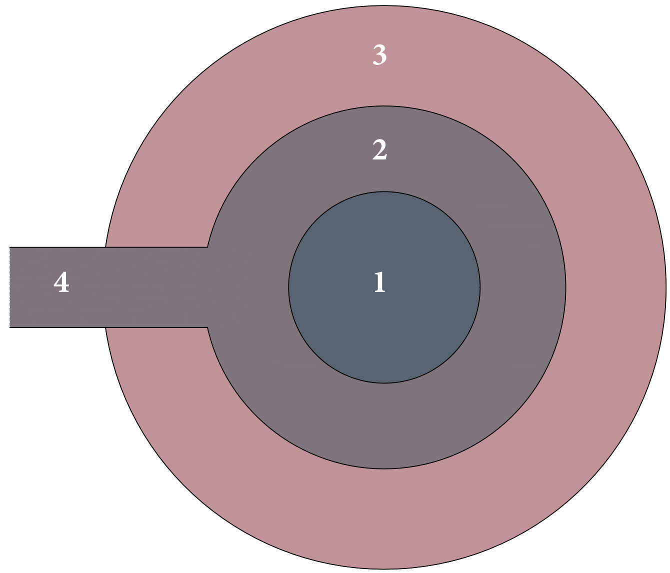
Paul van Susante defined a list of activities a permanent landing pad needs to withstand. (Van Susante 2012)

- landing
- hovering
- launching
- crashing
- exploding
- driving on (vehicles)
- walking on (astronauts, robots)
- crane lifting
- refueling
- maintenance
- lunar Environment
- manufacturing
- repair
- minimize debris / sandblasting of other assets
- safety

Several construction techniques have been suggested for launch and landing pads. While not one single method has yet been confirmed as ideal in all aspects, the Centre for Lunar and Asteroid Surface Science (CLASS) has established a Planetary Landing Team from the world's leading experts to develop landing pad technology and materials to mitigate plume effects. Currently under research are lunar regolith sintering and lunar concrete, the use of gravel and pavers, robotic tools for grading and compacting landing zones, 3d-printing regolith, and several non-ISRU methods like inflatable berms. (CLASS 2020)

Excavating the loosely packed top layers of regolith to bare the densely compacted regolith at 30 centimeters depth is one promising approach. (Mueller et al 2009) A novel concept envisaged by Van Susante and Metzger uses in situ rocks in a multi-zone approach (fig. 2.3). For this, the landing pad consists of a temperature and gas resistant central zone with a sintered surface or interlocked pavers. An outer apron, which doesn't need to resist direct



1 - thick overlapping pavers on top of compacted regolith
2 - compacted regolith with protective cover
3 - compacted regolith and rocks
4 - connection road to transport support equipment and crew

Fig. 2.3 | Layout of a multi-zone landing pad, based on Van Susante

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plume impingement but prevent soil erosion by a horizontal layer of gas, can carry supporting equipment like rovers or landing beacons. (Van Susante 2012; Van Susante, Metzger 2016; Van Susante et al 2018)

Power Generation Zone

The power generation facility should be in close proximity to the other zones in order to reduce transmission losses, while still ensuring safety measures against possible contaminations. Nuclear generators need a minimum distance of several hundred meters, while solar arrays need to be protected from the dust generation of other areas. (Kennedy et al 2007, p.19f)

Science and Industry Zone & ISRU Zone

Depending on the mission objectives, a separate science and industry zone would protect the research from disturbances from other zones. (Kennedy et al 2007, p.19f)
The location and layout of the ISRU zone depends heavily on the exploited resources; conventional lunar mining equipment and cryogenic storage equipment is amongst the vital equipment. This zone requires special attention to dust-shielding, to prevent contamination of the other facilities. (Ibidem)

2.1.1 Structures at the HAVEN Compound

The main focus for the design of the HAVEN Lunar Port and Base lies on a habitation facility, a storage hangar for lunar lander components, and a launch and landing zone to support a coordinated and safe arrival procedure for the exploration of the lunar South Pole. A small ISRU facility evolves in size as various missions progress; a separate science facility can be added in later expansion phases of the outpost.

Habitation Structure

The habitable structure at the HAVEN outpost is intended for a long-term crew of four astronauts who will run the arrival port and research the effects of lunar habitation. In addition, the habitat offers room for four shifting crew members from various missions, which will spend the initial days (up to ten days) of their lunar stay in the HAVEN habitat to adapt to the environment and get trained in lunar gravity locomotion by the permanent crew.

Storage Hangar

HAVEN's storage hangar facility serves to put landing vehicles, as well as their disassembled components, into interim storage.
The hanger is not pressurized but provides shelter from radiation, micrometeoroids, and the most extreme temperature fluctuations, thus preventing material degradation and damage through micrometeoroids.

Launch and Landing Pad

The launch and landing area at the HAVEN facility provides a permanent, reusable pad at a safe distance to the habitation zone; it is accessible via rovers and in emergencies on foot. This landing area serves as an arrival zone for lunar explorers, who will - after an initial acclimatisation stay and training at the HAVEN habitat - be distributed to other outposts at the lunar South Pole. During the prestaging and robotic construction phase of the HAVEN compound, instant pads with the FAST approach will be used in close proximity to the construction sites. A permanent reusable pad with a multi-zone approach and an overall diameter of 120 meters will be created before the arrival of the first crew. This arrival zone will be set at a safe 2 kilometers distance to the HAVEN habitat.

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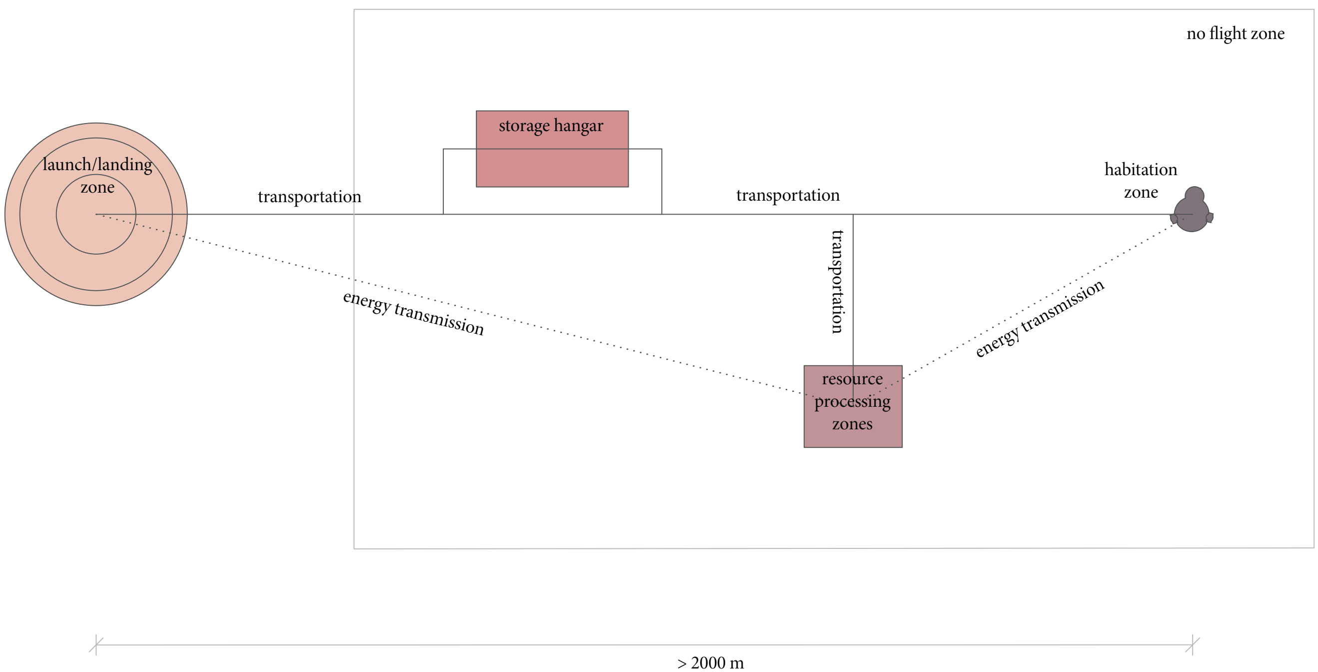

Fig. 2.4 | HAVEN compound layout - schematic
(see Fig. 6.1 for a detailed sitemap)

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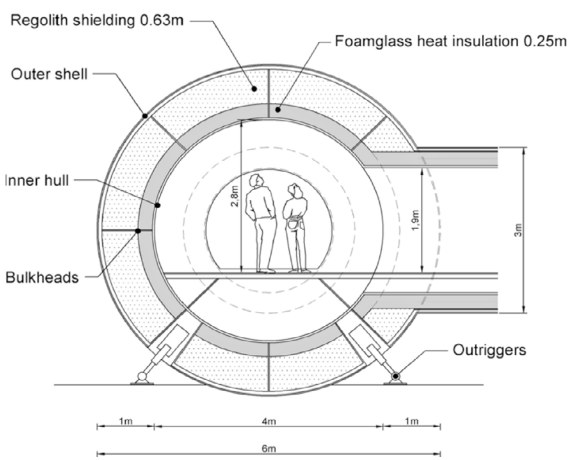

Fig. 2.5 | LESLA concept, Boeing

Fig. 2.6 | Cross-section of the double shell system, rigid base by W. Grandl

2.2 Habitat Composition

Basic compositions for lunar habitation have been categorized into three classes by Kriss Kennedy and Marc Cohen in NASA's Habitats and Surface Construction Technology and Development Roadmap. (Cohen, Kennedy 1997)

a) Pre-integrated, hard shell modules

The construction of these types of habitats is entirely Earth-based. The structure is manufactured and integrated before being delivered to orbit or a planetary body, where it can be used immediately. Pre-integration on Earth allows the structure to be fully tested before launch, however it also limits volume and mass to the launch vehicle payload size capabilities. (Kennedy et al 2007)

b) Pre-fabricated, surface assembled habitats

These flexible habitats focus on the fabrication, but not integration, of a structure on Earth. Once launched to space, or placed on the site of habitation on a planetary body, the structure is deployed autonomously. The use of such deployable or inflatable modules allows for an increase in volume, as the habitat is much less restricted by the launch vehicle's payload capabilities. Critical subsystems can still be tested on Earth before the launch. The habitat requires assembly time by humans or robotics prior to being used. (Ibidem)

c) ISRU-derived structures with integrated Earth components

Deriving structures from in-situ resources means that the habitat is manufactured on site under the use of indigenous materials. The autonomous on site construction bears the necessity for manufacturing machinery and infrastructure, as well as failure detection and self-repair capabilities. While critical subsystems can still be tested and launched form Earth, these subsystems need to be integrated on site. The construction process,

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including internal outfitting, requires human and robotic time investment prior to the habitation phase. ISRU-derived structures are least restricted in regard to size and volume. (Ibidem)

2.2.1 Rigid Structures

Lunar habitats that draw on rigid compositions are abundantly present in early designs. Their compositions are mostly kept as simple as possible, using existing technologies and minimizing both lunar surface preparation and crew activity time.

An initial concept for the Lunar Exploration System for Apollo (LESLA) envisaged in 1963 by Boeing shows a simplistic upright cylindrical module for up to six astronauts (fig. 2.5). Regolith shielding on top oft the structure, as well as in between the inner and outer walls, provides shielding. (Benaroya 2018, p.105ff)

A design study by Werner Grandl for the European Space Exploration Programme AURORA suggested a lunar base assembled from six rigid cylinders, which are made from aluminium sheets. Each module has a length of 17 meters at a diameter of 6 meters; the outer walls are built as double-shell systems with 0.25 meters foam glass heat insulation and 0.65 meters of regolith filling to shield against radiation, temperature, and micrometeoroids (fig. 2.6).

The base is intended to host a crew of eight with the potential of adding additional modules to expand to a larger settlement. Each of the six modules would be launched with an ARINAE 5 rocket; in addition a tele-operatable rocket crane for landing the structures is required. (Grandl 2006)

Despite the benefits simplistic rigid designs offer, possible structures are liable to payload and landing capacities. As Benaroya explains fittingly: *"While rigid structures are still likely to be the first and the early lunar surface habitats, we expect that rigidized inflatables and ISRU-derived, layered, manufactured structures are increasingly likely early-on."* (Benaroya 2018, p.114)

2.2.2 Inflatables and Deployables

Inflatable and deployable[2] structures are high-strength materials, that are stacked together to form the outer shell and pressure hull of space habitats. Such modules permit fully integrated structures with a larger working volume than the volumetric payload capacity of the launch vehicle. Furthermore, they can provide some measure of flexibility while under pressure. (Chmielewski 2001) In addition, the use of inflatable structures can considerably speed up the construction of a habitable space on the Moon, given suitable packaging, deployment, and possibly rigidization. (Benaroya 2018, p121)

A successful deployment has to be preceded by an adequate site preparation, such as smoothing or excavating the surface. (Ibidem)

Despite notable design challenges, such as structural and material aspects, suitable packaging, deployment, and potential rigidization mechanisms, the inherent benefits of deployable elements make them attractive alternatives to rigid designs. Benaroya defined following advantages of inflatable structures over a rigid approach in the space environment: (Benaroya 2018, p.114ff)

- 50% weight advantage, due to the material thickness of 0.25 mil to 10 mil
- 25% packaging advantage
- inherent strength due to load resistance over a large surface
- reduced costs
- possible repeated inflation
- variety of possible shapes
- favourable dynamics regarding resonances
- favourable thermal behaviour due to ability of large surfaces to reject heat

2 - The terms inflatables and deployables are used inconsistently throughout literature. There is a tendency to use inflatable for soft and foldable materials, whereas deployable refers to mostly rigid but nevertheless foldable structures. This thesis, while using the terms interchangeably, shall adhere to that inclination.

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LEVEL 4
Pressurized Tunnel Area

LEVEL 3
Stowage, Crew Health Care

LEVEL 2
Mechanical Room, Crew Quarters

LEVEL 1
Wardroom, Galley

Fig. 2.7 | TransHab, NASA

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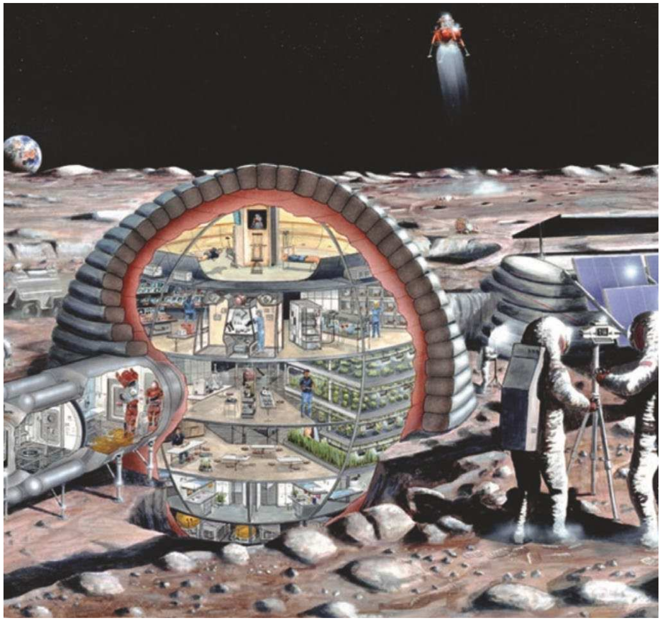
Fig. 2.8 | Inflatable Lunar Habitat, structure, JSC, Roberts

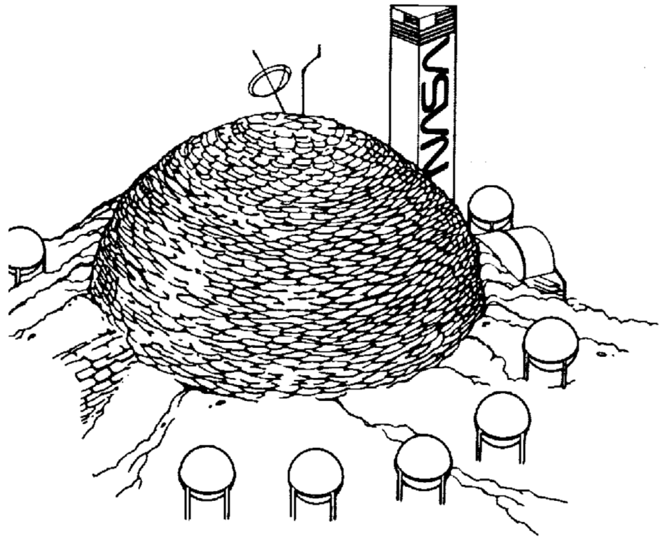
Fig. 2.9 | Regolith-filled sandbag protection, JSC, Roberts

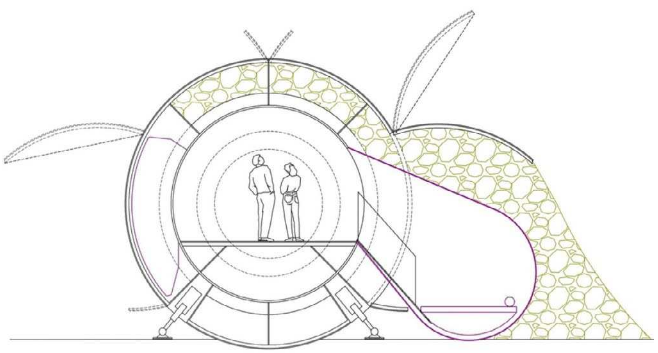
Fig. 2.10 | Inflatable extension to the Rigid Lunar Base, W. Grandl

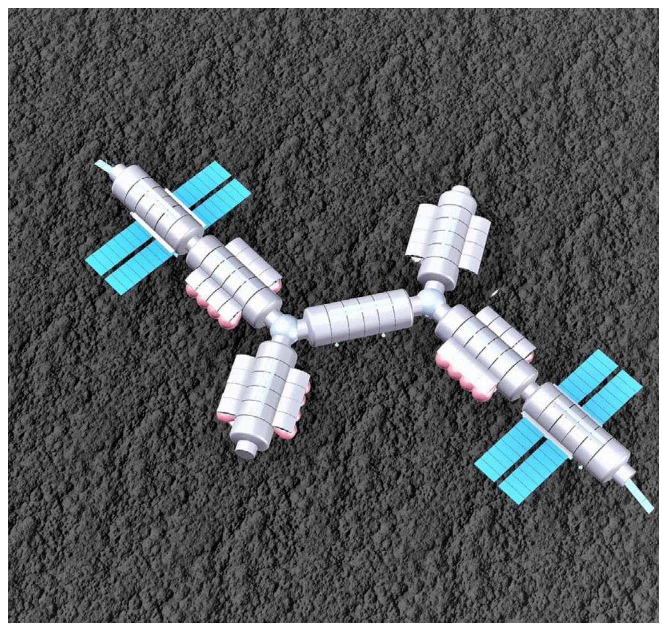
Fig. 2.11 | Visualisation of the extended Rigid Lunar Base, W. Grandl

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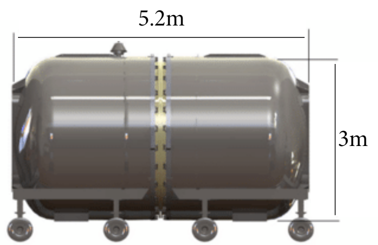
Deployable structures have been profitably applied both on Earth and in LEO, drawing on a short but intense history of success as space applications. Beginning in the 1950s, the field of application for inflatables in the space sector spans a broad variety of operations. Sandra Häuplik-Meusburger and Kürşad Özdemir give an overview of the history and ambit of inflatables and deployables, ranging from the first pneumatic constructions over the use of inflatables by Goodyear Aerospace Corporation for search radar antennas, radar calibration spheres, and inflatable parabolic reflectors, to the deployment of inflatable airlocks and the development of long duration habitats, such as NASA's TransHab (fig. 2.7). They also highlight space suits as *"the smallest nflatable habitat"*. (Häuplik-Meusburger, Özdemir 2012, p.473)

While the numerous applications of inflatables in space would go beyond the scope of this thesis, there are several notable concept designs for lunar habitation with the use of inflatable designs.



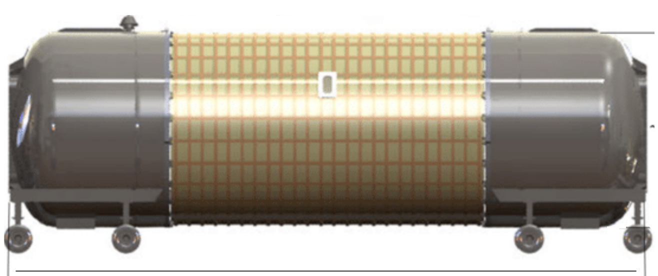


Fig. 2.12 | X-hab, undeployed and deployed, ILC Dover

Case Example: Inflatable Lunar Habitat | Johnson Space Center, M. Roberts

An early concept for inflatable lunar habitation was presented by M. Roberts in course of the Johnson Space Center's 'Lunar Base Systems Study'. The habitat for a crew of a dozen astronauts leverages the volumetric benefits of a sphere with a diameter of 16 meters (fig. 2.8, fig 2.9). A structural cage is used to support both the envelope in case of pressure loss, as well as the interior fitout, allowing for a sizable open volume of 2145 m^3 with five interior levels. From highest to lowest, the levels encompass crew quarters, crew support, base operations, mission operations, and ECLSS and stowage. The airlock for dust migration mitigation is set on level 2, meaning that the sphere's lowest two levels lie beneath the lunar surface.

To shield the rest of the habitat from radiation, the design proposes placing a 3 meter layer of regolith in sandbags on top of

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the structure (fig. 2.11).
In the description if this concept, Roberts lists the benefits of inflatable designs, namely cost savings due to smaller launch payloads, the possibility to work with and test bulky equipment inside the pressurized volume, and interior expandability. Furthermore, Roberts mentions another – and in his words "*the greatest*" – advantage of inflatable habitats, namely the increase of habitability through the possibility of perceptible volume. (Roberts 1992, p.250)
In a later adaption, structural adjustments to the interior framing and exterior support structures are made and the crew quarters are relocated to the lowest level for an increased radiation protection. (Benaroya 2018, p120)

Case Example: Initial Lunar Camp | W. Grandl, C. Böck

Grandl recently suggested an adaption to his rigid base design for AURORA. Inflatable elements expand the rigid cylinders to create additional pressurized volume that can be used as private quarters (fig. 2.10, fig. 2.11).
To counteract the structural challenges of these inflated elements, Grandl highlights the importance of adding additional protection through a layer of regolith right after inflation. Integrated heat fabrics are used to minimize the temperature difference between the inner surface and the internal air. (Grandl, Böck 2020)

Case Eample: Expandable Lunar Habitat | ILC Dover

A more current study is the concept for ILC Dover's Expandable Lunar Habitat, subbed X-Hab, which was part of a larger study of inflatable space habitats conducted for NASA's Constellations Program. The design envisages a flexible module made from Vectran, which is stored in a one-meter segment between two rigid end-caps during launch and flight (fig. 2.12). On the chosen site of habitation, the mid-section, as well as a light-weight floor structure, is deployed to a length of 5 meters (fig. 2.13). A coating of the pressure bladder, which is operable at 9 psi internal pressure, prevents leakage of the inflation gas. During flight mode, the rigid end caps act as logistics storage. (Häuplik-Meusburger, Özdemir 2012, p.497f)

2.2.2.1 Structural Setup of Inflatables

The setup of an inflatable structure consist of various high-strength materials that are stacked up to provide both structural and environmental protection. According to Gerard Valle et al this setup can be broken down in five primary sub-assemblies (interior/pressurized to exterior/unpressurized): (Valle et al 2019)

1 - Inner Liner Layer
2 - Bladder Layer
3 - Restraint layer
4 - Micrometeoroid/Orbital Debris (MMOD) Protection Layer
5 - Thermal Protection (MLI) Layer

The **Inner Liner** is the inner-most layer, directly bordering the habitable space and also known as a scuff layer, as it creates a barrier between the inhabitants and the rest of the structure. It has to be flame and puncture resistant, durable, easy to maintain, and provide acoustic dampening. A well-suited material for this layer is the highly resistant Nomax. (Ibidem)

The **Bladder** is the habitat's gas barrier and thus categorized as the most critical layer. It is common to compose this pressure bladder of multiple layers in order to increase the safety through redundancy. The materials used for this layer are mainly polymeric and need to be durable, flexible, and have a low permeability at both high and low temperatures. The various bladder layers can be separated by bleeder layers to protect the individual bladders from damage. (Ibidem)

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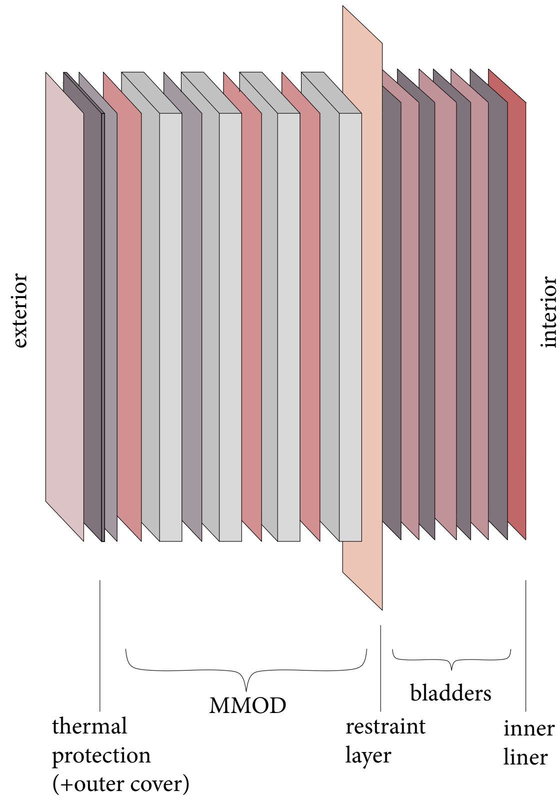

Fig. 2.13 | Structural setup of an inflatable, based on the example of TransHab

The **Restraint Layer** acts a structural layer to carry the high membrane loads and stresses imparted by the internal pressure of the habitat. The materials for this layer need to have a wide variety of properties from strong and stiff to flexible and foldable. In habitation modules the restraint layer is made from loose or tight webbing, depending on the extent of the loads. (Ibidem)

The **MMOD Protection Layer** protects the habitat from the hyper-velocity impact damage caused by micrometeoroids and orbital debris (in case of a module set in LEO). It is a multi-material make-up of ceramic fiber bumper layers, separated by low density foam, and a high strength rear wall layer. This layer is very thin in its packaged state during launch and flight. Upon deployment, the vacuum packed foam layers expand. The number of layers depends on the habitat's location. (Ibidem)

The **Thermal Protection Layer** is the outermost layer of the inflatable and contributes the passive thermal protection system to the setup to help control the internal atmosphere. This layer can be compared to the thermal protection system of spacesuits with their multi-layer insulations. Very thin sheets of reinforced, double-aluminised material between two layers of aluminised polyimide film are used to create this layer. The number of layers is again depended on the conditions; however, the overall stack-up stays very thin. (Ibidem)

2.2.2.2 Volumetric Considerations

Theoretically, inflatable structures can come in any shape imaginable; depending on the chosen form, structural support elements, such as reinforcing cables or hoops, are required. However, specific geometrical volumes can be leveraged to avoid or minimize the need of such support cages, namely the sphere, the cylinder, and the torus.

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Sphere

In the course of the Lunar Base Systems Study for the Johnson Space Center, Roberts analysed these three shapes, concluding that *"the spherical shape is the most volumetrically efficient with the least surface area and mass for a given volume."* (Roberts 1992, p.3) The sphere also enables a uniform stress throughout the structure. However, it displays a low architectural efficiently, due to the doubly curved walls. (Roberts 1992)

Cylinder

Contrary, a cylinder's walls are curved in only one direction, enabling different architectural setups depending on the cylinder's orientation. Wall and membrane stress of a cylinder, especially in a vertical setup, are higher than that of a sphere. (Ibidem)

Torus

To save payload mass, the shape of a torus could be leveraged, as it doesn't pose the same necessity of end caps needed for a cylinder. A torus also provides the great benefit of compartmentalization, which increases habitat safety with the possibility to isolate parts in case of a pressure loss or similar emergencies. Depending on the minor diameter, a torus provides similar architectural setups as a sphere, or a ring-like layout at the loss of open volume. (Ibidem)

With any of the three given shapes, attention has to be paid to factors like membrane stress, leakage and puncture resistance:

Membrane stress: Membrane stress is the stress in the inflatable's wall created mainly through internal pressure and measured in N/m. It is depended on the structure's volume and defined by the two factors of internal pressure and the local radius of the curvature. In a sphere, for example, the membrane stress is calculated by

$$stress = (pressure \times radius)/2$$

This means that the larger the inflatable, the larger the membrane stress. Very large inflatables have to be supported by structural cages, even if in the shapes of spheres, cylinders or tori.

Leakage: It must be ensured that the walls are sealed against potential gas leakage, which means the structure must be impenetrable to air. In particular added interfaces, such as hatches, airlocks, or windows, pose the danger of leakage and thus have to be designed with special care.

Puncture resistance: A wall puncture can be fatal to an inflated habitat because an unsupported inflatable will collapse of its own weight when the internal pressure is lost. This issue can be solved by making sure the internal framework, which is needed in any case to support floors, walls, and equipment, will also support the pressure envelope, as well as potential shielding on top of the structure, in emergencies. If this is given, an inflatable is *"no more inherently vulnerable to puncture than a rigid pressure vessel"*, so Roberts. (Roberts 1992, p.6)

2.2.2.3 Packaging, Deployment and Rigidization Mechanisms

All deployable aerospace concepts aim to fulfill three main assignments – first, the survival of immensely high static and dynamic loads at launch. At this point the deployable will still be tightly packed. The second obstacle is the successful deployment itself – the small package has to be deploy to the intended structure and design without harming itself or the surrounding infrastructure and equipment. Those first two phases are vital to the fulfillment of the third assignment, namely the actual purpose it was designed for. (Weaver Smith, Main 2001, p.203) In the case of this thesis the third purpose would be providing the baseline for a secure and habitable environment on the Moon.

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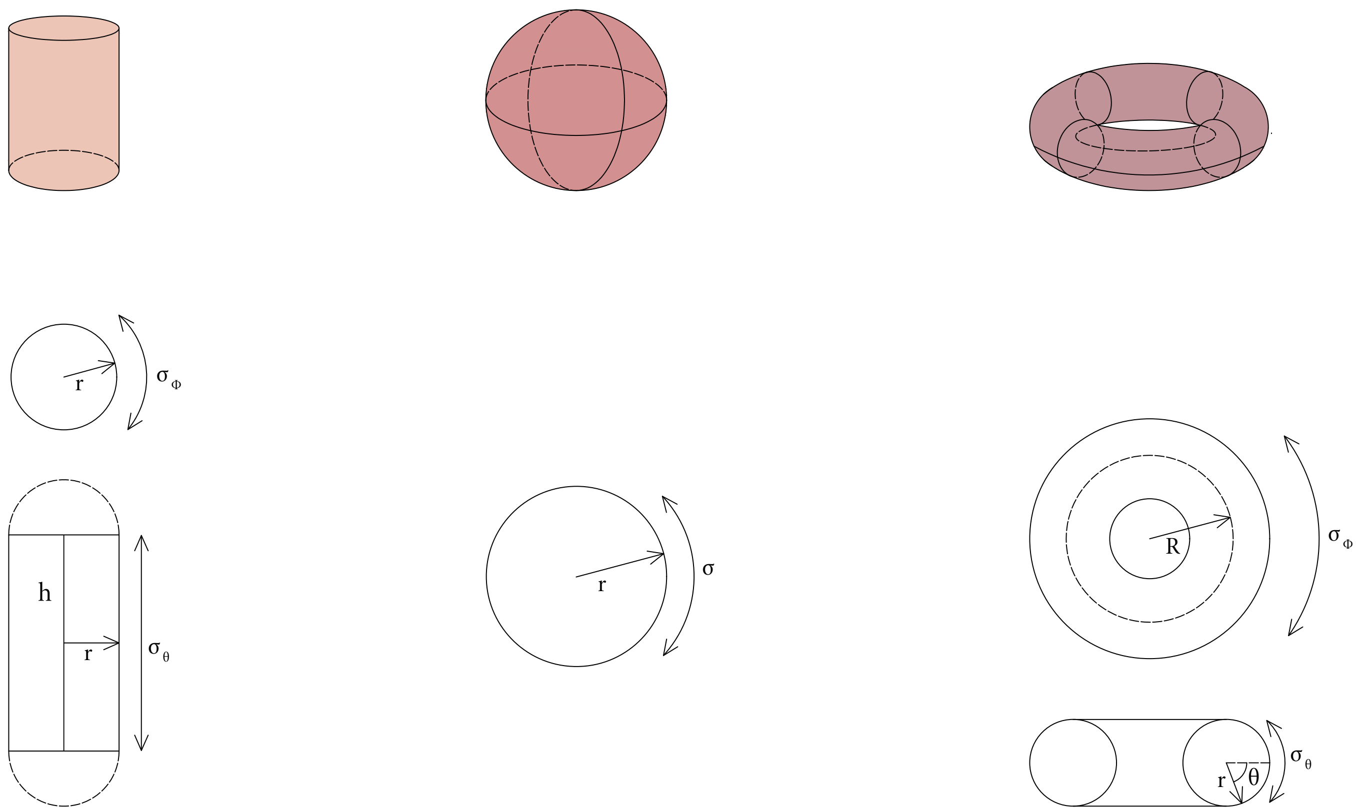
Cylinder **Sphere** **Torus**



Cylinder:

$$V = \pi^2 r^2 h$$

$$\sigma_\theta = \frac{Pr}{2}$$

$$\sigma_\Phi = Pr$$

Sphere:

$$V = \frac{4}{3}\pi r^3$$

$$\sigma = \frac{Pr}{2}$$

Torus:

$$V = 2\pi^2 r^2 R$$

$$\sigma_\theta = \frac{Pr}{2}\left(\frac{2+r\,\mathrm{Sin}\,\theta/R}{1+r\,\mathrm{Sin}\,\theta/R}\right)$$

$$\sigma_\Phi = \frac{Pr}{2}$$

Fig. 2.14 | Volumetric considerations of inflatables and their associated stresses - sphere, cylinder, torus

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Packaging

A suitable packaging method ensures both, a space efficient and safe transportation of the structure, and provides the foundation for a controlled deployment.

Packaging principles used today go as far back as the ancient art of origami and are rooted in the parachute industry. From there on, the techniques developed to robust and accurate systems, suitable for aerospace usage.

The ultimate goal in packaging methodology is to create a scheme that provides the highest packaging efficiency (PE) without interfering with the performance of the inflatable structure. The PE is dependent on the size, packaging method, and additional hardware of the structure, as well as on the material density. It can be calculated through a simple equation and is measured in percent [%].

PE = (Inherent material volume/Packaging container volume) x 100

When deciding on a packaging method, many factors have to be taken into consideration, the most important of which are:

- The packaging method may not restrict the inflation of the structure.
- The packaging method has to be selected in consideration of the deployment method, since it has a great impact on the controlled deployment.
- Packaging and deployment will result in material degradation, which has to be allowed for from the start.
- During the ascent, trapped gas may have to be vented – paths for this have to be included in the packaging method design.
- Strain energy, induced as a result of the packaging, has to be considered relative to the deployment mechanism.

(Grahne, Cadogan 2001, p.428ff)

Deployment Mechanisms

When considering different deployment mechanisms, it has to be taken into account, that a deployment mechanism is required which doesn't only control the rate of deployment, but also the directionality. During the process of inflation, the structures are often at their most unstable. Therefore, the deployment mechanism has to allow control of following points:

- The deployment direction has to be minded, in order not to violate any vulnerable surrounding areas or instruments.
- Rate and smoothness of the deployment have to be controlled, so that impulse forces and moments will stay in acceptable boundaries – changes in the deployment rate could alter internal pressures, which affects the system rigidity.

While a uniform internal pressure inside the structure during deployment is imperative, this required pressure is dependent on material and application and thus has to be calculated as part of the deployment mechanism. (Grahne, Cadogan 2001, p.420ff) The vast variety of deployment control techniques is described in detail by Marc Grahne and David Cadogan in their analysis of 'Deployment Control Mechanisms and Packaging Methodologies for Inflatable and Membrane Space Structures'. Some systems of importance are compartmentalization, columnation devices, and different types of roll-up devices: (Ibidem)

Compartmentalization works through the staged inflation of different cavities within the structure. This approach is most helpful when used in combination with other devices, as it will improve the overall deployment function due to being able to maintain a relatively constant wall stress.

Columnation devices allow a linear growth of an inflatable tube from a fixed base. A mandrel, behind which the tube is stored before the inflation, with an aspect ratio bigger than one is necessary to make sure the deployment doesn't happen at an

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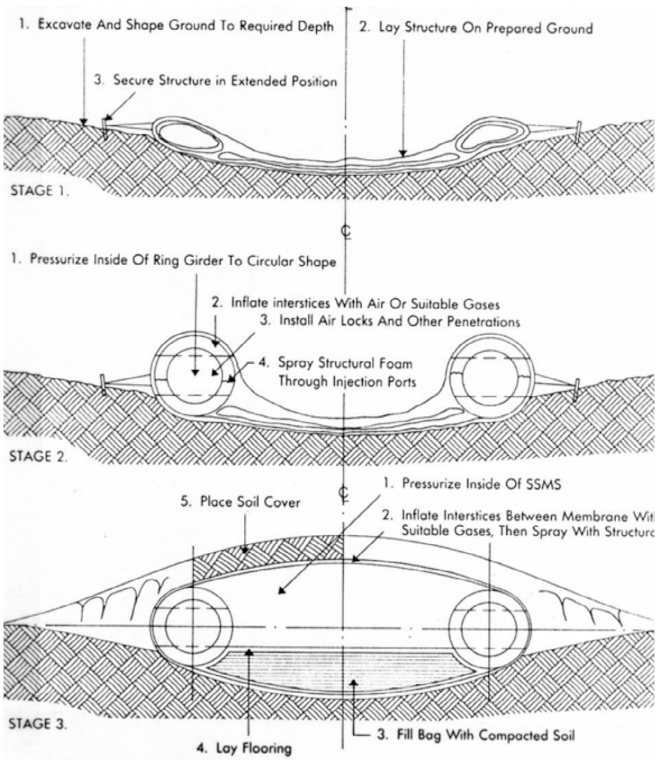

Fig. 2.15 | PMSS inflation process, P.Chow, T.Y.Lin International

angle. The mandrel's circumferential seals confine the pressure to the deployed sections, provide friction against the tube wall to slow the deployment, and inhibit premature inflation.

Roll up devices are of special viability with tubes and struts; they use a rolled inflatable tube to which inflation gas is introduced. The rate of unrolling is controlled either by an embedded mechanism or by a mechanism at the end of the tube. Simplified, the function of roll up devices can easily be grasped when imagining small party-horns, which unfurl when blown into. By adding velcro strips to the exterior of the tube, the control over the deployment of roll up devices can be increased. This also improves the maintenance of the packaging shape during launch vibrations.

Rigidization Mechanisms

In order to achieve a robust space inflatable, rigidizable materials can be used. Those are defined as *"materials that are initially flexible to facilitate inflation or deployment and become rigid when exposed to an external influence. The external influence can come in many forms, such as heat, cold UV radiation, and even the inflation gas itself."* (Cadogan 2001, p.257)
Therefore, rigidizable systems provide the opportunity to deploy a flexible structure and afterwards turn it into a rigid system. There are several mechanisms of rigidization, many of which are successfully tested in a space environment. Amidst the wide range of requirements, following points are only a few selected demands to show the many factors that have to be considered in the design of rigidizable structures. (Cadogan 2001, p.257f)

- A rapid and predictable rigidization process is important, to minimise the time spent in the more delicate state of inflation – while being inflated the structure is less stiff and therefore more vulnerable to damage, such as punctures of the surface.
- Firm control over the process of rigidization is vital, since

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a premature rigidization in the stowed state or during deployment could be fatal to the whole system.

- Thermal expansion should be near-zero.
- The rigidization needs to be operable in many different thermal environments.
- The energy consumption of the rigidization process needs to be calculated for and kept at a minimum.
- Storage life needs to be given despite humidity and temperature fluctuations.

A wide range of systems can be applied to achieve a successful rigidization, including but not limited to: (Cadogan 2001p.262ff)

Thermally Cured Thermoset Composites are outstanding in their structural performance and flexible design; they consist of a fibrous reinforcement that is impregnated with a thermoset polymer matrix resign. The matrix resin is chemically hardened, or cross-linked, when exposed to heat. The duration of this process depends on the material and can last up to several hours. Heat is provided by various methods, either through solar illumination or through embedded heater elements. Thin polymeric films encase the composite material on both sides, to create a pressure barrier and block the material in the packed state.

UV Cured Thermoset Composites follow a very similar process, with the difference that the rigidization depends on UV energy, provided by either the sun or an artificial source. An advantage of this technique is that the rigidization reaction can be limited to specific wavelengths, which minimizes the danger of premature rigidization. However, it also brings the limitation of needing a reinforcement material, which is transparent to UV energy, e.g. fiberglass or quartz – consequently those materials have less structural performance than high-performance fibers such as graphite.

Foam Rigidization can be used in many ways to create structures in space, one of which is the complete or partial filling of cavities. However, it can also be used in the deployment as the inflation medium itself. Therefore, foam can be the structural material itself or used to augment stiffness and strength in combination with other materials. However, the application of foam materials need more complex and large application systems.

Aluminum Laminates are comprised of thin layers of soft, ductile aluminium and polymeric films, such as Mylar or Kapton, which are laminated together with an adhesive. The polymeric film creates a pressure barrier to protect the aluminium from developing pinholes when flexed and to make the material more robust due to its increased resistance to tear.

Case Example: Pressurized, Self-Supporting Membrane Structure (PSSMS) | P.Chow, T.Y.Lin International

An example for an inflatable extra-terrestrial habitat with a complex and well-deliberated deployment and rigidization process is a concept patented by Phil Chow and T.Y. Lin International. The Pressurized, Self-Supporting Membrane Structure (PSSMS) is an outpost design consistent of a double-skinned membrane filled with structural foam, supported by a pressurized torus substructure (fig.2.15).

The first step towards a successful deployment is a suitable site preparation, so the deflated structure can be spread on the ground without suffering damage. In a next step the torus is pressurized to inflate to its 18.3 meters diameter and quick-hardening foam is injected. The internal compartment is pressurized to create a usable volume of 566.3 m^3. Compacted soil in the bottom of the inflatable acts as stabilizer and to create a flat interior floor surface. Regolith on top of the structure provides radiation shielding. (Benaroya 2018, p122f)

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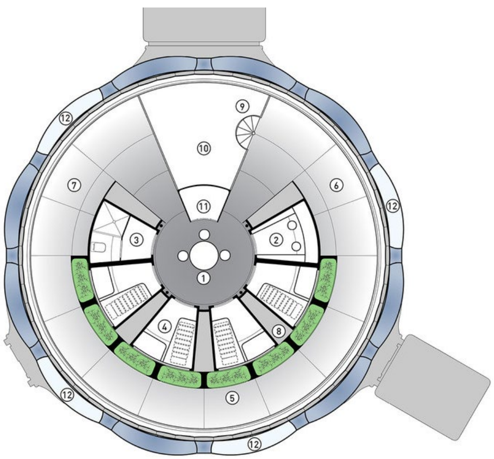

01 - Crew Quarters
02 - Study
03 - Hygiene Unit
04 - Crew Unit
05 - Greenhouse
06 - Storage
07 - Storage
08 - Mechanical
09 - Stair
10 - Open to Below
11 - Storage
12 - Vision Windows

Fig. 2.16 | Lunar Outpost Design, Foster + Partners

Fig. 2.17 | Mars Ice Home, Clouds AO, SEArch, LaRC

2.2.3 ISRU-based Structures

For several reasons, the future of extra-terrestrial habitation will be shaped by the use of ISRU-derived resources. Using such in-situ resources for a lunar outpost doesn't only offer the advantage of saving payload costs; it allows an increase of flexibility and autonomy.
The interaction of materials with the harsh lunar environment can cause severe material degradation, which can lead to structural failures. Especially affected are material composites. Material fatigue, embrittlement, and mircocracking are only a few of the effects caused by material degradation. One solution to minimize the contact with the lunar environment, and thus avoid its many hazardous effects, is to leverage the Moon's resources to shield the vulnerable structures from the lunar environment.
Given enough time, so Benaroya, it should be possible to produce all the basic materials necessary for the construction of habitats – and for survival in general - from indigenous resources. (Benaroya 2018, p178ff)

2.2.3.1 ISRU - Regolith

Geoffrey Landis summarizes the lunar ISRU with a focal point on material refinement. He suggests the production of oxygen, metals, silicon, and glass by processing the lunar regolith with fluorine brought from Earth. Landis concludes that *"there seems to be no insurmountable barriers to producing from lunar materials the main raw materials required for basic manufacturing, including semiconductor-grade silicon and structural materials.*" (Landis 2007, p.914)
Apart from extracting elements from regolith, the lunar soil is also highly coveted as a construction material for lunar infrastructure itself. Through microwave sintering, the regolith could be the foundation for roads and launch pads (see Chapter 2.1), while covering a habitation structure with regolith would shield both the structure and its inhabitants from radiation, tempera-

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ture fluctuations, and micrometeoroids.

A vast variety of regolith utilisation techniques have been suggested, from filling bags or double shell systems with unprocessed regolith, over sintering the material or creating bricks from lunar concrete, to 3d-printing shells with lunar soil. A recent study from ESA's Advanced Concepts Team (ACT) in cooperation with the University of Østfold successfully investigated the use of urea as admixture for lunar regolith geopolymers. As urea, the second most abundant component in urine, will be provided in ample measures in any inhabited settlement, being able to use it as a resource in construction would be most beneficial. (Pilehvar et al 2019)

In a structural assessment study, Stephen Indyk and Benaroya investigated the strength of unrefined sintered lunar regolith in comparison to other ISRU-derived structural materials. They found the unrefined sintered regolith to be one of the strongest of the sample group. The application of unrefined lunar regolith would offer the advantage of requiring much less specialized equipment, which again would be a high payload and cost saver. (Indyk, Benaroya 2017)

Case Example: Lunar Outpost Design | Foster + Partners, ESA

An especially well-published example of using regolith as construction material is the Lunar Outpost Design by the architectural firm Foster + Partners, which was developed in the course of ESA'S *3D Printing Building Blocks for Lunar Habitation* study. The design, which focuses on the use of 3d printed regolith as environmental shelter, consist of an inflatable volume, a rigid cylinder as airlock, and a dome-shaped, 3d printed shell to protect the structure (fig. 2.16). With a height of 5 meters, the interior space is designed to encompass two levels.

Instead of using conventional gantry systems, Foster + Partners suggest the use of several small robots for the printing itself. These robots would individually place small amounts of regolith on the selected printing site and solidify it. The approach requires an additional support inflatable as a base to print on. After the construction of the regolith shell is complete, the support structure is replaced with the actual inflatable pressure bladder. A vacuum cavity between this inflatable and the regolith dome acts as an insulator. (Foster 2015)

As 3d printed regolith has a very low tensile strength, a geometric pattern was developed for the print, to ensure mainly compression forces. (Ibidem)

2.2.3.2 ISRU - Water

One of the most valuable resources for a lunar outpost is water, which could be found in the form of ice in the Moon's PSRs (see Chapter 1.3.5).

Apart from the more obvious uses, such as drinking water, irrigation purposes, and extracting oxygen, water could also prove to be a valuable asset in the construction of a lunar base. As a hydrogen rich molecule, water is well suited to absorb radiation and thus provide radiation shielding. (NASA 2008-I)

NASA's TransHab module, a concept that was originally designed to support Martin and ISS habitation and later purchased by the private company Bigelow Aerospace, uses radiation shield water tanks in the core structure, as well as additional 5-7.6 centimeters thick water jackets around the crew quarters to protect the astronauts from solar flares. (Kennedy et al 2001, p.528ff)

Case Example: Mars Ice Home | Clouds AO, SEArch, Langley Research Center

A concept design that uses water as radiation shielding in planetary habitation is the Mars Ice Home, which was developed by Clouds Architecture Office (AO) and Space Exploration Architecture (SEArch) in collaboration with the NASA Langley Research Center (LaRC). The main structure consists of an inflatable torus surrounded by a shell of water ice (fig. 2.17).

The merit of using water as the radiation shield for this concept lies in the translucent quality, which allows the crew to benefit

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from diurnal light. An insulation layer lies between the inflatable volume and the ice water, an external restraint layer encloses the ice layer on the outside. (LaRC et al 2017)
Inside the habitable volume, living and working space is spread over two levels. The first floor provides workspace that can be tailored to the specific mission objectives. The second floor, with four personal quarters located around the core, could further host logistic storage or an integrated greenhouse. Optional, a separate greenhouse derivative of the Mars Ice Home could be attached to one of the access ports. (Ibidem)

2.2.4 Structural Systems for the HAVEN Habitat

From a structural perspective, the HAVEN habitat consists of a hybrid setup. An inflatable outer shell is deployed from a rigid central core and protected by a cover of regolith.

Rigid centre
Shape: cylinder (diameter: 4 m, height: 8.8 m (incl. Cupola)
Material: composite; carbon-filled-carbon (Cohen 2004)

Inflatable shell
Inflated shape: torus with oblate sides (external radius: 4m)
Material: multi-layers; Nomex, Kevlar 29, BT 180, Nextel, open cell foam, aluminised Mylar

Regolith cover
The habitat's lower level is located subsurface. The upper level is surrounded by a ring of regolith-filled propulsion tanks; on top, regolith-filled bags protect HAVEN from radiation and impact damage. Both the tanks and the bags are covered with an additional layer of less-tightly packed regolith.

Packaging/in-flight storage
An important factor to take into account during the volumetric design process, as well as the decision for in-flight packaging, is the possibility to pre-integrate equipment and certain interior fittings before the launch. In the case of an inflatable structure, these elements are commonly placed inside the rigid part of the module. Hereby the stowage volume may have to be shared between the equipment and the deflated structure itself, resulting in limited space for the equipment. A solution for this is to externally line up the inflatable with the hard shell, thus circumventing the need for deployment from within and freeing up the stowage space for pre-integrated elements. (Häuplik-Meusburger, Bannova 2016, p.123ff)
The HAVEN habitat utilizes such a system during flight mode (fig. 2.18):

- Packaging system: external folds
- Packaged dimensions: diameter: 5.4 m | height: 8.2 m
- In-flight storage capacity: ~ 100 m^3
- Deployed habitat (radiation shielding excluded): diameter: 12 m | height: 8.8 m

Certain systems, which are located in the rigid module, are pre-integrated and tested on Earth. This includes the aeroponic green walls (deatil on p. 142) and all the major installations; a vertical maintenance shaft for sanitary and electrical installations, as well as ventilation, runs in the rigid wall and ends in the technical room, which is located in the lowest section of the rigid component. Necessary installations in the inflatable habitation space run in the floor space and can easily be connected to the pre-installed main systems of the rigid part.

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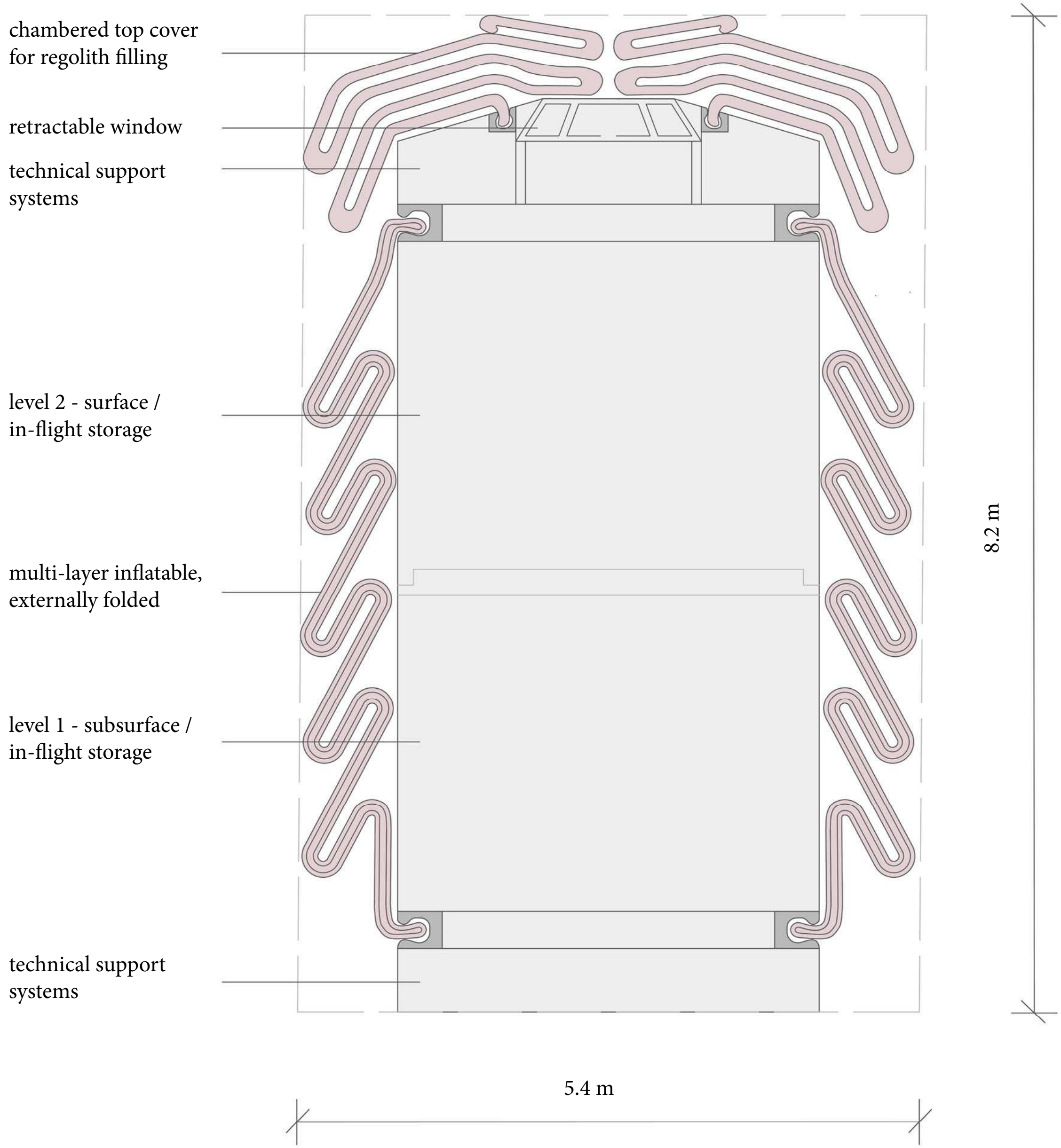
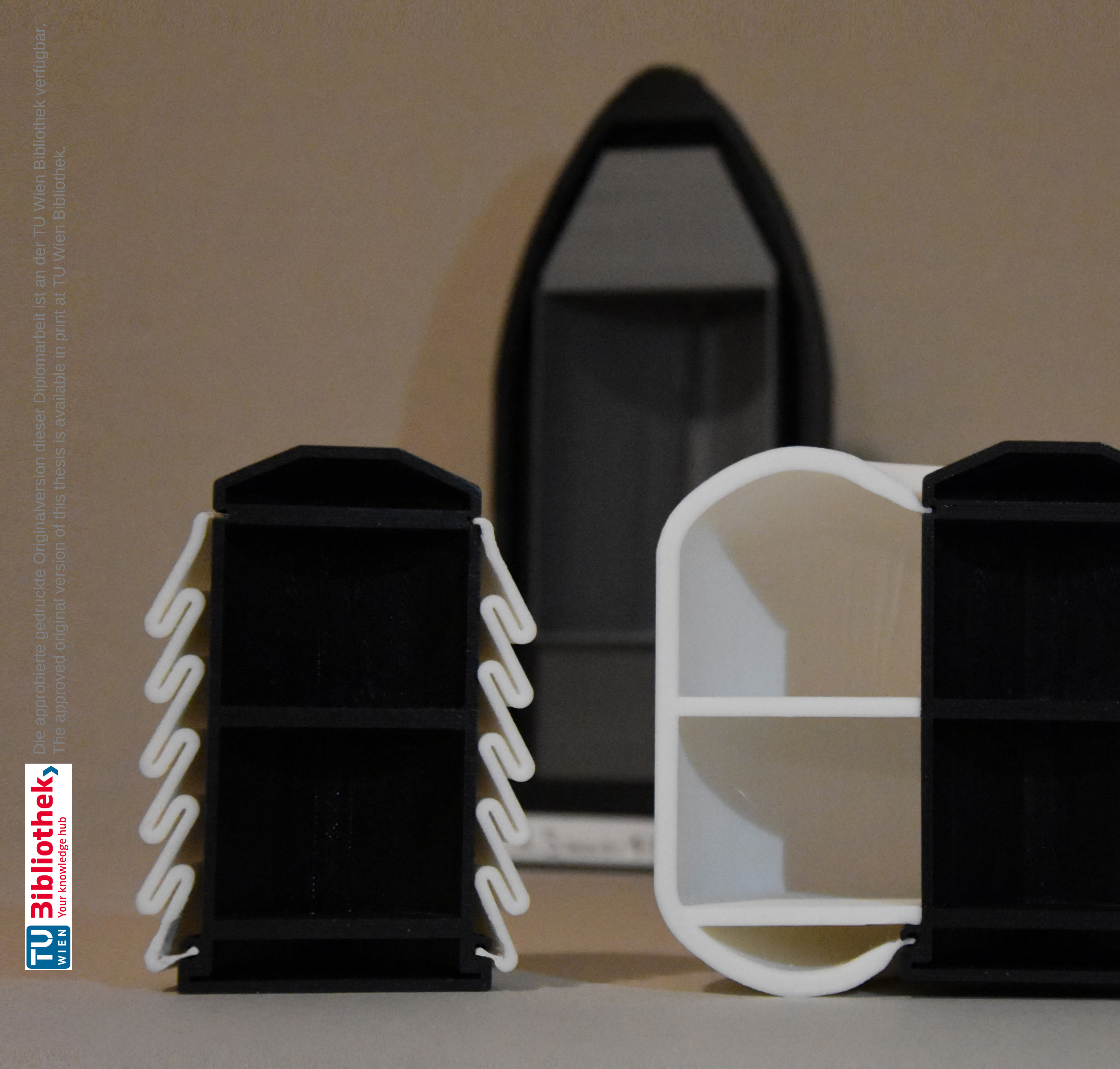


Fig. 2.18 | Schematic view of the packaged state of the HAVEN habitat



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HAVEN's Volumetric Increase Upon Deployment

By deploying the inflatable module attached to the rigid centre, the habitable volume of HAVEN increases more than sixfold (fig.19), enabling the design of spacious living and working areas for a crew of eight, while the habitat in its packaged state still easily fits into the chosen launch system's cargo fairing (see Chapter 4.4):

- Volume packaged habitat: ~ 187 m^3
- Habitable volume rigid core: ~ 80 m^3
- Habitable volume inflatable module: ~ 515 m^3

(Details on the deployment process: p.113)

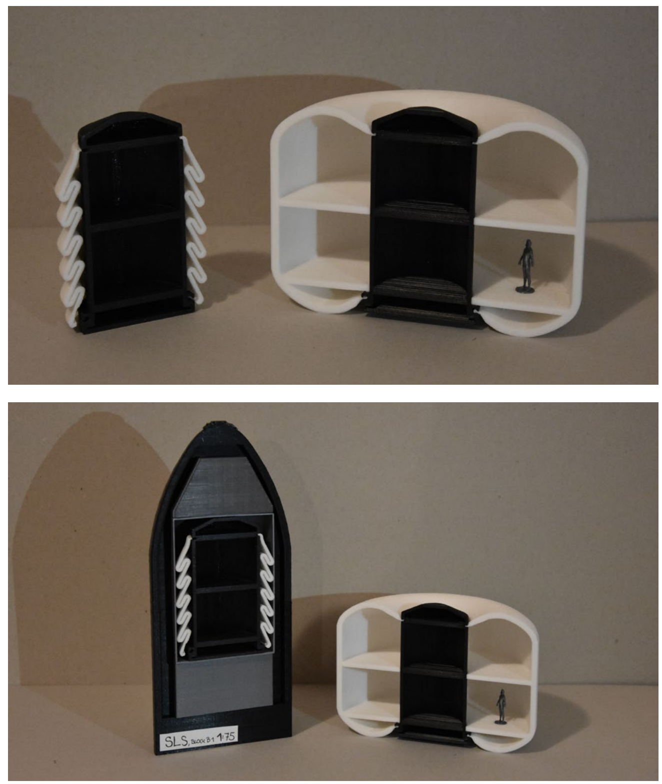

Fig. 2.19 | Model photos: HAVEN packaged, deployed, and in the launcher

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2.3 Dimensioning of Habitat Components

Selecting the proper dimensions for the habitat's components is a crucial step in the design process. Technical success, safety aspects, and habitability levels are directly dependent on the proper sizing of constructive elements. The following paragraphs explain the dimensioning of relevant components of the HAVEN habitat.

Ceiling Height

To find an ideal ceiling height, the lunar gravity has to be taken into account. Floor-to-floor heights between 2.5-4.00 meters have been suggested for lunar habitats in different literature, however the lower bound of these proposals seems to lack in required vertical space to allow for movements in 1/6 G. Additionally, support systems, such as lighting and ventilation, require some amount of vertical space.

An overall ceiling height of 4.00 meters would facilitate the installation of such support systems while leaving the crew with 3.50 meters of clear height to comfortably move in 1/6 G. (Benaroya 2010)

Lunar Staircase

On Earth, the measurements for a conventional staircase are strictly regulated. They can slightly vary, depending on national guidelines of the respective country, as well as on the function (private, public) and location (indoor, outdoor) of the staircase. In Austria, for example, the size of the rise can lie between 16-21 centimeters, while a tread of 21-30 centimeters is possible. (OIB-300.4).

On the Moon, however, due to the lower gravity, a much steeper incline has to be assumed. Using the terrestrial ratio for a staircase in a lunar base would result in a safety hazard; whereas steep inclines can be overcome easily. A positive by-effect of these steeper steps is that the staircase will be of overall smaller dimensions, which saves habitable volume and payload mass.

At HAVEN, the lunar staircase connects the work-level to the level with the private crew quarters and crew lounge. Consequently, the rate with which the staircase is frequented is limited to a few times each day. The chosen ratio lies at:

- Tread: 22 cm
- Rise: 42 cm

Regolith Shielding

As mentioned, regolith has remarkable shielding capabilities, both against radiation and extreme temperature.

To counteract the galactic radiation of around 0.3 Sv/year a layer of regolith with considerable depth is required. At a depth of one meter of regolith, the annual radiation dosage is comparable to that on Earth with about 2 mSv/year. However, it is important to note, that certain shielding materials release an additional dose of about 0.1 SV/year in the form of neutrons, by interacting with the cosmic-ray particles. The recommended offset of a regolith shielding layer lies at 2-3 meters. This would provide shielding of about 40 g/cm^2. In comparison, the shielding capacities of Earth's atmosphere lie at around 100 g/cm^2. (Benaroya 2018, p.46f)

However, the required radiation depth can be adjusted to the site of construction – at the Moon's poles, where almost constant sunlight can be measured, the Sun would relatively rotate around a point, causing the radiation to hit the surface at an almost horizontal and thus very low angle. In this case, an offset of 1.5 meter of shielding would effectively protect a structure against solar radiation, as in the case of the Foster+Partners/ESA Lunar Outpost design, which is located at the Shakelton crater, in immediate neighbourhood of the HAVEN construction site on the South Pole. (Foster 2015)

It is furthermore important to keep in mind, that during a solar event, such as solar flares, a much higher shielding capacity of around 700 g/cm^2 is required. (Benaroya 2018, p.46f) This necessitates the construction of a Safe Haven, a separate radiation

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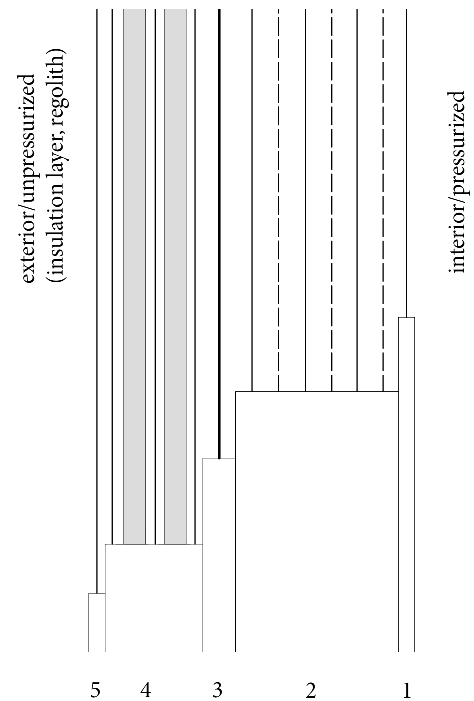
shelter or special area within a habitat that can be sought out during the duration of these predictable events. To achieve the necessary radiation protection levels, one solution could be to place the Safe Haven underground.
In addition to shielding against radiation, a layer of regolith is an excellent means of reducing the extreme temperature variations, due to its low thermal conductivity. At the Apollo landing sites, a temperature variation of only 1° C was measured at a depth of 40 centimeters, in comparison of 282° C on the surface. Thus, the 1.5-3 meter offset for the radiation shielding will easily suffice to help reduce extreme temperature variations. (Ibidem)

At HAVEN an overall regolith layer depth of 2.4 meters will protect the inhabitants from radiation. This consists of 1.8 meters of regolith, filled in lander propulsion tanks, topped with a less-tightly packed raised layer of 40 centimeters that covers the structure and protects the tanks' exteriors from external influences. Due to the angle of repose, which defines the steepness of this layer, a variable thickness with a somewhat larger offset at the bottom eventuates.
The top of the habitat is protected by regolith filled bags of 1.5 meters, in accordance with the low angle of the Sun.
The Safe Haven is located subsurface, thus leveraging the shielding of the Moon's body itself.

<u>Inflatable Pressure Bladder</u>

Depending on the habitat function and location, the inflatable shell can reach thicknesses of up to 50 centimeters, comprised of more than 60 layers. (Valle et al 2019)
At the HAVEN habitat, the inflatable layer is bordering the habitable space on the one side and an insulation layer, followed by the regolith shielding layer, on the other side.
As this regolith layer takes care of the majority of radiation shielding and micrometeoroid protection, the dimension of HAVEN's inflatable shell can be somewhat smaller than for habitats without such a regolith cover or for space-born habitats, where the radiation dose is much higher than on the Moon. (fig.2.20)



HAVENS inflatable shell is composed as follows:

1 - Inner Liner: Nomex, flame and puncture resistant, 1.5cm
2 - Pressure bladder: Kevlar 29/BR 180 (alternating), 15cm
3 - Restraint Layer: Kevlar 29 (tight webbing), 3cm
4 - MMOD: Nextel/open cell foam (alternating), 9cm
5 - Thermal Protection Layer: Aluminised Mylar layers, 1.5cm

Fig. 2.20 | Structural setup and dimensions of the HAVEN inflatable

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2.4 Life support

Several high performance systems are required to ensure the survival of the crew within and without the structural components of a habitat on the Moon. These include systems to maintain pressure and oxygen, to filter water, and to regulate the temperature inside the habitat, but also entail systems like airlocks and spacesuits to keep the astronauts alive when performing EVA duties.

2.4.1 Environmental Control and Life Support System (ECLSS)

In order to ensure a livable atmosphere within the structural components of a habitat, special life support systems are needed, such as the Environmental Control Life Support System (ECLSS) aboard the ISS.
The ECLSS consists of three components

- the Water Recovery System
- the Air Revitalization System
- the Oxygen Generation System

to address the necessary main functions of

- recycling wastewater (including urine) to produce potable water and technical water (for flush and oxygen generation)
- producing oxygen
- filtering the air (removing CO2, particulates, microorganisms, volatile organic trace gases, …)
- monitoring and controlling the air partial pressures of nitrogen, oxygen, carbon dioxide, methane, hydrogen, and water vapour
- maintaining total cabin pressure
- detecting and suppressing fire
- maintaining cabin temperature and humidity levels
- distributing air /ventilation.

Systems derived from life support systems for space have furthermore been adapted to local needs and applied in developing countries to provide benefits such as clean drinking water. (NASA 2017-I)

2.4.2 Thermal Control System

To ensure that the temperature inside a space habitat stays within optimal limits, a dedicated Thermal Control System is utilized. This includes both active and passive approaches.
Aboard the ISS, the Passive Thermal Control System(PTCS) entails insulation, surface coatings, heaters, and heat pipes. The Active Thermal Control System (ATCS), which only activates when the heat loads exceed the PTCS's capacities, pumps fluids in closed-loops circuits to collect, transport and reject the excessive heat. Thus, water is used inside the ISS habitation module to cool equipment and the environment. (NASA 2017, p.92)

2.4.3 Spacesuits

Ultimately, spacesuits are just small, individual life support systems. Thus, a spacesuit's main components are, as in the example of the Apollo suit (the only spacesuit tested on another planetary body), fittingly named:

- the Portable Life Support System (PLSS)
- the Oxygen Purge System (OPS)

The PLSS's - and hence a spacesuit's - main functions are

- pressurizing the spacesuit

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- supplying oxygen
- removing CO2, particulates, and odours
- controlling humidity
- insulation against extreme temperatures.

The OPS, a small unit on top of the PLSS, is a purge-flow emergency backup system that would, in case of a failure of the PLSS, enable the astronaut to return to safety. (Thomas 2020)

Airlocks and Suitports

Leaving the safety of a habitat does not only entail donning a spacesuit and walking through a door; a secure depressurisation procedure in an airlock is required. Overall, the whole egress/ingress process is a highly time and energy consuming procedure; each egress either has to sacrifice the atmosphere inside the airlock, or preserve it though procedures with a high energy and time consumption. The same procedures are performed in reverse order during ingress. (Cohen 1995)

An efficient solution is the Suitport Extravehicular Access Facility (fig. 2.21) – short suitport – by M. Cohen, which minimizes the necessary pump-down volume and thus the required time and power. The design entails a rear-entry spacesuit that is attached to and sealed against the hull of a pressurized space module. The astronaut enters the suit through a hatch in the back, then seals the suit, as well as the opening in the space module. Subsequently the suit is unsealed from the module. The benefits of the suitport systems are a considerably faster egress/ingress process, as well as a substantial decrease in atmosphere loss. (Ibidem)

The same benefits can be listed for docking a rover, as it would allow the astronauts to directly transfer from the habitation module to the vehicle. While docked, the rover could also act to increase the habitable volume, offer additional window space, and act as a radiation-hard emergency shelter. Furthermore, a rover can be equipped with additional suitports. (NASA 2008)

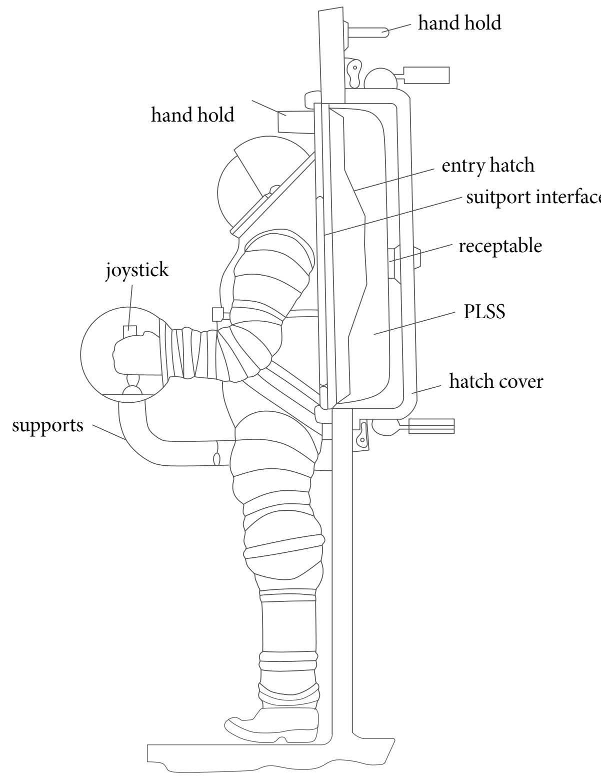
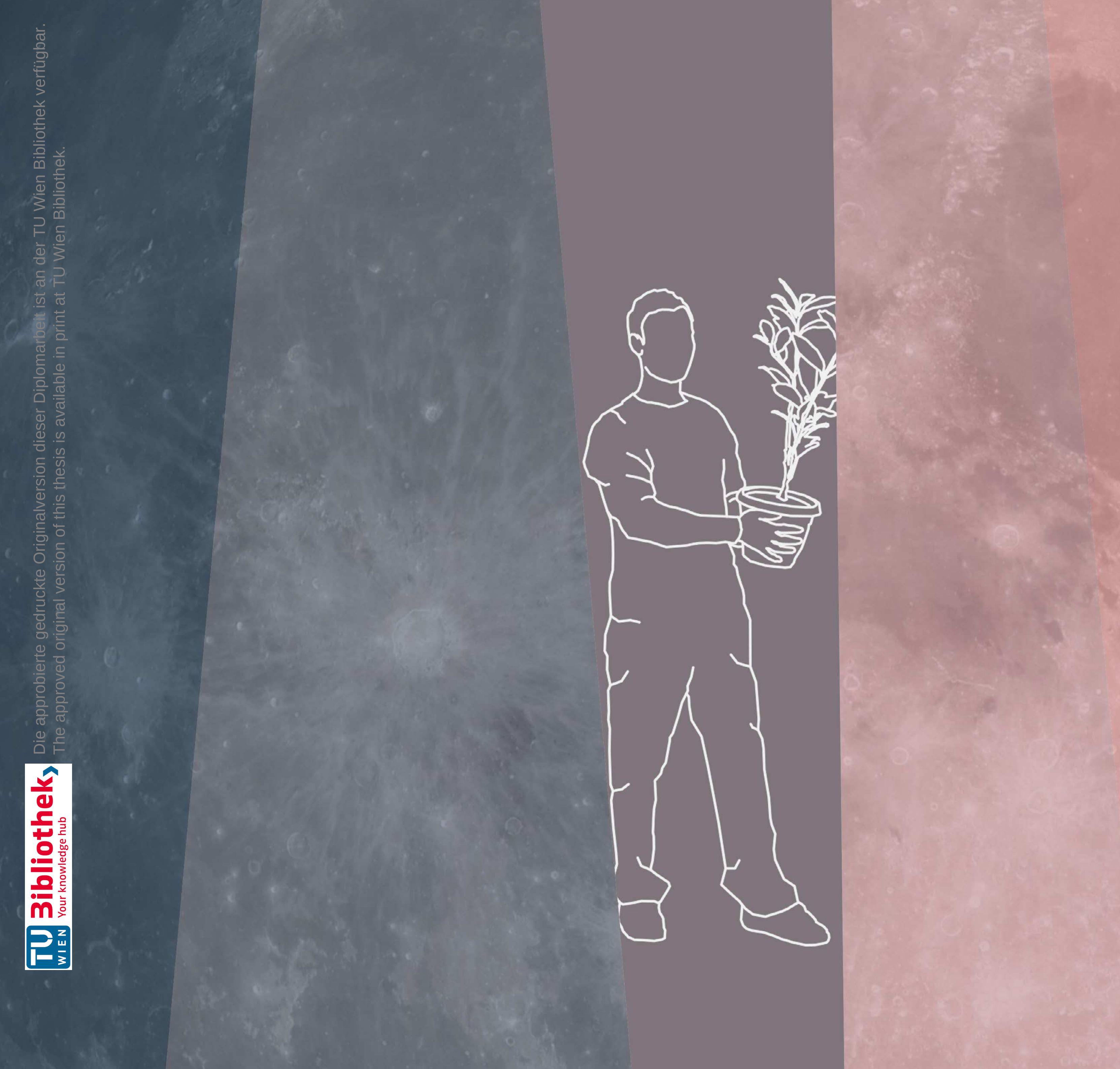


Fig. 2.21| Suitport design by M. Cohen



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CHAPTER 3

Elements of Habitability on a Lunar Outpost

Given the basic technical requirements, human survival on the Moon can be ensured. However, safe compound logistics, a secure habitat structure, and functional life support systems are not enough to offer a habitable environment for a human crew, especially in the case of long-term missions. A great number of additional factors, stemming from diverse fields, such as social science, psychology and interior design, have to be taken into account to increase the habitability of a lunar base. The spatial allocation of functions, illumination conditions, and the social matrix are just a few of the factors that are vital to a successful space architecture.

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3.1 Defining Habitability

The term habitability has been defined many times throughout literature. It can be determined as *"a general term that connotes a level of environmental acceptability"*, as Conners et al explain in their book 'Living Aloft – Human Requirements for Extended spaceflight'. They further state that *„the requirements for conditions to be ‚habitable' change dramatically with the circumstances. For brief periods, almost any arrangement that does not interfere with the health of the individuals or the performance of their jobs would be acceptable. Over the long term, conditions must support not only individuals' physical, but also their psychological health."* (Conners et al 1999, p.59)

In 'Architecture for Astronauts' Häuplik-Meusburger uses the term to *"describe the suitability and value of a built habitat (house or spacecraft) for its inhabitants in a specific environment (Earth or Space) and over a certain period of time,"* and further explains that *"set into the space context, habitability can be understood as the measure of how well the (built) environment supports human health, safety and well-being to enable productive and reliable mission operation and success."* (Häuplik-Meusburger 2011, p.xi)

Closely tied into the issue of habitability are the design aspects of Human Factors, which means applying psychological and physiological principles in engineering and design tasks. The term Human Factors is often used interchangeably with the term ergonomics. As defined and ratified by the International Ergonomics Association in 2000, Human Factors are *„the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance"*. (IEA 2020)

While habitability itself has traditionally been a low priority item in the planning of space missions, it is crucial to understand the potentially grave effects of impaired habitability and the great potential this field bears to improve the chances of a successful mission. It should be the objective of space architecture, to create a suitable living environment, that supports both physical and psychological well-being of the inhabitants. (Häuplik-Meusburger, Bannova 2016-I)

Habitability, as defined above, includes numerous factors from life support systems over hazard mitigation to social and psychological elements. This chapter shall focus on the latter items, and especially on the tools, such as spatial arrangements and design applications, that space architecture can leverage to improve habitability. As Conners et al state, *"psychological and social factors will become increasingly important determinants of the success or failure of future space missions."* (Conners et al 1999, p.3)

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3.2 The Social Environment

One of the most crucial factors of any space mission is the social environment. While confined habitation and severe isolation have psychological effects on the crew, the social support the astronauts are used to is taken from them at the same time; they face a completely new social matrix.

As Häuplik-Meusburger and Bannova put it "*Social interaction is very important for maintaining a crew's psychological health and can be facilitated through design interventions and architectural solutions.*" (Häuplik-Meusburger, Bannova 2016, p.110)

It is furthermore important to note, that this new social matrix will not be limited to the crew on site, but include a larger circle of individuals back on Earth, which are involved to various degrees (active participation or passive observation) in the lives of the astronauts.

3.2.1 Entering a Microsociety

One of the most challenging factors for the crew of a lunar base will be adapting to a completely different social environment than what is common on Earth. What we call a macrosociety - the complex social matrix of our terrestrial relationships, including family, friends, and any other social interaction we are involved in – will be replaced by a much less diverse circle of social interaction. The great variety of social roles we tend to take up in everyday day life on Earth, as well as the possibilities to interact with numerous social counterparts, will be replaced by the small matrix of a new microsociety; a new community with potentially new rules, roles, and procedures. This involves intense contact with a small number of people and a rapid, often unnatural transition into this new social group. (Conners et al 1999, p.9f)

The architectural setting in which this microsociety is acting is an important factor in the development of new social structures. A well thought through spatial background can support the process of acclimatisation and integration; an unsuitable setup, with for example a lack of privacy, on the other hand can amplify the social challenges.

3.2.2 Team Performance

Both the composition and cohesion of a crew can have great effects on the health and performance of the astronauts. A careful selection and training of the team members is therefore crucial to a successful long-term mission. In the context of space exploration, such a team can be understood as *"a collection of individuals that is assigned to support and achieve a particular mission. Thus, depending on context, this definition can encompass both the spaceflight crew and the individuals and teams in the larger multi-team system who are assigned to support that crew during a mission."* (Schmidt et al 2009, p.8) The new microsociety for a lunar base has therefore to be understood as a matrix that involves both the in-situ crew, as well as the remote support on Earth.

When considering crew cohesion and performance, the mission duration is regarded as an important factor. The duration of a mission at the HAVEN Lunar Port and Base (for the permanent part of the crew) is planned for up to six months, after which the crew rotates in a dedicated rotation schedule. Compared to the only crewed lunar surface missions so far, the Apollo missions (with the longest surface stay lasting just under 75 hours), this means a stark increase of mission duration and poses significant social challenges within the crew and larger team.

An increasing number of ground-based analog research is nowadays studying the effects of long duration missions, as investigations on board the ISS – while highly valuable in the area of spaceflight - do not suffice in regard to planetary missions. (Schmidt et al 2009) Simulations at Antarctica stations or lunar and Martian analog habitats, such as the Hawai'i Space Exploration Analog and Simulation (HI-SEAS) or the Mars Desert

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Research Station (MDRS), are used to gather data on crew performance and psychology for long duration planetary missions by recreating the challenging environments.
Schmidt et al define the conditions, which effect coordination, cooperation, psychological well-being, and performance of the crew: (Schmidt et al 2009, p.7)

- social isolation
- physical confinement
- a small and diverse crew
- communication delays between crew and ground
- a long duration
- a high consequent environment

The functioning and well-being of the crew exposed to these challenges can be influenced by a number or factors and approaches, such as selection, composition, and training.

The Multi-Team – Who Is Part of the Mission?

As mentioned above, in regard to crew functioning and well-being, it is most important to take a multi-team approach into account. The core crew will interact with a number of additional groups, teams, and individuals back on Earth, which are assigned to support the crew during their mission.
Conflicts between the Mission Control Centre (MCC) and the crew may influence the mission, just as much as conflicts between the core crew members itself. CapComs can act as liaisons between the different groups and therefore they have to be compatible with both groups. As both the Mission Control Centre team and the CapComs themselves are organised into three work shift rotations during each 24 hours period, the multi-team's composition increases in diversity. Stark differences in the cohesion between the core crew and these different support teams are possible; it is vital to maximise compatibility across all multi-team compositions.
A further important factor for the multi-team performance on long duration missions is the communications delay resulting from the great distances. This can impede complex relationships between the core crew and the mission control personnel on Earth, which bedevils psychological support and further restricts the social circle of the core crew. It also results in a greater crew autonomy. (Schmidt et al 2009)
While with around three seconds, the delay on a lunar mission is only a fraction of that on missions to farther away destinations, it still has to be understood that non-immediate communications will hinder crew support strategies like psychological conferences with experts on Earth.
In regard to the multi-team approach, it also has to be taken into account that an intrusion of outsiders to the group's privacy has been found to cause problems. During Apollo 7, astronauts removed sensors that conveyed their physiological functions to the ground-base team; the Soyuz 36 crew shut off their radio contact with ground control; and the Skylab 4 astronauts decided to circumvent ordered procedures, which resulted in a tense atmosphere throughout the whole mission. Protection of the crew's right of sub-group privacy is an important step towards ensuring a successful interaction of the multi-team. (Conners et al 1985, p.94)

Crew Selection – Who Is Chosen to Live on the Moon?

Historically seen, there has been a shift in the astronaut selection process. In the 1950s and 1960s approved candidates were mainly military test pilots; the focus on desired characteristics was almost solely on performance in high-stress and high-risk situations, while little to no attention was given to team skills.
Since the Shuttle and ISS selection processes, the focus has shifted more towards a scientific qualification and a diverse background. Nowadays, a crew is composed of a variety of expertise and personalities and includes different genders, ethnicities and nationalities.
Rigorous testing during the selection process includes both,

Fig. 3.1 | EMMIHS-II analog astronauts at the HI-SEAS habitat

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non-team-related factors, such as physiological health, and personality tests to evaluate flexibility, adaptability, and balance. Specific team simulations are used to further assess teamwork tendencies.

Overall, team-oriented, resilient, adaptable, and emotionally stable personalities are preferred for long duration missions. (Schmidt et al 2009)

Crew Composition – What Makes a Well-Functioning Crew?

A successful crew composition relies heavily on the selection of suitable individuals who are able to function well within the team. Homogeneity of personalities, complementary needs, shared interests and values, and emotional attitude have to be considered when creating a crew, as well as demographic differences, such as language, age, gender, expertise, and nationality. Taking such individual traits into account can mitigate the formation of subgroups, which has shown to negatively affect crew performance. (Ibidem)

This is an especially important factor for the HAVEN mission, which faces such subgroup tendencies due to the two separate crews. Therefore, while ensuring suitable privacy for both groups, the HAVEN architecture aims to strengthen the perception of cohabitation in shared spaces to encourage the sense of being one large crew.

Crew Training – How is the Crew Prepared?

A large amount of an astronaut's career is spent in training. Piloting skills, survival skills, emergency response, technical systems skills, communication protocols, physical conditioning, group training, and public relations are just a few of the possible subjects. Next to physical and scientific skills, sociological aspects are an important factor the training of a crew. A specific Assigned Crew Training starts as soon as the astronaut is selected for a mission; special training sessions can also take place in simulation analogues. For a mission on the ISS there will be additional in-flight training aboard the space station.

"Our preflight training is very good, but many details associated with living and working on the Space Station are impossible to simulate and train on the ground. Under normal crew rotation schedules, we hand over those 'tricks of the trade' during the 2 to 4 months, which we overlap on the ISS. By the time the senior crew departs, the junior crew is ready to take the lead, then train the incoming new crew," explains Astronaut Mike Fossu. (NASA 2017, p.215) He further states that, when the ISS was threatened with a full decrew, a situation which would prevent any in-flight personal experience handover, the crew prepared videos for the next crew, explaining the most important procedures. (Ibidem)

Overall, training efforts are not limited to the astronaut crew, but also include the flight controllers to ensure a successful interaction of the multi-team.

Most of the training events entail some element of team skill to enhance team performance; especially for long duration missions well-developed skills of functioning and living within the team are vital. The training of such skills should be a process that is expanded regularly. (Ibidem)

3.2.3 The Multi-Crew System at HAVEN

At full occupation, the HAVEN habitat is home to a crew of eight astronauts. This overall crew consists of two sub-crews:

A permanent crew of four is responsible for running the arrival port and habitat, as well as for instructing the guest crews. The permanent crew stays at HAVEN for the maximal possible mission duration (180 days).

Changing guest crews of up to four astronauts join the permanent crew. These are astronauts that arrive at the HAVEN Arrival Port and stay for up to ten days to acclimatise to the lunar gravity and learn the procedures at a lunar base, before moving on to their respective own research outposts.

The guest crews bring to the habitat a changing social element and the possibility to enrich the microsociety on the base. However, the changing crew members and short duration of their

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stay also bears the potential for additional conflict in between sub-crews. Thus, the design for the HAVEN habitat aims to answer to this multi-crew situation and the resulting different levels of privacy requirements. While all eight astronauts combined will be one crew for the duration of their shared stay, and there should be enough shared spaces and possibilities for interaction, privacy and clear lines between various crew spaces are crucial.
During their stay, guest crews at the HAVEN Lunar Port and Base will receive dedicated on-site physical and technical training in order to adapt to the lunar gravity and learn the proper procedures for running a lunar base in 1/6 G. This part of the training is in character similar to the in-flight training aboard the ISS. Additionally, the arriving crews, as well as the permanent crew, undergo regular on site training to expand and uphold social skills and teamwork, with special attention to the tasks of running a lunar base. These trainings furthermore include the support team on Earth to keep up consistent functionality within the larger multi-team.

3.3 Habitable volume

As the only habitat to have been used in field on another planetary body, the Apollo Lunar Module, is the logical starting point when researching lunar habitat compositions and volumes. However, while this minimum habitat allowed humans to survive on the lunar surface for several days, any mission of longer duration requires a structure that allows for much more habitability. A larger gross pressurized volume is the foundation and inevitable starting point in this; however, a balance in the trade-off between habitable volume and component weight has to be found.
Estimates of the required gross pressurized volume for long-duration extra-terrestrial habitats can be made on the basis of both experiences during human spaceflight events and research in analog missions. (Häuplik-Meusburger, Bannova 2016, p.122f)
Fig 3.2 shows the habitable volumes and mission durations during past missions of space exploration. (Kennedy, Capps 2000)

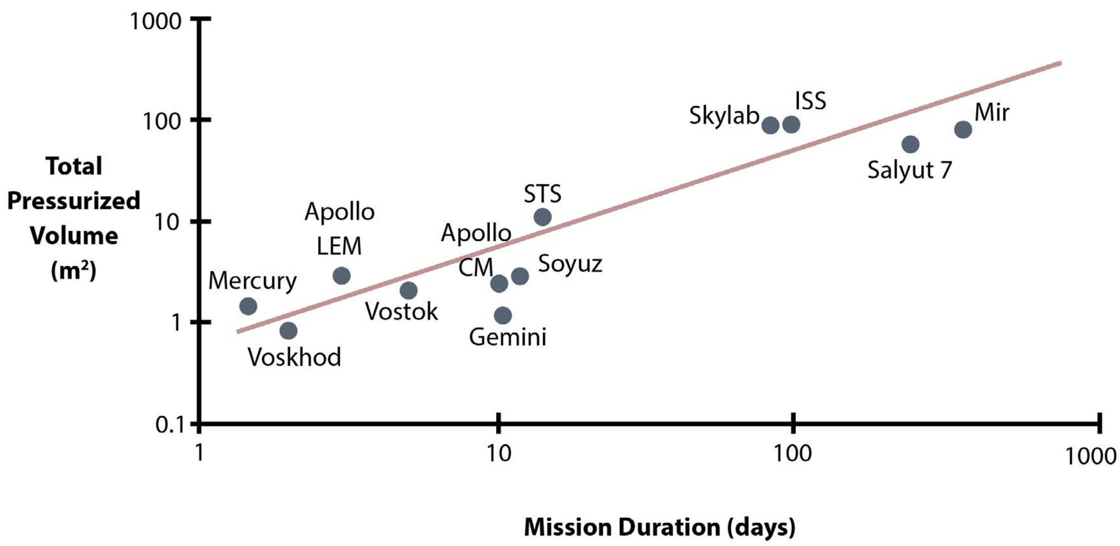

Fig. 3.2 | Pressurized volume of historic spacecraft dependent on mission duration, based on Kennedy and Capps

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Defining the optimal pressurized volume of a space habitat is a challenge that has been given a lot of attention over the last decades. Numerous studies have determined different values for the required volume, however the numbers are influenced by many factors, such as duration, function, or crew size, and experts have yet to agree on a common strategy. Häuplik-Meusuburger and Bannova define three rules of thumb, based on an analyses of the Celentano Curve hypothesis, which seeks to predict the volumetric requirements per crew member: (Häuplik-Meusburger, Bannova 2016, p.122f)

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

Kennedy et al classify habitation volume into three categories, based the NASA Human-Systems Integration Standards: (Kennedy et al 2007, p.4)

1. Minimum tolerable limits
2. Minimum performance limits
3. Preferred limits

In their book 'Human Spaceflight: Mission Analysis and Design' Pranke and Larson suggest a pressurized volume of at least 70 m^3 per crew member for a long duration (>180 days) surface base. (Larson, Pranke 2003)
The HAVEN habitat exceeds this demand by offering a mean of 73.5m^3 of habitable volume to each member of the crew (excl. airlocks) (fig. 3.3). However, the distribution of the volume is not equal between all astronauts - the members of the permanent crew are allocated private quarters of 11 m^3 volume, with a floorspace of 4.5 m^2, each; the visiting crews' private spaces are stacked, pod-like chambers with a volume of 4 m^3 each, at a floorspace of 2.8 m^2, as the duration of their stay is much shorter.

3.3.1 Spatial Setup

While the volume of the habitable space itself is a defining factor, it also has to be taken into account that the spatial layout can optimize or decrease the usability of the pressurized volume. Roberts mentions the possibility to create open volume as the key element to improving habitability. (Roberts 1992)
There are different possible setups for the spatial organisation, namely radial, linear, in a grid, or circular, which all interact with the aspects of interior circulation, zoning, and access and egress points. (Häuplik-Meusburger, Bannova 2016, p.123ff)
The interior spatial layout can greatly affect other elements of habitability, such as privacy or safety aspects.

Mission Duration	**Total Press. Vol. (m^3/crew)**	**Standard**	**Recom. Total Vol. (m^3) (4 crew, 180 days)**
Short (3-14 days)	5-15	tolerable	20-60
Medium (2 wks - 4 mths)	30-50	performance	120-150
Long (>6 months)	60-80	optimal	240-320

Tabel 3.1 | Recommended volumes according to Kennedy et al 2007

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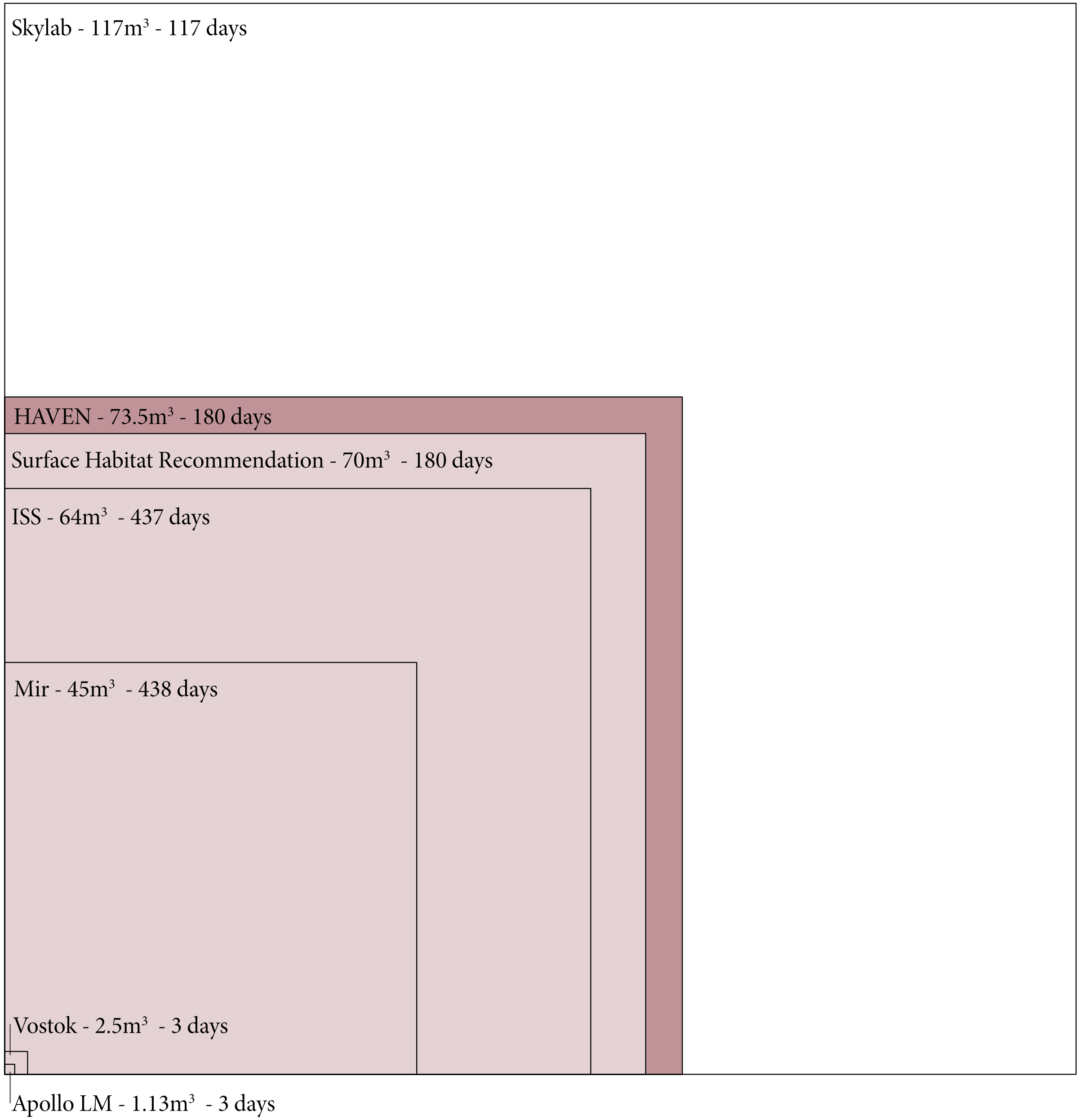

Habitat - habitable volume per crew (at max.configuration) - max. mission duration

Fig. 3.3 | Comparison of volume per crew member, historic missions and HAVEN

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3.4 Privacy

Space habitats are notorious for very confined living situations and accordingly low levels of privacy. In order to ensure a sufficiently high rate of habitability, design factors like volumetric considerations, a smart interior organisation, and flexible systems need to be leveraged. Especially in a habitat with such versatile crew occupations as at HAVEN, the privacy options need to be tailored to the social situation.
While privacy is generally accepted as every individual's basic right and research suggest that privacy regulation is a culturally universal process, the practice and extent of this diverges based on cultural backgrounds. (Conners et al 1985, p.83f)

3.4.1 Defining Privacy

Privacy relates both to the management of personal interactions and the controlling of information. The ability to choose the extent and timeline of interaction, as well as the information revealed to others, are defining factors. (Conners et al 1985, p.83f)
An ideal amount of interaction is sought by individuals to reach a balance of openness and reticence. This so-called homeostasis - the optimal balance - is what is perceived as privacy. (Altman 1975)
Häuplik-Meusburger and Bannova furthermore classify privacy as *"a continuum from being all alone to being completely social"*. (Häuplik-Meusburger, Bannova 2016, p.109)
According to Stephan Margulis, privacy can be categorized into three basic functions with different levels of centrality: (Margulis 1977)

- Self-identification (privacy as a tool to distinguish between the self and others; most central)
- Self-definition (finding self-definition in relationships and role-definition)
- Balancing interaction (achieving the desired level of interaction with others; least central)

In order to shape certain aspects of privacy, the physical environment and objects in it can be leveraged. Personal possessions, space and clothing can become an *"extension of the person"*. (Conners et al 1985, p.86)
Margulis defines four mechanisms that are commonly utilized to control privacy. All four of these stem from behavioural concepts. (Margulis 1977)

- Verbal action
- Nonverbal action
- Environmental mechanisms
- Cultural norms

Personal Space

The definition of privacy furthermore requires the term of personal space, which was first introduced in the 1960s by the psychologist Robert Sommer as *"an area with invisible boundaries surrounding a person's body into which intruders may not come."* (Sommer 1969, p.61) The size of this described area can not be generalised; it varies from individual to individual, depending on their personal background. Due to the limited volume in extra-terrestrial habitats, personal space is a scare resource, which results in the feeling of lack of privacy and crowdedness. The extent of this can be connected to the demographic composition of the crew, as well as personal sympathies amongst crew members. Studies found that mixed sex crews require less personal space than single sex crews, while female crews and women in general require less personal space than men. (Dams, Stickland 1989)

Crowding

Crowding - or the feeling of crowdedness - is not directly related to high density, but rather to the environmental variables and the levels of restrictions. These can include resources, stimuli, or

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freedom in general. High density in public places is, for example, perceived as a much smaller stressor than high density in work spaces or residential areas. Additionally, relational variables have to be taken into account – strangers and formal gatherings require much more private space than friends and informal groups. (Conners et al 1985, p.87ff)

Spaceflight, which exhibits stark restrictions in most resources and social activities, as well as offers mainly confined space, is especially susceptible to trigger a feeling of crowdedness. The stress caused by this can be a threat to both physical and psychological health. (Ibidem)

While alleviation of crowdedness can be achieved if the affected individual feels in control of the situation and can predict the duration of the confinement (Conners et al 1985, p.89), the feeling of crowding and its negative effects increase with the occurrence of (body) odours, personal littler and waste. (Dams, Stickland 1989)

Thus, the task of (space) architecture is not only the provision of comfortably-arranged space, but an elaborate organisational setup and the facilitation of well-functioning support systems.

In regard to the effects of crowdedness, a relation to gender has been observed. Overall, men react more negatively to crowded situations than women; while men become increasingly competitive and withdrawn, women display a much higher social adaptability by becoming more cooperative and cohesive. However, long time chronic crowdedness results in more health problems in women and less group stability over time. (Conners et al 1985, p.87ff)

3.4.2 Solving Privacy Issues in Extra-Terrestrial Habitats

In extra-terrestrial habitation the issue of privacy is of increased importance, as many of the mechanisms to control privacy related situations are not accessible to the crew. At the same time, space habitats offer increased opportunities to minimize personal identity and individuality, such as a severely limited number of private items. The serious restriction of physical space enforces interactions and often leaves individuals permanently exposed to each other, while at the same time the opportunity for social interaction is limited to a small number of personalities.

In order to improve the situation, mechanisms that emphasize the crew members' individuality need to be increased. This can span from allowing personal choices in the decoration of certain areas to the individual selection of clothing. Ensuring the physical separation of private areas is a spatial contribution to helping the crew deal with the minimized privacy. (Conners et al 1985, p.90ff)

According to R. Dams and R. Stickland, extra-terrestrial habitats should cater to several aspects of privacy: (Dams, Stickland 1989)

- areas to retreat (separate working and living areas, areas for private communication)
- different degrees of interpersonal contact (private quarters, semi-private areas, common areas)
- areas for undisturbed work (private work and team work)
- space for stowage (personal items)
- multiple hygiene facilities (good ventilation, auditory barriers)
- possibilities for expressing individuality

Private Crew Quarters and Storage

Even allowing the crew members to decorate and personalise small areas like private stowage compartments can greatly enhance their feeling of having some manner of private space. Ideally, each crew member should be designated a spatially separated, personal crew quarter that may be decorate to individual taste. This task of committing personal style to an area has been found to have positive connotations. (Conners et al 1985, p.92)

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Private quarters should allow space for storing personal items and clothes, while at the same time it should be avoided to store general items in the crew quarters, as this has been found to be perceived as an intrusion of privacy on Skylab missions. (Häuplik-Meusburger 2011)
Portable stowage units, similar to what is already in use on the ISS, would be a practical solution for planetary missions, as these allow for easy transport between different outposts and exploration vehicles. (Ibidem)

Apart from offering a personal retreat and storage of private items, the crew quarters fulfill the impotent task of being the crew's sleeping accommodations. While hammocks were perceived as quite comfortable by, for example the Apollo 16 crew, long duration missions require more substantial sleeping arrangements, such as bunks. (Interview with C. Duke, Chapter 5)
Spatially seen, sleeping quarters should be always accessible and separated from activity areas to ensure a calm sleeping environment. However, access to communication and warning systems should be integrated close by in case of emergencies. (Häuplik-Meusburger 2011)

Aboard the ISS, habitability and privacy needs are addressed in NASA's Space Station Crew Quarters (CQ). These 2008 installed units contain: (Schlesinger et al 2013)

- enhanced sound insulation through acoustic blankets
- individually adjustable ventilation and illumination systems
- integrated communication equipment (laptop power and Internet connections)
- personalisable interfaces
- stowage opportunities (Velcro and bungee attachment points)
- additional radiation protection

Fig. 3.4 | A view into the ISS private quarter of Astronaut Karen Nyberg

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While the limited gross pressurized volume of extra-terrestrial habitats prevents the design of large private spaces, mindful application of architectural elements, such as textures and geometric forms, can help increase the perceived volume of these private areas. (Häuplik-Meusburger 2011)

The HAVEN habitat offers several approaches towards increasing the feeling of privacy inside the habitat, ranging from flexible walls, which allow the creation of private areas or the shielding of work spaces from visual disturbances, over the possibilities to personalize private spaces, to a crew lounge, which alleviates crowding through the open ceiling towards the window two levels above.
The most challenging factor in regard to privacy at HAVEN is the fact that the habitat will house a circle of astronauts, which will in many ways perceive themselves as two separate crews, but at the same time will have to act as one large crew in overall habitation procedures. This means that, while still having to function as one crew in the main tasks of the day, as well as the training activities, there can be no denial of a distinction between the four permanent crew members and those four guests that stay only for up to ten days. HAVEN answers to the need of privacy in between the groups by classifying areas in the habitat with access restrictions: certain spaces are accessible only to the permanent crew, including critical systems and research areas, while other areas are commonly accessed. The quarters and hygiene facilities of the two crews are spatially separated and each crew has an individual small gathering area, while larger shared spaces, such as the wardroom and crew lounge, enable common activities between both crews. (See Chapter 6)

3.5 Illumination Conditions and Exterior-Interior Relations

"The most important component of man's senses is his sight. This makes it especially important for people in a spacecraft to have proper lighting in their work, rest and living environment." (Dams, Stickland, p. 8.20)
In space or on another planetary body, the crew can not rely on the same natural illumination conditions we are used to on Earth. While the lunar equatorial region experiences a cycle of 14 terrestrial days of daylight and 14 days of night (Schrunk et al 2008, p.114), at the chosen location of the HAVEN Port and Base at the lunar South Pole, the crew will have to live with almost constant daylight. It is crucial to provide some manner of control over the illumination conditions inside the habitat to maintain conventional day and night cycles.
Adequate illumination for any required task has to be ensured. However, enabling vision is not the only aspect of lighting that needs to be considered. Changes in illumination can influence motor activities and noise levels (Conners et al 1985, p.68f) and lighting levels are correlating to visual comfort (Häuplik-Meusburger, Bannova 2016, p.118).

Dams and Stickland define three main requirements for the lighting situation in spacecraft, that can be applied to a lunar outpost: (Dams, Stickland p. 8.20)

- Enabling the easy and correct completion of visual tasks
- Contributing to a working and living environment that is both psychologically and physiologically satisfactory
- Permitting the visual appreciation of all aspects of the habitat

Reacting to the individual perception of environmental conditions, one approach of increasing the habitability in regard to illumination is to provide the crew with the possibility to adjust

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the lighting to their personal preferences, especially in private crew quarters. An example for such adjustable lighting is to be found in the ISS CQ. (Schlesinger et al 2013).

3.5.1 Natural Light

While artificial light systems are crucial to ensure the fulfillment of the lighting requirements as defined by Dams and Stickland, providing some amount of natural light inside the habitat is inevitable for habitability and crew health. Long-term outposts call for a system that allows some way of sunlight ingress.

Apart from the conventional solution of integrating windows into the design, natural sunlight can also be led into a habitat with optical fibre. Such systems capture the high intensity direct component of the sunlight and focus it into optical fibres, which lead the light into the habitat where the visible part of the light is distributed (fig. 3.6). Optical fibre systems can provide a high quality of light with outstanding illumination performances. The use of such an application would not only provide the crew with natural light but also contribute to energy conservation. (Lingfors, Volotinen 2013)

At the HAVEN outpost, with its almost constant daylight, the system constitutes a virtually endless source of light. Thus, in all areas of the HAVEN habitat, natural sunlight is provided, in addition to artificial light systems, through optical fibre applications.

3.5.2 Windows

The integration of windows in a space habitat doesn't only provide a conventional approach to expose the crew to natural light; windows offer the unique advantage of a view. The inclusion of windows has been a part of space architecture from the early

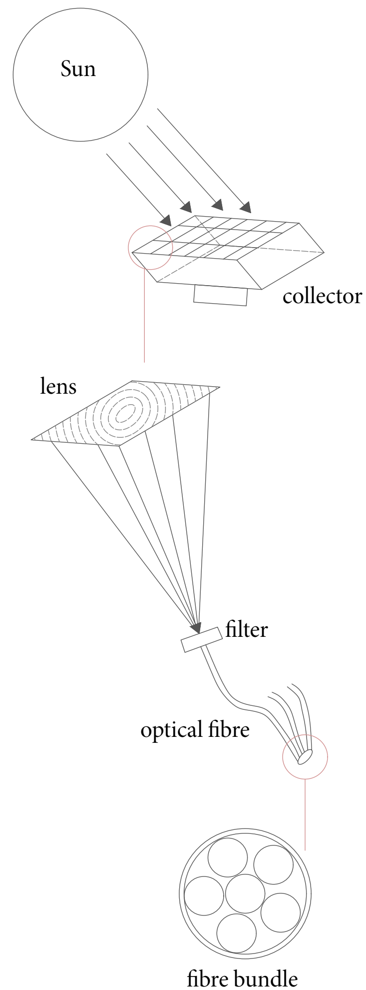

Fig. 3.5 | Astronaut Karen Nyberg "windowgazing" through the ISS Cupola

Fig. 3.6 | Schematics of an optical fibre system, based on Lindfors and Volotinen

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stages. The space stations Salyut and Mir had several windows, some even located in the crew quarters. The installation of a large window in Skylab was first met with resistance from engineers but finally approved and proved to be a highly appreciated asset. Countless recounts of astronauts assert that "window gazing" is the most common leisure time activity on the ISS (fig. 3.5). (Häuplik-Meusburger 2011) The same popularity was assigned to observing the rugged lunar terrain during the Apollo missions. (Interview with C. Duke, Chapter 5)
However, it should be possible to cover all windows to protect the inhabitants from the intense sunlight and harmful radiation. Additionally, windows create a relation between the exterior and interior. A surrogate for an actual window could also be provided through virtual windows. These digital placeholders could be used to establish a connection with the exterior or else display sceneries not connected to the outside at all. (Benaroya 2018, p.93)

At HAVEN, a large central window offers the possibility to stargaze, as well as increases habitability by alleviating the feeling of crowdedness and confinement. This Cupola is located in the central rigid part of the base. On the subsurface level, the crew lounge is open towards the window due to the see-through floor above; on the surface level a gallery with floor-integrated seats circles this opening and allows the crew to stargaze and enjoy the feeling of open space. For a more close-up view of the stars and the rugged lunar surface, the crew can enter the Cupola directly via a pull-down ladder (detail on p.147).
Virtual windows in the crew quarters allow the astronauts to either enjoy live streams of the lunar landscape or display their favourite terrestrial environment.

Fig. 3.7 | The colourless enviorment inside HI-SEAS during EMMIHS-II

3.6 Colour

Colour is yet another factor that affects psychological and physiological functions, and thus can be either beneficial or, if not applied correctly, harmful to the habitability levels. A certain variety in colour applications is important - reports of Skylab astronauts described the lacking variations of colour as *disturbing*. Applying diverse colours to a space habitat can break the monotony of the environment and even maintain a certain connection to Earth. (Conners et al 1985, p.67f)
Häuplik-Meusburger and Bannova list three main purposes of using colour in a space environment:

- Spatial orientation (to increase coordination, bearings and guidance)
- Colour-coding (to increase the visibility of certain items and surfaces)
- Comfort and spaciousness (to increase the perception of spatial commodities and overall well-being)

The influence of colours for an individual's well being is dependent upon the personal traits. For persons with visual dominance colour applications are rated at much higher importance than for vestibular dominant people. (Häuplik-Meusburger, Bannova 2016, p.118f)

A research experiment by the author during the EMMIHS-II lunar simulation at the HI-SEAS analog habitat revealed the importance of colour for the overall crew mood and performance. While the first half of the mission was spent in an entirely black and white environment (fig. 3.7), including interior surfaces, personal items, science applications and tools, as well as the crew's clothing, colour was re-introduced during the second part of the mission. A noticeably increase in the crew's performance was observed, associated with a boost of the overall mood. Several members of the crew stated that they f*elt lighter, more cheerful,*

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and *more motivated to do their work*. They also mentioned that the monotonous black and white environment of the first mission half had felt *draining* and *lethargic*. Furthermore, the author found personal choice to be a key element in leveraging the benefits of colour, as well as observed the process of re-adding and choosing colour to be an important event of crew bonding.

3.6.1 Colour Selection

While personal perception plays an important role in the rating of colour, research suggests overall tendencies in the attractiveness of certain colours (rated from high to low preference):

blue – red – green – violet – orange - yellow

When deciding on colours, the size of the coloured area is an important factor:

- Small areas: saturated colours
- Large areas: shades, tints

Furthermore, colour selection should also be made with the function of the area in mind, as certain colours can cause emotional and even physical responses, such as the stimulation of activity. To leverage these reactions, different colours (and their tints) should be allocated to rest and work spaces:

- Sleeping and resting areas: blue, green, violet
- Work and recreation areas: red, yellow, orange

(Dams, Stickland 1989, p.8.24f)

At the HAVEN outpost the dominant colours are of light and cool shades, to provide a calm backdrop for visual highlights and colour coded items, as well as to increase the feeling of spaciousness.

Very deliberate applications of colour highlights are used to break the monotony and allow the inhabitants to differ between work and recreational areas. Furthermore, different colour systems are used to distinct between the private areas of the permanent and guest crew.

Flexible interfaces allow a free choice and quick change of colour applications inside personal quarters and common areas.

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3.7 Greenery and Vegetation

„Green has always been a part of the vision for space. (...) The role of plants in a manned facility on the Moon is multi-faceted. (...) Plants can become as crucial to human survival in space as oxygen." (Benaroya 2018, p.167)

In 2019, the first successful attempt was made by the Chinese National Space Administration (CNSA) to grow plants on the lunar surface. Inside a sealed stainless-steel canister, part of the Lunar Micro Ecosystem (LME) experiment aboard the Chang'e-4 probe, a cotton seed had germinated (fig. 3.8) about two weeks after Chang'e-4's historic landing on the far side of the Moon. (Universe 2019) However, the plant never made it to the fully grown stage. The sprout froze when temperatures in the unheated mini-biosphere plummeted to about minus 170 degrees in the lunar night. (Phys Org 2019)

Nevertheless, the experiment was an interesting start to what will be a vital part of future lunar outpost missions - cultivating greenery on the Moon.

Providing a sufficient supply of fresh produce from Earth for a long-term crew on the Moon would pose significant challenges, amongst them the limited shelf life of crops with high water content, such as tomatoes, and the momentous number of required resupply missions. Overall, sustaining a lunar outpost on terrestrial produce would be infeasible over a longer period of time; a greenhouse to grow the produce in-situ is a necessary addition to any long-term outpost mission. (Zeidler et al 2017)

Possible produce on a lunar base would be tomatoes, peas, mizuna and other greens, as well as fast growing herbs. They would provide both nutritional supplements, such as fibres and vitamins, and enhance the flavour, fragrances and textures of the meals. (Häuplik-Meusburger et al 2010) Staple crops, such as wheat, soybean, potato, sweet potato, and rice would offer high levels of carbohydrate, but would require larger and more energy intense greenhouse systems. Human dietary needs demand up the 15 different crops to be grown in a lunar greenhouse for a

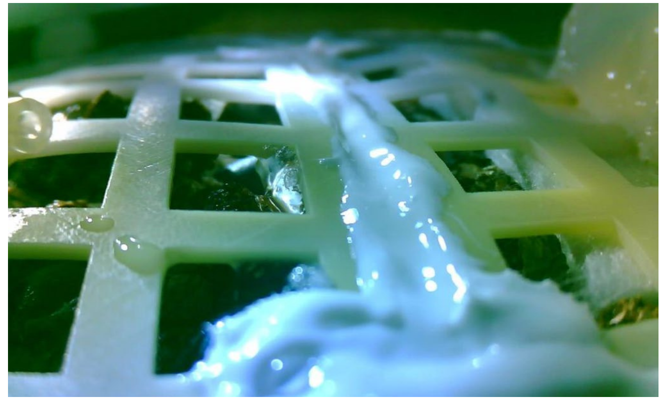

Fig. 3.8 | Germination of a cotton seed on the Moon, CNSA

Fig. 3.9 | Cosmonaut Valery Korzun with a plant experiment on the ISS

Fig. 3.10 | A hydroponic system being tested at the Kennedy Space Centre,

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complete menu. The selection of these species depends heavily on size, growth speed, nutritional value, fast plant cycles and high harvest indices. (Monje et al 2003)

3.7.1 Psychological Benefits of Greenery in Space

Apart from providing necessary sustenance in a fresh form, plants contribute a variety of many-sided benefits to life on a lunar base, many of which are important in raising the habitability levels. Medical value, biotechnologies, and material extractions are just a couple of numerous possible applications for plants and bacteria on the Moon. Furthermore, greenery has a special value in maintaining emotional balance and avoiding depressions amongst the crew. (Benaroya 2018, p.160ff)

For this last, but maybe most important benefit, the focus is on the relationship between humans and plants. A fruitful history of growing things in space lets us look back at missions like Salyut 6, where Valery Ryumin covered the space station in greenery by growing plants from empty food containers and film cassettes, or on the Salyut 1 flax seed sprouts, which were soon seen as beloved pets by their caretakers Viktor Patsayev and Vladislav Volkov. The emotional connection and mental health benefits of tending to plants in space are undeniable. After the disturbing Columbia incident the crew members on the space station were assigned additional greenery time to maintain their mental equilibrium. (Häuplik-Meusuburger et al 2014).

On the one hand, benefits stem from the activity of tending to something alive and helping something delicate grow. On the other hand the sensory facet of plants in an extra-terrestrial environment may not be underestimated. In their paper 'Greenhouse Design Integration Benefits for Extended Spaceflight,' Häuplik-Meusurger et al describe this aspect: *"In particular, there is anecdotal evidence demonstrating the pleasure involved in the sensory aspects of plant interaction; the feeling of different textures of living material, the smell of soil and greens, the visible growth and change over time, and the visual variation they add to the interior of the spacecraft.*" (Häuplik-Meusburger et al 2010, p.87)

3.7.2 Greenhouse Design

When designing extra-terrestrial greenhouses it is vital to take into accord the different gravitational conditions, as these will influence the movements of water, heat, and gas. Having some amount of gravity, even if only the lunar 1.62 m/s^2, facilitates the operation of a greenhouse. With the possibility of gravity-driven drainage systems, the use of a hydroponic (fig. 3.10) is an option. (Monje et al 2003) Due to the use of a light-weight growing medium, hydroponics, as well as aeroponics, which uses no growing medium at all, are very payload efficient. A lunar greenhouse also offers the possibility of soil-based systems like on Earth. (Häuplik-Meusuburger et al 2014). Local resources, such as regolith and ice water, can be used to operate such a lunar greenhouse. (Monje et al 2003)

Häuplik-Meusburger et al list three main requirements for the design integration of greenhouses. A greenhouse should accordingly:

- provide sensory enrichment for crew members
- provide spatial enhancement of the habitable volume
- allow and encourage personal handling by the crew

At the same time, the greenhouse needs to be designed in accordance with plant growth demands, be as lightweight and low volume as possible, have a minimal energy consumption, and be easy to maintain by the crew. (Häuplik-Meusburger et al 2010, p.88)

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3.7.3 Greenhouse Maintenance

While all main greenhouse systems, such as lighting and irrigation, can be automated, a certain amount of human maintenance and pruning will remain imperative. The necessary crew time in this area should be limited as much as possible in order to avoid time intensive obligations. However, the option of tending to the plants has to be preserved, to allow for the important mental health benefits. By making recreational gardening a possibility, rather than a requirement, it can be adapted to individual needs and preferences. While free time is highly restricted on ISS missions, alleviating boredom will play an important role on a lunar mission, where long-duration stays are combined with limited leisure activity options. Tending to plants will be a valuable tool in occupying the crew, as long as adaptable to crew preferences.
An approach to this is the Mobile Plant Cultivation Subsystem (MPCS), suggested by Häuplik-Meusburger et al. These mobile growth units could increase habitability levels and provide food supplements, while offering the two options of being tended to by individual crew members or being docked to a larger greenhouse facility and therefore not needing additional upkeep. (Häuplik-Meusuburger et al 2014)

At HAVEN, a small agricultural greenhouse docked to the main habitat provides the crew with fresh produce and caters to various nutritional needs. While this separate greenhouse is focused on the supply of sustenance and maintained by technical subsystems to ensure a smooth growth process and abundant harvest - and thus not meant for crew interaction beyond the necessary maintenance and harvesting -, an aeroponic green wall in the central rigid component increases habitability levels by creating a liveable atmosphere and allowing the crew to interact with the plants, as well as enjoy the sensory benefits.

3.8 Flexibility

Maintaining a high level of flexibility in all the above-mentioned design aspects is an important tool in increasing habitability in confined habitation.
When seeking to define the terms *flexibility* or *flexible*, the Merriam-Webster dictionary offers three meanings: (Merriam-Webster 2020)

1 - capable of being flexed
2 - yielding to influence
3 - characterized by a ready capability to adapt to new, different, or changing requirements

Referring to the third definition, flexibility in the design of a space habitat would mean to allow for quick and easy-to-apply changes of the interior in order to support the creation of different living and working environments. Especially the confined situations of extra-terrestrial habitats call for designs that make optimal use of the little space available. Thus, multi-functionality or multiplexing - the multiple usage of the same area for different purposes - is crucial.

3.8.1 Applications of Flexibility

"It is generally accepted that the interior design of a spacecraft should have built-in flexibility," explain Conners et al in their book 'Living Aloft – Human Requirements for Extended Spaceflight'. (Conners et al 1985, p.67) They suggest movable partitions, removable wall covers, and projectable designs as solutions for such flexibility, and highlight the benefit of considerate application of texture and colour to introduce variety to the habitat. (Ibidem)
Apart from different coloured and sized panels and screens, movable, re-arrangeable, or foldable furnishings would also

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contribute to greater interior flexibility. Furthermore, this can achieve a psychological redefinition of areas. (Dams, Stickland 1989, p.8.54)

Crew Quarters

A flexible design of the personal quarters needs to enable the quick change of functions from nighttime ("sleeping") to daytime ("private tasks", "personal recreation"). (Häuplik-Meusburger 2011, p.125)
As mentioned before (see Chapter 3.4), allowing the crew members to individually decorate, arrange, and control their personal quarters can be an important factor in increasing habitability. This however, does not only support privacy aspects, it also helps break the monotony by allowing flexible changes to be made whenever the inhabitants feel the need. (Conners et al 1985, p.92) Digital screens and virtual windows are a most helpful tool in this, as they enable an instant change of colour and imagery.

Movable partitions could be used to connect or close off work and sleep areas. This would offer the possibility of a visual or physical connection to the group whenever desired. (Häuplik-Meusburger 2011, p.125)
A flexible design of the crew quarters themselves could furthermore allow the possibility to combine two quarters into one larger accommodation to allow for private conversations or recreational activities. An additional option would be to install screened openings between the quarters that allow a flexible connection between the units. (Dams, Stickland 1989, p.8.13ff) The possibility to flexibly connect and separate two private quarters could furthermore be an especially attractive feature for long-term outposts, where the formation of new and more intimate relationships is a conceivable possibility.

Work Area

A flexible design of the work area is an important booster of productivity; it would enable an adaption to different types of tasks, as well as to personal working preferences. A work station needs to allow for a change in the number of workers, but also for changing equipment. Furthermore, adjustable lighting is crucial in such a dynamic work environment. (Häuplik-Meusburger 2011, p.259)

Leisure Area

On a long duration mission, a flexible space for spending one's leisure time is crucial. While both private quarters and a large space for the whole crew are important parts of the room schedule, there is still the need for areas to accommodate smaller, intimate groups of around three crew members. (Häuplik-Meusburger 2011, p.289) Flexible partitions could support the creation of such spaces and allow a fast adaption of the area in accordance with to the group's size.

Safety Aspects

Allowing for a certain amount of flexibility can also support the safety procedures inside the habitat. Dams and Stickland for instance state the importance of allowing for flexible window covers, to shield the interior from the intense sunlight and radiation while no direct view of the outside is required. (Dams, Stickland 1989, p.8.55) Including such flexible parts therefore enables a maximum of security while still allowing for certain much needed habitability boosters.

Flexible Systems at HAVEN

HAVEN offers a multitude of flexible elements to enable multiple living situations and functions from intimate gatherings, different workout situations, and individual recreational activities. Such flexible systems are of special importance to create a healthy balance between the permanent and guest crews.

Expandable furniture in the wardroom answers to the challenge of the changing crew size by allowing an adaption in size and location.

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Flexible walls in the instruction area allow the creation of different-sized spaces (including a private working area for the guest crew), the shielding of noise, and the adaption of the space in accordance to temporary needs and various instruction scenarios.

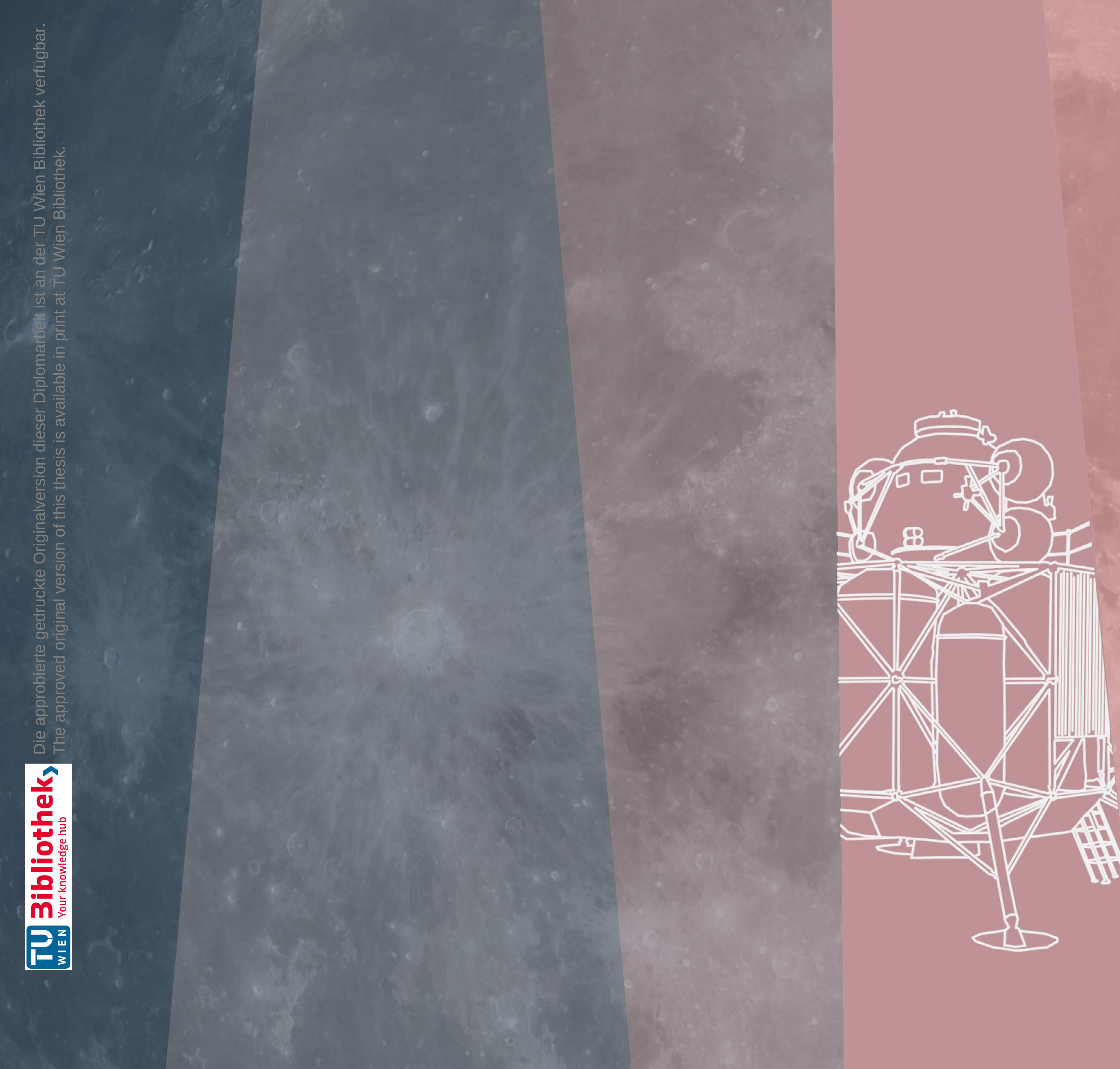
Sliding walls in the work-out area allow for a broad variety of work-out options for groups of various sizes, as well as the optimal usage of available space at any time (detail on p.152).

Pull-out furniture transforms the private crew quarters of the permanent crew from a nighttime version with high privacy to a space for intimate gatherings between two crew members (detail on p.136).

Individual control panels allow the personal adaptation of lighting, ventilation and temperature in all private quarters.

Media screens with a virtual-window-function offer the possibility to instantly change the atmosphere inside all private quarters.

Expandable beds in the permanent crew quarters allow for the shared use of the quarter between a potential couple.



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CHAPTER 4
Mission Scenario

A well-conceived mission scenario is the foundation of a successful operation. This includes the elaboration of objectives and a mission timeline, which play an important role in ensuring that a design can cater to the intended range of activities; furthermore the mission scenario entails a sound reasoning for important parameters, such as the chosen location or support equipment.

Robotic support equipment plays a crucial role in the successful construction and operation of a lunar base and has therefore to be considered in the architectural design.

The same holds true for the launch and landing systems, which are vital for the transfer of habitat components from Earth to the Moon, and act as determining factor for shape, size and materials.

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4.1 Mission Objectives

The HAVEN mission objectives focus on two main targets, the first being the construction and running of a lunar port as an arrival, acclimatisation, and distribution point for other lunar outposts. Arriving crews have the opportunity to learn how to conduct tasks securely in lunar gravity. While all procedures will be trained on Earth, many tasks require different locomotion and object handling in 1/6 G, which calls for some amount of on-site training and experience. (Heiken et al 1991, p.28; NASA 2017, p.215)

The second, albeit smaller, focal point lies on the scientific and exploration objectives based at the HAVEN habitat, which are focused on the effects of lunar habitation. An important factor in the mission objectives is the reuse and storage of lander components to limit payloads and to avoid the creation of a lunar junkyard.

MO1 - Establishing a safe Lunar Arrival Port in the South Polar region

- secure, reusable landing pad for multiple arrivals and departures
- certified, reliable arrival procedures run from the HAVEN habitat
- necessary resources and expertise on site (permanent HAVEN crew)
- dedicated on-site training and instruction of arriving crews (guest crews)

MO2 - A sustainable handling of the lunar environment and economic recycling of arrival components

- using lander components in the construction of the base in order to limit the expansion of the lunar junkyard
- using lander components in the construction of the base in order to limit required construction time, energy, and cost

MO3 - Establishing an exploration and research base on the South Pole

- enabling and supporting the exploration and research of impact craters, PSRs, and resources at the South Pole
- human mapping of the South Pole
- definition and approval of suited sites for future science outposts; support of the deployment and setup with expertise, machinery, and resources
- research in the field of human habitation in 1/6 G
- research of recycling possibilities for lander components

4.1.2 HAVEN Crews

As mentioned in previously, the HAVEN habitat will be home to a crew of eight astronauts, composed of two subgroups:

Permanent Crew

- Crew members at maximum capacity: 4
- Mission duration per person: 180 days
- Objectives: running the arrival port procedures and communications with Earth and other lunar outposts, instructing the guest crew/passing on expertise, research in the area of habitability and lunar gravity

Guest Crew

- Crew members at maximum capacity: 4
- Mission duration per person: 5 - 10 days
- Objectives: acclimatising to the lunar gravity, practical training of procedures in 1/6G

The training includes lessons in the indoor training area (locomotion, fine motor skills, suitport handling, maintenance, medical emergency protocols), as well as on an outdoor EVA training site (locomotion, rover-driving, sample-taking, medical emergency protocols, robotic maintenance).

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4.2 Site

The site selection of the HAVEN Lunar Port and Base depends on several factors to ensure the fulfillment of the mission objectives, as well as a safe construction and sustainable operation of both the port and base.

In a greater regional perspective, the Lunar South Pole has been chosen as location for the mission. This area offers a number of geological merits and benefits for habitation and exploration, a fact that has also been recognised by current space programs, such as NASA, who has highlighted the South Pole region (fig. 4.2) as a target destination for their Artemis program. Steven Clarke of the Science Mission Directorate at NASA Headquarters in Washington explains this choice: *"We know the south pole region contains ice and may be rich in other resources based on our observations from orbit, but, otherwise, it's a completely unexplored world (…) The south pole is far from the Apollo landing sites clustered around the equator, so it will offer us a new challenge and a new environment to explore as we build our capabilities to travel farther into space."* (NASA 2019-I, p.1)
The South Polar region around Shakelton crater has also been announced an area of high interest for lunar exploration by the European Space Agency in view of their SMART-1 project. Detailed maps, generated from images and data collected by SMART-1, reveal an auspicious illumination situation.
"The SMART-1 south polar maps indicate very exciting targets for science and future exploration, within travel reach from a rover or humans at the south pole", says Jean-Luc Josset, one of the SMART-1 Principal Investigators. (ESA 2008)
Apart from offering both PSRs with potential volatiles and areas almost constantly exposed to sunlight (fig. 4.3), the South Pole bears another great benefit. Due to the elliptical orbit of the Lunar Reconnaissance Orbiter (LRO), the Moon's South Pole is the (robotically) most precisely investigated region on the Moon. While LRO's nominal mapping orbit was circular, thus allowing for a global range, both the initial and current orbit is of elliptical shape, with its periselene near the South Pole. (Gläser 2017) This results in a much more detailed mapping of the South Pole's topography, illumination conditions, and temperature fluctuations in comparison to other lunar regions, thus enabling a well founded choice of landing site.

In order to select a specific site for the HAVEN compound, an area at the South Pole with both favourable illumination and temperature conditions, as well as close proximity to a PSR and other potentially interesting exploration sites, was identified.
In the course of a system study of ESA, several areas for potential landings were defined based on LRO data. (De Rosa 2012) A further classification of these selected sites, as well as additional areas of interest, used large-scale and high resolution Digital Terrain Models by the Lunar Orbiter Laser Altimeter (LOLA) on board LRO. (Gläser 2017)
In addition to identifying the regions of highest illumination at ground level, in a second step clusters of high average illumination at two meters above the ground were defined. Consideration of this factor is a vital step, as solar arrays are commonly set at around two meters height and the illumination situation at ground level doesn't coincide with that at this height. While the ground-based areas of permanent illumination may reach several kilometers of length along a ridge, their width is limited to around 20-40 meters. Contrary, illumination clusters at two meters above ground can span up to several hundred meters across a crater rim or ridge, revealing much more favourable locations for solar power generation. In addition to defining illumination clusters, adjacent PSRs (fig. 4.4) were identified and the shortest distance to the potential sites evaluated.
In order to explore and exploit the assumed resources, a PSR doesn't only need to be in close proximity, it also has to be accessible by rover, making the sloping of the terrain an important factor (fig. 4.5). (Gläser 2017)
After a detailed analysis of the suggested sites based on the pa-

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Parameter	Value
Latitude [°]	89.4398
Longitude [°]	222.83
Max average illumination [%]	88.0
Max solar visibility [%]	92.1
Max time in shadow [h]	112
Size of illumination cluster, + 2 m [m²]	135,2
Size of PSR [m²]	5200
Average slope PSR [°]	9.2
Maximum slope PSR [°]	12.8
Distance to PSR [m]	100

Table 4.1 | Key parameters of the HAVEN site, Connection Ridge C1-0

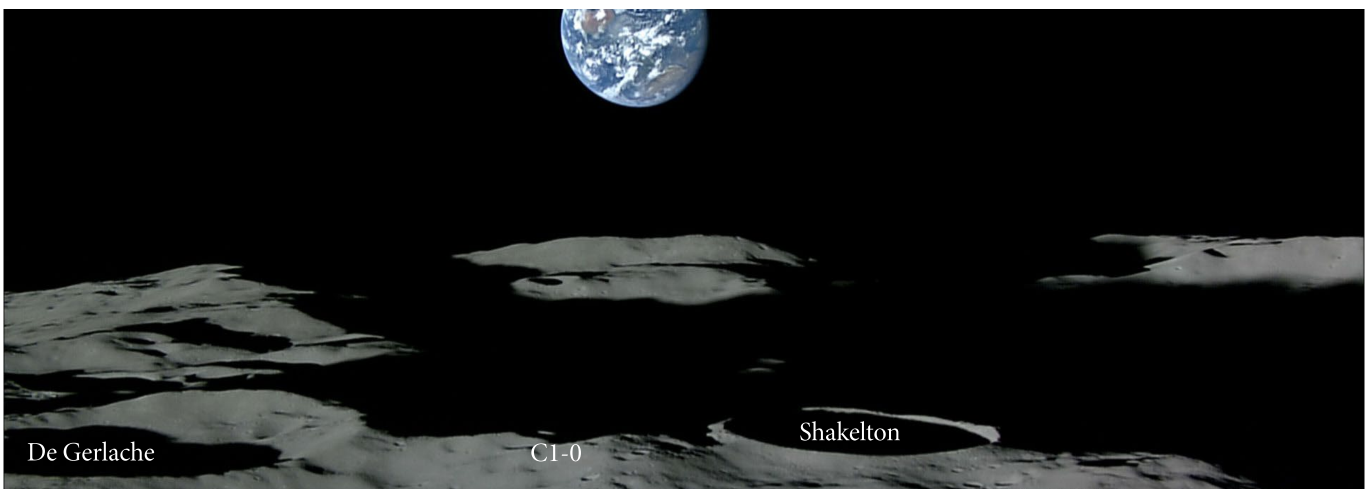

Fig. 4.1 | Earthrise over the HAVEN site C1-0, JAXA

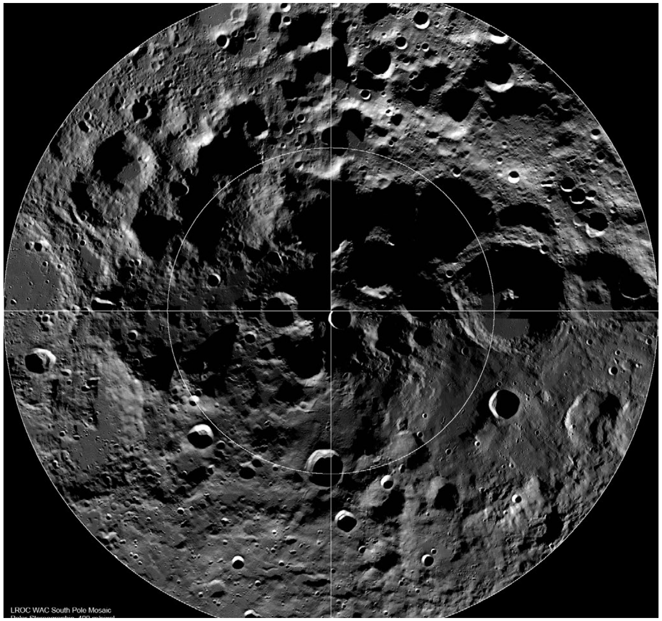

Fig. 4.2 | Lunar South Pole, LRO

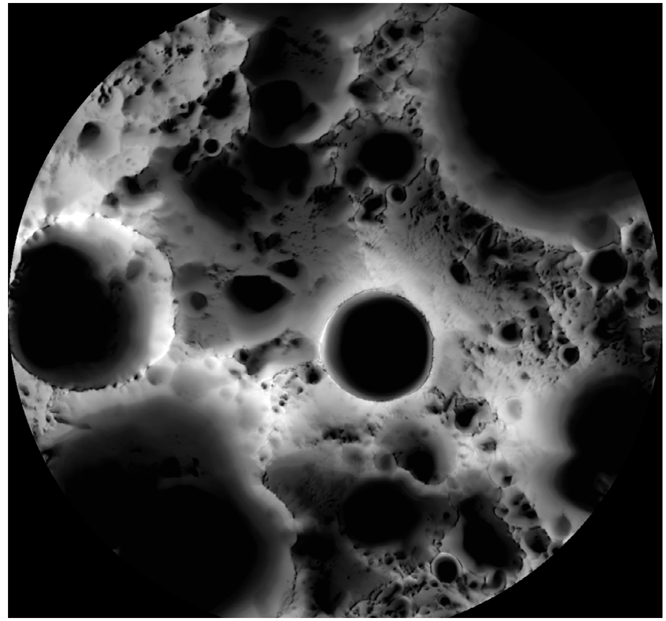

Fig. 4.3 | Illumination Map, Lunar South Pole, LRO

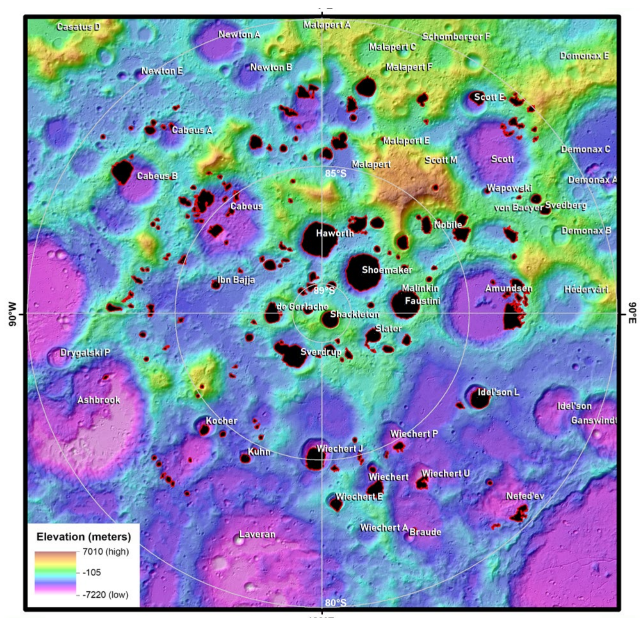

Fig. 4.4 | PSRs, Lunar South Pole, LPI

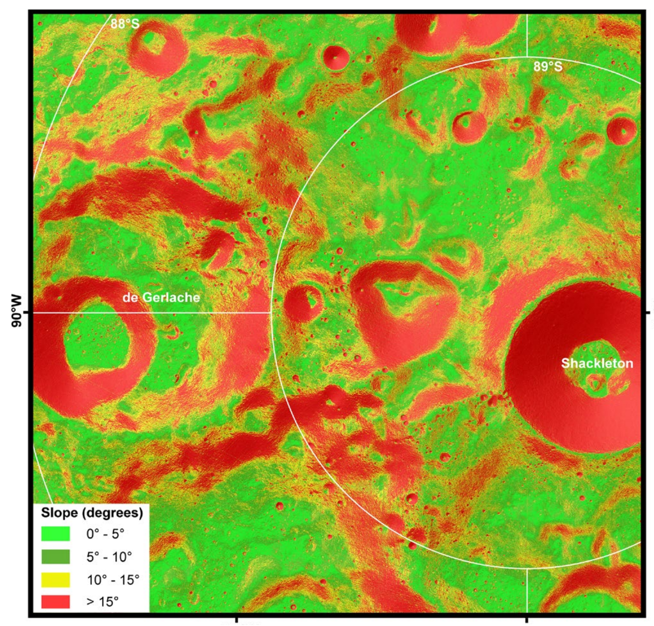

Fig. 4.5 | Slope map between Shakelton and De Gerlache, LPI

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rameters listed above, an area on the ridge between Shakelton and De Gerlache craters (fig. 4.1) has been selected as the ideal site for the HAVEN Lunar Port and Base. Of several possible sites at the South Pole, the chosen area referred to as *Connecting Ridge C1-0* offers the best combination of above-mentioned factors.

C1-0 shows a high rate of ground-level illumination and the highest maximum illumination at two meters height. It is also the spot where the longest solar visibility can be found. With an average slope of 9.2° the closest PSRs to the chosen landing site C1-0 lies within easy rover accessibility. (Gläser 2017)

Another mentionable feature of this site is the close proximity to the geographical South Pole point, which lies on the rim of Shakelton crater. This region, as well as Shakelton crater itself and the close neighbour De Gerlache crater, offer many opportunities for human and robotic exploration in various scientific fields.

The selected site provides the HAVEN crew with desirable research objectives, but furthermore places the HAVEN Port within reach of a range of other interesting sites for additional lunar outposts.

4.3 Robotic Support Equipment

For the successful construction and operation of the HAVEN Lunar Port and Base, several robotic devices have to be deployed to the mission site. The mission requires a number of basic tools or devices for lifting, translating, and precisely placing payloads, as well as professional equipment for trenching, digging, and excavating lunar soil. The possibility of tele-operation and self-deployment is a vital factor that has to be ensured.

A secure means of human transportation, both within the HAVEN compound, as well as between HAVEN and selected exploration sites, is necessary.

Most devices designed for Earth-based construction are not suited for the required applications, due to two reasons. Firstly, Earthen construction equipment is poorly suited for the use in the harsh lunar environment, especially in regard to the danger of regolith contamination. Secondly, terrestrial constructions rely on a high number of special purpose devices, while HAVEN, as any lunar outpost mission, depends on devices with versatile applications, in order to minimize the launch payloads. As a result, all equipment has to be specifically designed and selected for the use in a lunar outpost mission. (Doggett et al 2008)

4.3.1 Operational and Technical Requirements at the HAVEN Lunar Port and Base

Following operational and technical requirements need to be provided for a successful construction and operation of the HAVEN Lunar Port and Base:

I. Payload Manipulation System (PMS)

- unloading payloads from lunar modules
- removing propulsion tanks from lunar modules
- transporting components to designated locations and placing them with high accuracy

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- transporting lunar landers between the launch and landing pad and the storage hangar

II. Human Mobility System (HMS)

- secure transportation of astronauts from the landing pad to the HAVEN base
- secure transportation of astronauts between the storage hangar and the HAVEN base
- secure transportation of astronauts between the HAVEN compound and South Polar exploration sites
- secure transportation of astronauts between the HAVEN compound and additional outposts

III. Lunar Soil Manipulation System (LMS)

- excavating of lunar surface to prepare the site for the habitat deployment
- excavating, collecting, and placing of regolith for ISRU use
- preparing landing pad areas
- banking up radiation shielding regolith

IV. Technical and Operational Requirements of I.-III.

- lightweight, composite components
- compact packaging for launch
- operative in the harsh lunar environment and rugged terrain
- tele-operatable systems for remote control from Earth and the HAVEN communications area
- simple in-field reconfiguration and repair

4.3.2 Selected Robotic Devices for HAVEN

In order to incorporate all the above-listed requirements I-IV as efficiently as possible, a selection of systems has been made to support the HAVEN Lunar Port and Base.

A. Lunar Surface Manipulation System (LSMS)

The Lunar Surface Manipulation System (LSMS) is a multi-functional device developed by NASA's Langely Research Center, which offers novel approaches towards heavy lifting and precision positioning of payloads on the lunar surface. The hybrid-design (fig. 4.6) of the LSMS combines the functional characteristics of both crane-type devices and robotic manipulators, thus enabling an accurate positioning of payloads with optimal control over parameters like translation and rotation. Additionally, the LSMS is equipped with an automated quick-change device at the tip, which provides the availability of end effectors or special purpose tools, such as buckets, grappling devices, forks, sensor and visualization packages, or pallet forks. This makes the LSMS a highly versatile machine with potential applications in manipulating both payloads and in-situ resources, such as regolith. The envisioned truss architecture grants a lightweight composition by using pure compression and tension members. Both a high structural efficiency and a large range of motion are granted due to the use of multiple spreaders, which are automatically engaged by rod portions of the tension members. (NASA 2014)
The LSMS can function in conjunction with mobility systems, for example by being mounted on rovers and transportation devices, such as NASA's All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE). (Doggett at al 2008)

For the construction and operation of the HAVEN Lunar Port and Base the LSMS's capability to perform cable suspended crane operations are of particular importance in the unloading and precise positioning of the undeployed HAVEN habitat and other cargo, whereas the rigid grappling tool attachable to the tip of the LSMS enables the removal and accurate placement of the propulsion tanks (fig. 4.7). With an estimated mass of approximately 3% of the mass of the heaviest payload lifted at the tip (NASA 2014), the LSMS proves an efficient solution for lunar payload manipulation at the HAVEN compound and thus, a PMS based on the LSMS design serves to support the component and material handling at the HAVEN site.

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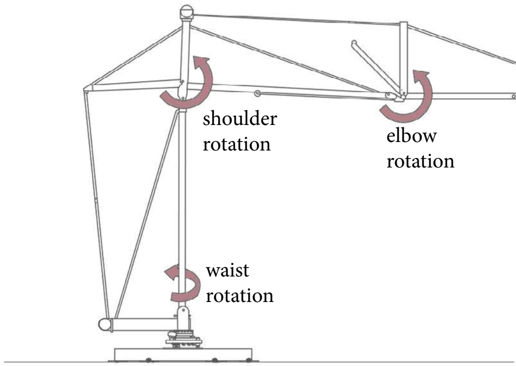

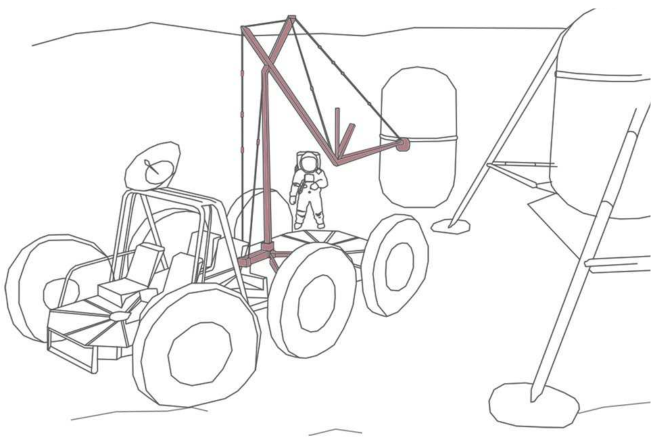

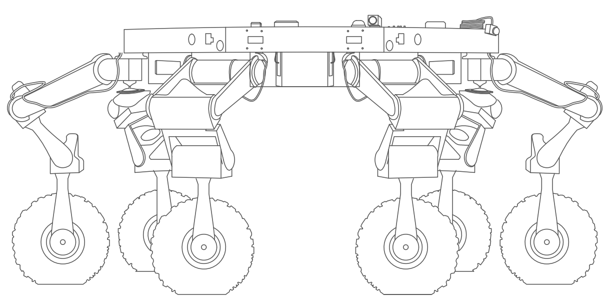

Fig. 4.6 | Diagramm of a LSMS, based on Dogett et al 2008

Fig. 4.7 | Mounted LSMS used to remove tanks from a lander, based on Dogett et al 2008

Fig. 4.8 | ATHLETE

B. All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE)

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) is a lunar utility vehicle developed in a cooperative approach by the Jet Propulsion Laboratory, NASA's Johnson Space Centre and Ames Research Centre, Stanford University, and the Boeing Company. The vehicle focuses on achieving a high mobility rate on the difficult lunar terrain while maintaining a relatively high velocity with 10 km/h. (Wilcox et al 2007)
ATHLETE is equipped with six limbs with wheel attachments (fig. 4.8). These legs can either be used as conventional wheels or as feet, to achieve its wide range of mobility and combine the advantages of both legged and wheeled vehicles. The possibility to equip the limbs with quick-disconnect tool adapters allows ATHLETE to provide a broad variety of tools and manipulators. This makes the vehicle an important asset in assembly, maintenance or servicing tasks and enables safe and easy operations in a height of up to 10 meters. Autonomous control, as well as human remote control, is enabled by cameras on each leg and the six hex-frame sides. (Ibidem)

Due to the very mountainous terrain at the lunar South Pole, an ATHLETE-type vehicle proves an indispensable asset for the HAVEN Lunar Port and Base. Payload and tank manipulations will occur in combination with the LSMS-based PMS. ATHLETE's tool adapter technology will be vital in the deployment, assembly and servicing of the HAVEN habitat.

C. Chariot Crew Mobility Chassis (CMC)

The Chariot vehicle, a modular wheeled-chassis design by NASA's Johnson Space Centre, is the prototype for a lunar surface truck with multipurpose abilities. It is able to function with a crew or by remote control from an outpost, lander, or even Earth. Besides crew transportation, Chariot's large number of functions include serving as a cargo carrier, manipulating resource materials or performing servicing and maintenance tasks, such

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as the laying of cables. Its design deviates from the traditional vehicle setup known from Apollo's Lunar Roving Vehicle (LRV). (Harrison 2008) The LRV, which was used in the Apollo Missions 15, 16, and 17, supported a crew of two astronauts at a maximum speed of 14 km/h. (NASA 1972) Instead of the LRV's side-by-side seating arrangement, the Chariot design has an in-line arrangement of standing astronauts. The crew capabilities have been doubled to four, which offers the possibility of using Chariot as an emergency rescue vehicle in combination with additional rovers. While the LRV was limited to conventional movements, Chariot is equipped with crab steering, allowing the six wheels to rotate 360 degrees in order to enable Chariot to move in any direction and turn at any point. The increased number of wheels enhances the traction on the difficult lunar terrain, at top speeds of 20 km/h, and offers the advantage of redundancy in case of failure. Another improvement in comparison to the LRV is the capability to lower the chassis for improved accessibility, while an elevated height can be maintained during driving mode to optimise ground clearance. (Harrison 2008)
The Chariot design serves as a basis for crew transportation at the HAVEN Lunar Port and Base. It is used in the following two configurations:

a. Small Pressurized Rover (SPR)

NASA's design for the Small Pressurized Rover (SPR) consists of a CMC equipped with a pressurized cabin module (fig. 4.9). This enables long excursions and work from within a secure pressurized volume without the restrictions of space suits. When directly accessing the lunar surface, the crew can perform a rapid EVA ingress/egress via the SPR's suitport, which offers a faster and easier transition than traditional airlocks. By means of the docking hatch the SPR can be mated with habitats, lunar modules and other pressurized rovers for a secure, pressurized crew transfer. While mainly intended for a crew of two, the SPR is able to support up to four astronauts in emergency situations. In the case of unexpected solar events, the SPR can even double as a radiation-hard emergency shelter for up to 72 hours. It is also suited to treat medical emergencies, such as decompression sickness. The cabin module and the CMC can be launched to the lunar surface pre-integrated or as individual elements. This allows for a later adaption of other CMC configurations. (NASA 2008)

b. Unpressurized Rover (UPR)

In order to use the CMC as an Unpressurized Rover (UPR), it simply has to be equipped with a chassis driving kit (CDK). CDKs are easy to install and remove, allowing or flexible adaptations of the CMC. (Mazanek, Troutman 2009)

In the initial phases, the HAVEN Lunar Port and Base will be equipped with one SPR-type CMC that allows the crew to access multiple locations within and without the HAVEN compound, and establishes a reliable connection between HAVEN and other potential lunar outposts. When not in use, the SPR will be docked at the HAVEN habitat, to serve as additional pressurized volume and additional emergency shelter.
In addition to the SPR, a chariot with an UPR configuration is deployed to the HAVEN Lunar Port and Base during the human construction phase to increase the crew's mobility within the compound, act as emergency rescue vehicle and assist the ATHLETE-type vehicle with servicing tasks and the compound construction. This CMC is reconfigured into a second SPR, docked at the habitat's second airlock, in the main habitation phase. The modular system allows for flexible configuration changes between UPRs, SPRs, or cargo rovers.

D. Percussion and Pneumatic Excavation Technology

While the basic functions of terrestrial construction equipment, such as backhoes, loaders and bulldozers, are commonly used as a foundation when designing tools for lunar soil manipula-

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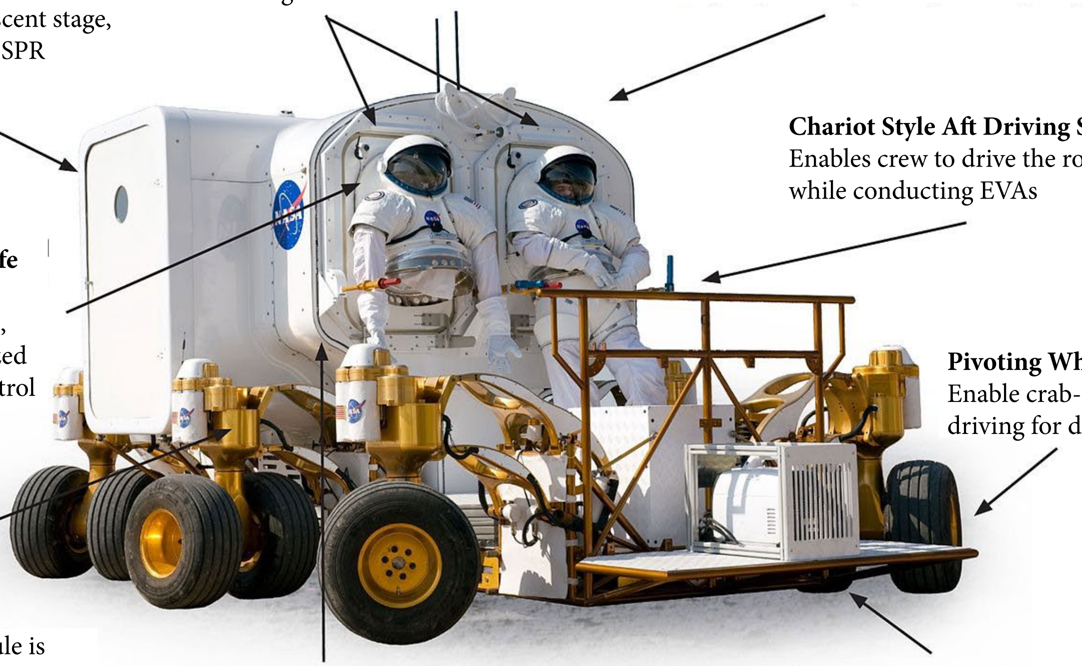

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Fig. 4.9 | A CMC configured as SPR, NASA

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tion, conventional Earthen machinery is not applicable in an efficient manner on the lunar surface. Terrestrial devices achieve the breaking-up and excavation of soil and rocks through brute force and hydraulic systems. Machinery on Earth reaches weights of several hundreds tons. (Zacny et al 2009)
For several reasons, these terrestrial approaches to soil-moving would not be feasible on the Moon, the first one being the immense costs that would arise due to the extremely heavy payload. Furthermore, machinery with a terrestrial hydraulic approach would be impeded by the low lunar gravity. (Zacny et al 2010)
Yet another facto is the high cohesion and friction angle of lunar regolith, which is caused - amongst other reasons – by unsatisfied bonds, as due to the lack of atmosphere no absorbed water or oxides gather on surfaces. (Ibidem)
Potential alternatives to conventional terrestrial techniques are the percussive and pneumatic approaches.

Percussive Digging

The percussive digging system greatly decreases the amount of downforce needed to penetrate soil. A direct result of this is the decrease of the necessary reaction loads and machinery mass.
Furthermore, it enables shovel blades to penetrate much stronger soils than would be the case with a conventional system.
The system uses high-frequency and low-energy impacts - the impact energy imparted by a reciprocating hammer is transferred through a scoop and utilized to penetrate the regolith. The regolith's resistance forces are decreased due to the generated vibrations, which enables an easy insertion of the scoop and even allows for the excavation of frozen or highly compacted regolith.
By using a percussive approach instead of a hydraulic system, a force 40 times lower than that of a non-percussive scoop can be harnessed for deeper and faster digging. As a direct result, the excavation device will be 40 times lighter.
Overall, the increased digging capabilities allow for much higher excavation rates, thus making percussive digging an immensely efficient approach.

Naturally, a percussive system comes with an increased energy demand; however, as energy can be generated in-situ by harvesting solar power, the enormous saving of payload mass - which in turn will save millions in launch costs - easily outweighs the increase in energy requirement. (Zacny et al 2009)
In addition, particle discharge into the bin is noticeably enhanced in percussive systems. (Ibidem)

Pneumatic Mining

A second novel approach to lunar soil-moving is pneumatic mining, which harnesses gas momentum to move particles into a bin. The technique is similar to a conventional vacuum cleaner, with the difference that in the air-less lunar environment, instead of creating a vacuum to suck up elements, the gas is used to push the soil up. The compressed gas can be delivered directly at the nozzle (fig. 4.11). After flowing through small tubes on the sides of the main chamber nozzle, it exits directly into the chamber. The gas is delivered in frequent pulses while the nozzle is dragged across the surface. Thus, soil is lofted and moved through a delivery tube into a mining bin. (Zacny et al 2004)
Extremely high efficiency rates of 6000 grams of regolith moved by only 1 gram of gas at few psia can be achieved. The gas itself can easily be salvaged from reserve propellant (LOX/H2) that would otherwise be vented from the tanks, or even by using the crew's exhaled carbon dioxide. (Ibidem) This is a highly efficient, economic and environmentally conscious approach, that fits well into the HAVEN project's aspirations of component and material reuse.
The system furthermore offers a convenient means of immediate transportation and storage of the material, by directly pushing the excavated elements through tubes to a storage silo or even directly into shielding bags at their final location. (Reuss et al 2008)

"The main advantage of the pneumatic system is in efficient regolith transport (…) while the main advantage of the percus-

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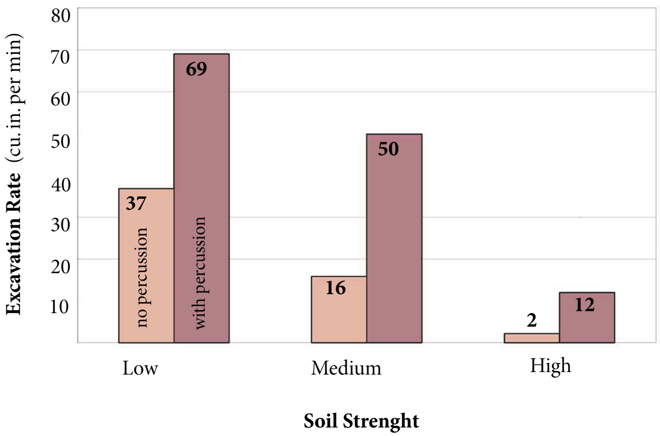

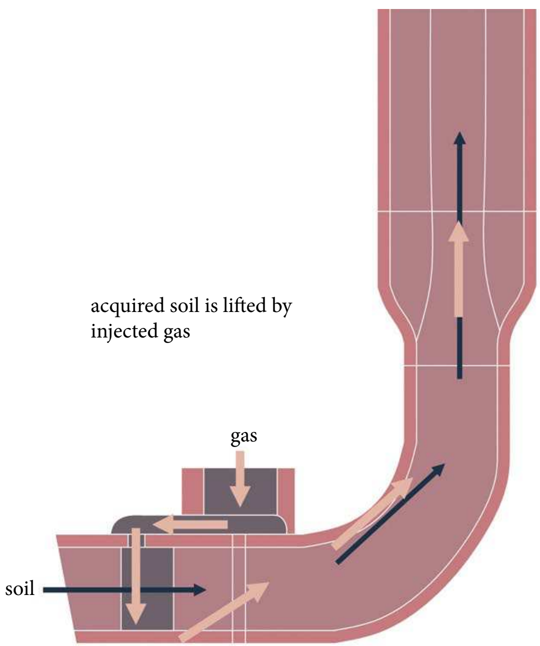

Fig. 4.10 | Comparison of excavation rate with and without percussion in varied soil strength, Craft et al 2009

Fig. 4.11 | Concept of pneumatic excavation by Zacny

sive system is in reducing excavation forces by up to 40x. Both systems (...) can be combined into a single highly synergistic system. For example, a percussive scoop could be integrated with the pneumatic lift of particles and the nozzle of the pneumatic excavator could be integrated with the percussive mechanism to enhance its deeper excavation capabilities." (Zacny et al 2004, p.1)

In conclusion, a combined approach of percussive digging and pneumatic excavation will be utilized for the HAVEN Lunar Port and Base. A scoop, similar to a backhoe, equipped with a percussive system, will be mounted on an ATHLETE-type vehicle or a CMC for digging purposes, such as creating the excavation for the HAVEN habitat (fig. 12). A percussion and pneumatic adapted bulldozer, likewise mountable on the robotic vehicles, is intended for creating the landing and launching pad, the utility roads between the pad, the hangar, and the habitat, leveling the habitat foundation, and to move in-situ resources for radiation shielding and further processing.
Especially for the purpose of filling the lander tanks and the hangar shielding bags, a pneumatic system proves most efficient, as it enables the direct transferal of the soil into the tanks at their final location.
This proves highly time, energy, and cost efficient, as no additional machinery or material has to be launched to the Moon and the excavated regolith, which poses a potential threat to systems and tools, is safely disposed off right away.

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4.4 Launch and Landing Systems

Deciding on fitting launch and landing system is an important preparatory step for any extra-terrestrial design, as the habitat's mass and geometry will be heavily influenced by the possible cargo fairings and payload capacities.

4.4.1 Launch System

The HAVEN missions aim to utilize the Block 1B configuration of the Space Launch System (SLS), which is set to play a major role in the establishment of the Lunar Gateway and the return of humanity to the Moon.

The SLS, which NASA is currently developing together with its private sector partners, is a modular super heavy-lift vehicle. The deep-space rocket aims to support missions to cislunar space and beyond; its architecture is planned to be upgraded in a blocked approach, thus permitting progressively heavier payloads (fig. 4.12). While the initial configuration, namely Block 1, aims to deliver at least 26 metric tons to trans-lunar injection (TLI), this capacity will increase up to 45 metric tons at the stage of Block 2B, which aims, amongst others, for Mars missions. Cargo fairings of 5-8.4 meters are envisioned, with considerations of even larger fairings in later stages. The Block 1B launches will provide an 8.4 meter diameter fairing in 19.1 meters or 27.4 meters length. The internal cargo diameter lies at 7.5m meters. The launcher is scheduled to be available in 2023(Cox et al 2018) and should therefore fit well with the HAVEN mission timeline (see p.96). However, as a potential backup system, a launcher from the Falcon line could be used for the HAVEN launches.

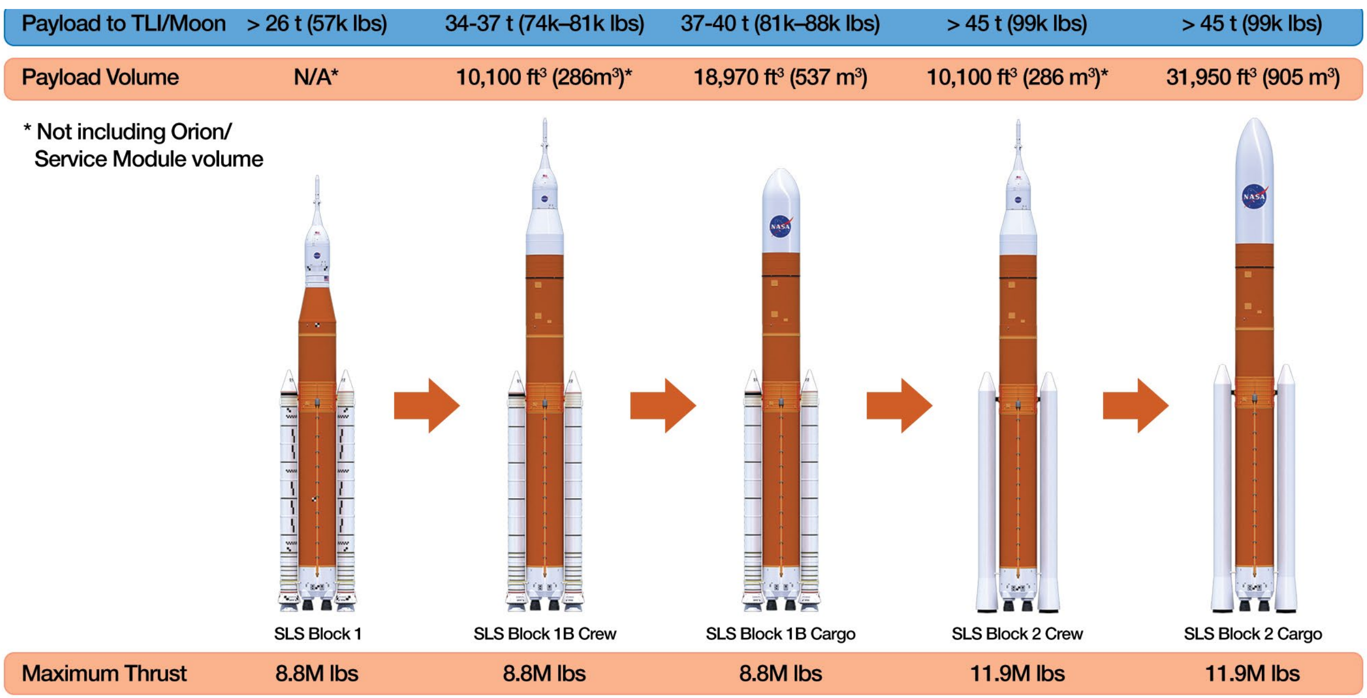

Fig. 4.12 | SLS developement, NASA

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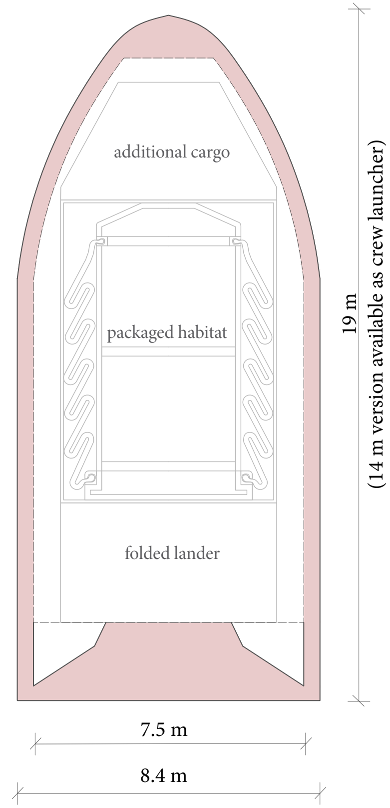

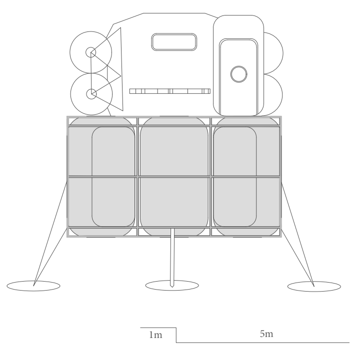

Fig. 4.13 | SLS Block 1B Cargo Fairing: $621 m^3$ possible payload volume

Fig. 4.14 | HAVEN lunar lander

4.4.2 Lunar Lander

A careful selection of the HAVEN lander's design, preceded by an analysis and understanding of contemporary lander architectures, is imperative, as the HAVEN lander contributes vital building bricks to the HAVEN compound. This approach will minimize the creation of a lunar junkyard and utilize the otherwise discarded propulsion tanks in an efficient, sustainable manner.

Technical Composition

In order to achieve a soft landing on the Moon's surface, specific surface access architecture is required. A great variety of designs for such architectures for both, the Moon and Mars, have been developed over the last decades, the earliest dating back to 1938[3].
A lunar lander is either crewed or uncrewed, depending on the objective of the mission. Crewed landers traditionally include an in-transport habitable space that supports the crew during their stay on the surface.
Conventional lander concepts can be categorized by their staging schemes. Depending on the design of the lander, it is composed of either one, two, or three stages. (Isaji et al 2018)

Two-Stage Landers

Currently most common are designs with two stages, which was also used for the Apollo Lunar Module and the concept for the Constellation Program's Altair lander, as well as is envisioned for the Artemis moon landings. The two-stage approach is constituted of an ascent and a descent stage. While the descent stage mainly carries the propulsion tanks that are needed for a secure landing, the ascent stage transports the crew, the habitable space with life support, and ascent propulsion for returning to lunar orbit. This means that while the ascent stage leaves the lunar surface at the end of the mission, the descent stage with the then empty propulsion tanks remains behind. (Ibidem)

3 - In 1938 the British Interplanetary Society (BIS) published the first official concept for a lunar lander.

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Three-Stage Landers

For a three-stage lander, a braking stage is added to the ascent and decent stage, to provide most of the descent propulsion. This third stage is usually detached from the rest of the lander before the landing, while the remaining two stages take care off the actual touchdown and later ascent in the manner of the traditional two-stage design. (Ibidem)

Single-Stage Landers

A single-stage lander is designed to be one element that descends and ascents in its entirety. While a reusable single-stage lander would be beneficial both from economical aspects and to avoid the expansion of the lunar junkyard, such designs still face major technical challenges in the areas of material, mass, and propulsion and are currently not feasible.

A single-stage design, the Mars Base Camp Precursor Lunar Lander, was proposed to NASA by the company Lockheed Martin in 2018. The design was supposed to work between the lunar surface and the Lunar Orbiting Platform-Gateway, which is currently under development by Lockheed Martin and NASA. (Cichan et al 2018) However, in 2019 another concept, this time for a two-stage lander, was announced. (Lockheed Martin 2020)

For the Artemis program, several industry partners have formed a cooperation to develop the Artemis lander. While the main contractor Blue Origin has presented its own design for a cargo lander with a stretched-tanks version as crewed lander, the current position is that Lockheed Martin will develop the ascent stage for Artemis, while Blue Origin produces the descent part. (SpaceNews-I 2019)

This serves to show that current exploration is still angled toward the two-stage, or respectively the three-stage, approach. In accordance with this trend, a two-stage design has been selected for the HAVEN lunar landers. The descent stages will be moved to a safe storage hangar where the valuable materials can be protected from degradation caused by the harsh environment and utilized at a later time. The main components of the descent stage, the propulsion tanks, will be removed and used immediately in the construction of the HAVEN habitat, by using them to contain the regolith for the radiation shielding.

Habitability Aspects

In regard to habitability, the qualities of a lunar lander are very limited. Due to a minimalistic approach in design, in order to reduce the lander mass, the habitable space of most lander designs is barely sufficient to perform crucial tasks, such as medical emergency procedures or suit maintenance.

The habitable space of the Apollo Lunar Module (LM), for example, consisted of a pressurized volume of 6.65 m^3 for two astronauts (fig. 4.14). The crew compartment, in the frontal area of the 234 centimeter diameter ascent stage, included the flight stations, control and display panels, equipment storage and a PLSS donning station. A 81 centimeter forward hatch, in lieu of an airlock, served to transfer the crew to and from the lunar surface and the Control Module (CM) during flight. The LM also comprised three windows with roll-up window shades - two triangular ones in the front face and one docking window above the Commander's flight station. (Grumman 1968, p.19)

While the LM's configuration proved successful in the Apollo missions and was declared as sufficient in regard to habitability by Apollo crew members, for a mission duration of more than a few days, the habitable space would need to be increased significantly. According to Apollo Astronaut Charlie Duke, specifically the areas of privacy and personal comfort, as well as food preparation and the ingress/egress system, should be adapted for a longer sortie mission and especially an outpost mission. (See Chapter 5 for the full interview with Astronaut Charlie Duke.)

For the planned follow-up of the Apollo missions, the Constellation Program, NASA ordered several studies to develop and improve technical and habitability conditions in the new lander. In the 2005 Exploration Systems Architecture Study (ESAS),

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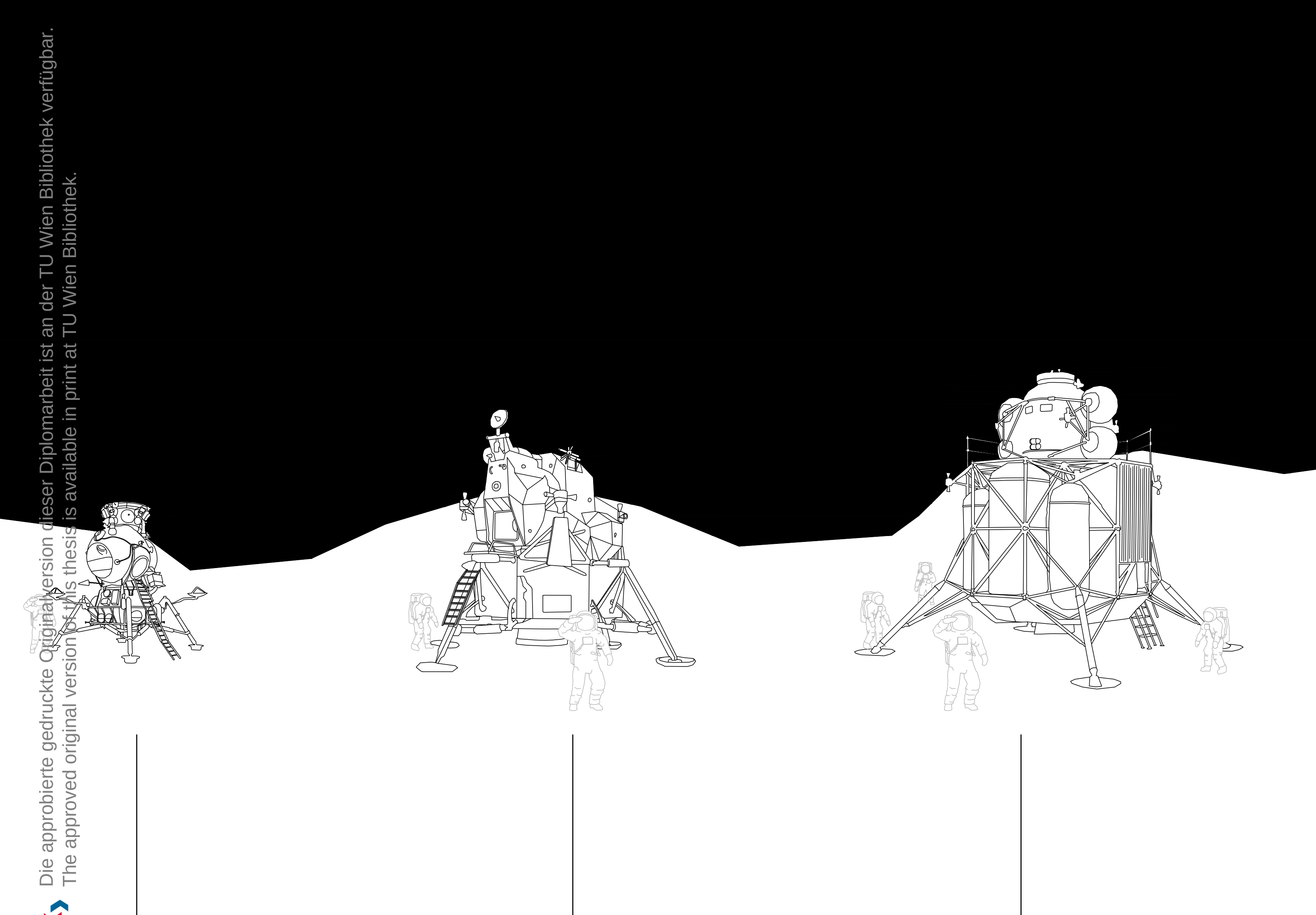

niy Korabl (LK) Lander
0s | Soviet Union, OKB-1 Korolyov

w capacity: 1
e: 2-stage
ation of lunar mission: around 48 hours
ght: 5.20 m | max width: 5.40 m | mass: 5,6 t
itable volume: 5 m³

(Meuser 2019, p.138f)

Apollo Lunar Module (LM)
1960s | USA, Grumman

crew capacity: 2
type: 2-stage
duration of lunar mission: 3 days
height: 7.04 m | max width: 9.45 m | mass: 16.4 t
habitable volume: 6.65 m³

(Meuser 2019, p.145ff)

Altair Lunar Lander
2000s | USA, Constellation Program

crew capacity: 4
type: 2-stage
duration of lunar mission: 7 days
height: 9.90 m | max width: 14.90 m | mass: 45.86 t
habitable volume: 19 m³

(Cohen 2009)

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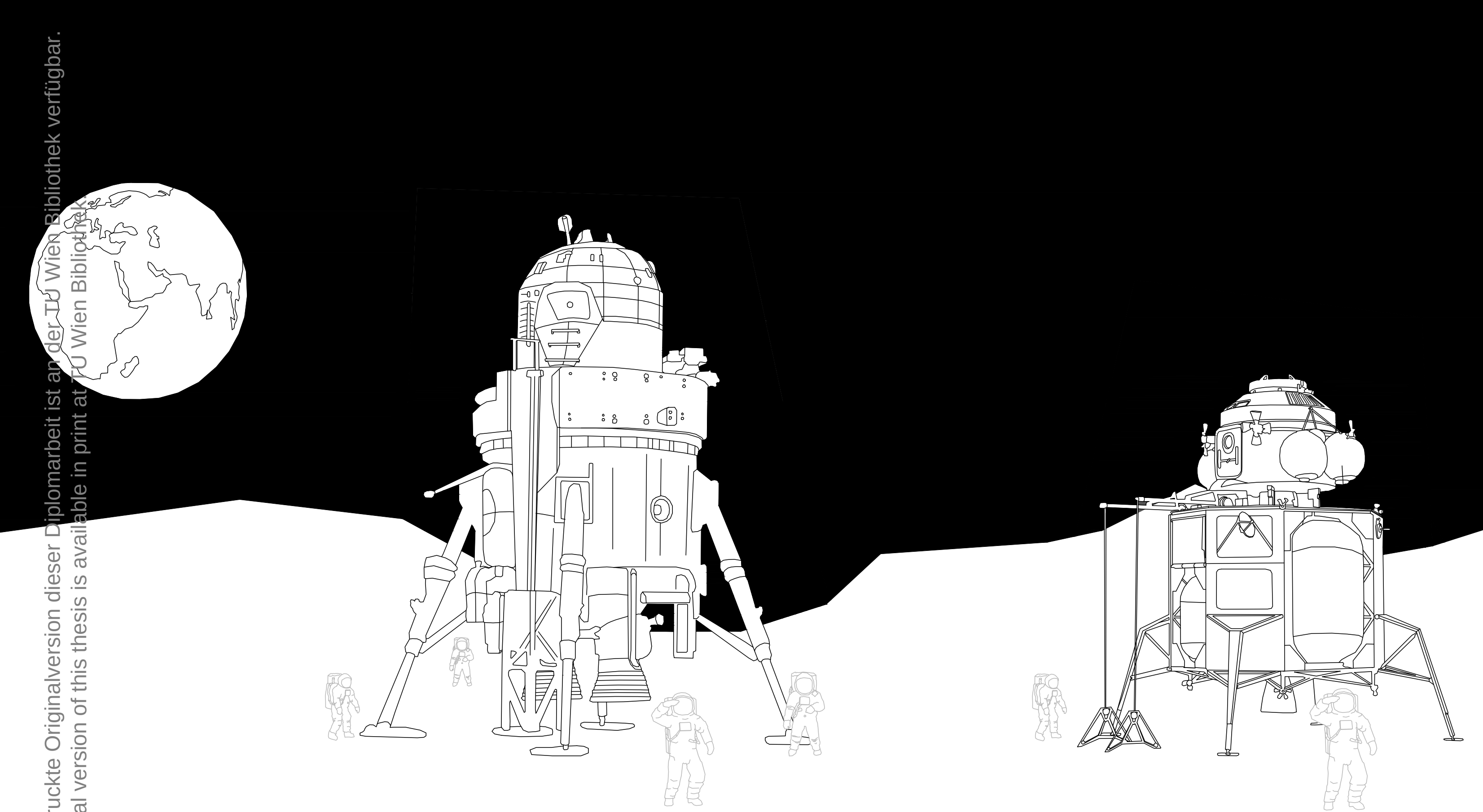

Mars-Precursor Lunar Lander
2010s | USA, Lockheed Martin

crew capacity: 4
type: single-stage
duration of lunar mission: 14 days
concept draft

(Cichan et al 2018)

Crewed Blue Moon Lander
2010s | USA, Blue Origin

crew capacity: 2
type: 2-stage
concept draft

(Foust 2019)

Fig. 4.15 | Comparison of lunar landers

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the Lander Design Analysis Cycle-1 (LDAC-1) in 2007, and the 2008 Lunar Lander Development Study (LLDS), amongst others, the industry provided data on the habitable volume allocation of lander concepts. Various concepts for the habitation part of the lander ranged from a minimalistic 10 m³ version for the entire ascent module proposed by NASA to a 23,2 m³ design recommended by Northrop Grumman. (Cohen 2009)
The official Altair design contains 4.75 m³ of pressurized volume per crew member. An 8 m³ airlock adds to the pressurized volume, which is designed for a seven day surface operation with a crew of four. (Cohen 2009-I)

For a mission lasting longer than seven days, a larger habitable volume than the space available in an ascent stage should be designed to meet the habitability needs of the crew.
However, the lander will have to support the crew during the human construction phase, before the crew can move into the actual HAVEN habitat. (Details on the construction phases on p.113) Consequently, the crewed version of the HAVEN lander will be equipped with an ascent stage that can support a crew of four for up to five days.

HAVEN Lander Parameters

In regard to size and composition, the two-stage HAVEN lander (fig. 4.14) is based on the Altair lander. Eight main propulsion tanks[4], a habitable volume of 5 m³ per crew member and a separate airlock of another 8 m³ pressurized volume characterize the lander's setup.

- Configuration — two stages
- Crew capacity — four
- Sortie mission duration — maximum five days
- Overall height — 7.5 m
- Width at tanks — 6 m
- Width at footpad — 8.5 m
- Habitable volume — 15 m³ (airlock excluded)
- Airlock volume — 7 m³
- LH2 tanks — four (d=1.90m, h= 3.4m)
- LOX tanks — four (d=1.20m, h= 2.8m)

(dimensions for the crewed version of the HAVEN lander)

4 - four tanks containing liquid hydrogen (LH2) and four slightly smaller ones for liquid oxygen (LOX)

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4.5 Mission Timeline

The overall mission timeline (fig.4.16) of the HAVEN mission stretches from the mission design, starting in 2020, over several phases of exploration and construction, to the habitation phase and possible spatial expansion of the outpost.

Phase 1 - Preparation and Prestaging

The mission design process is based on extensive robotic research and exploration, such as LRO data. Additional robotic exploration missions to the HAVEN deployment site will ensure a well-conceived preparation.
A series of prestaging launches will ensure the placement of the habitation module and all necessary support equipment.

Phase 2 - Construction

The main part of the outpost construction will be done robotically, before the arrival of the first human crew. This first crew finishes the construction and installation of critical systems, while first living in their lunar lander ascent stage for five days and then moving into the HAVEN habitat.
(Details on the construction phases on p.113)

Phase 3 - Initial Habitation

The initial habitation phase will see the installation of non-critical systems while the crew already lives in the HAVEN habitat. Subsequently, this first crew sets up processes and procedures at the arrival port and gathers expertise in lunar habitation. This phase does not include the visit of guest crews but consists of six permanent crew members to overcome initial difficulties.

Phase 4 - Arrival Port

The main phase of the HAVEN project takes place when the arrival port procedures are running. A permanent crew of four (rotating every 180 Earthen days in pairs of two) and guest crews of up to four (staying for five to ten Earth days) live at HAVEN.

4.5.1 Crew Rotation

Despite highly effective radiation shielding at the HAVEN habitat, the duration of an individual's stay on the Moon has to be limited to prevent medical issues. The scheduled duration of residence at HAVEN amounts to 180 terrestrial days, hence six Earth months.[5] After this, the crew returns to Earth; new members of the permanent crew arrive.

4.5.1.1 Traditional Crew Rotation Systems

For the crew exchange itself, two modes have successfully been used aboard space stations. In the indirect handover the old crew's vehicle undocks and returns to Earth before the next one launches, which means that the two crews don't meet each other in orbit. This causes a temporary crew reduction, which can be problematic in terms of work and research efficiency. In the indirect handover at the ISS, for example, the station is run by a crew of three for up to two weeks, until the new astronauts arrive.
A direct handover would mean that the new astronauts arrive before the old crew leaves; in a handover period of around ten days the station will host the old and the new crew simultaneously. While this means a higher crew number and more crowded living arrangements – which also causes a strain on the life support systems -, a direct handover period allows an easier transferral of specialist expertise. This system furthermore enables shorter stays of additional astronauts, which arrive with the new crew and leave around ten days later with the old one. (NASA Spaceflight 2017)
It was this approach that allowed Franz Viehböck to visit the space station Mir for seven days during the AustroMIR project, thus becoming the only Austrian to have flown to space to date.[6] (FFG 2020)
Regardless of the choice of a direct or indirect handover, it is important to rely on the direct transferral of experience, as in the case on the ISS between senior and junior crews. This means that

5 - This concerns the permanent HAVEN crew, not the visiting guest crews, which only stay for up to seven days.

6 - Viehböck started on October 2 1991 with Sojus TM-13 and landed back on Earth nine days later with Sojus TM-12.

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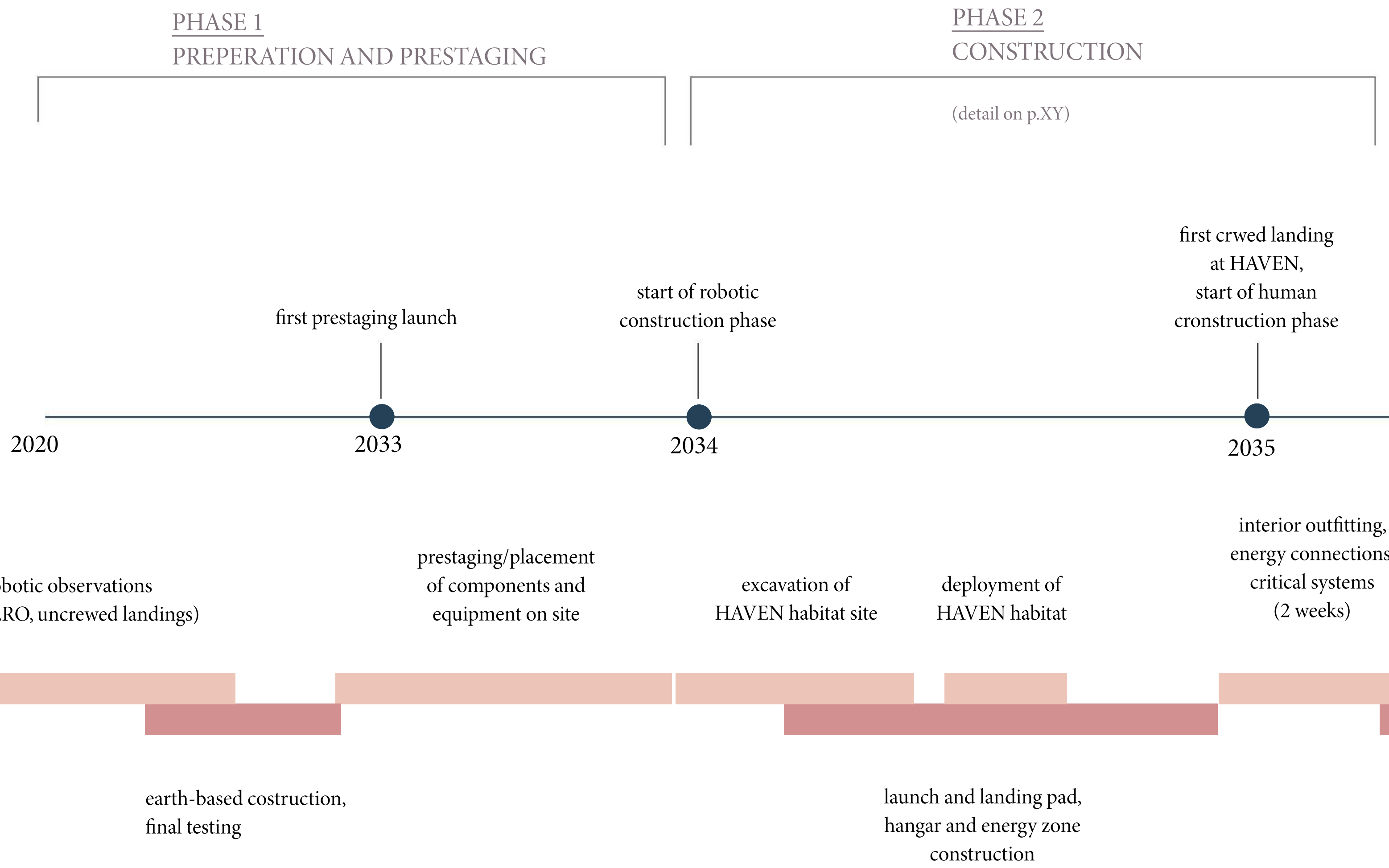
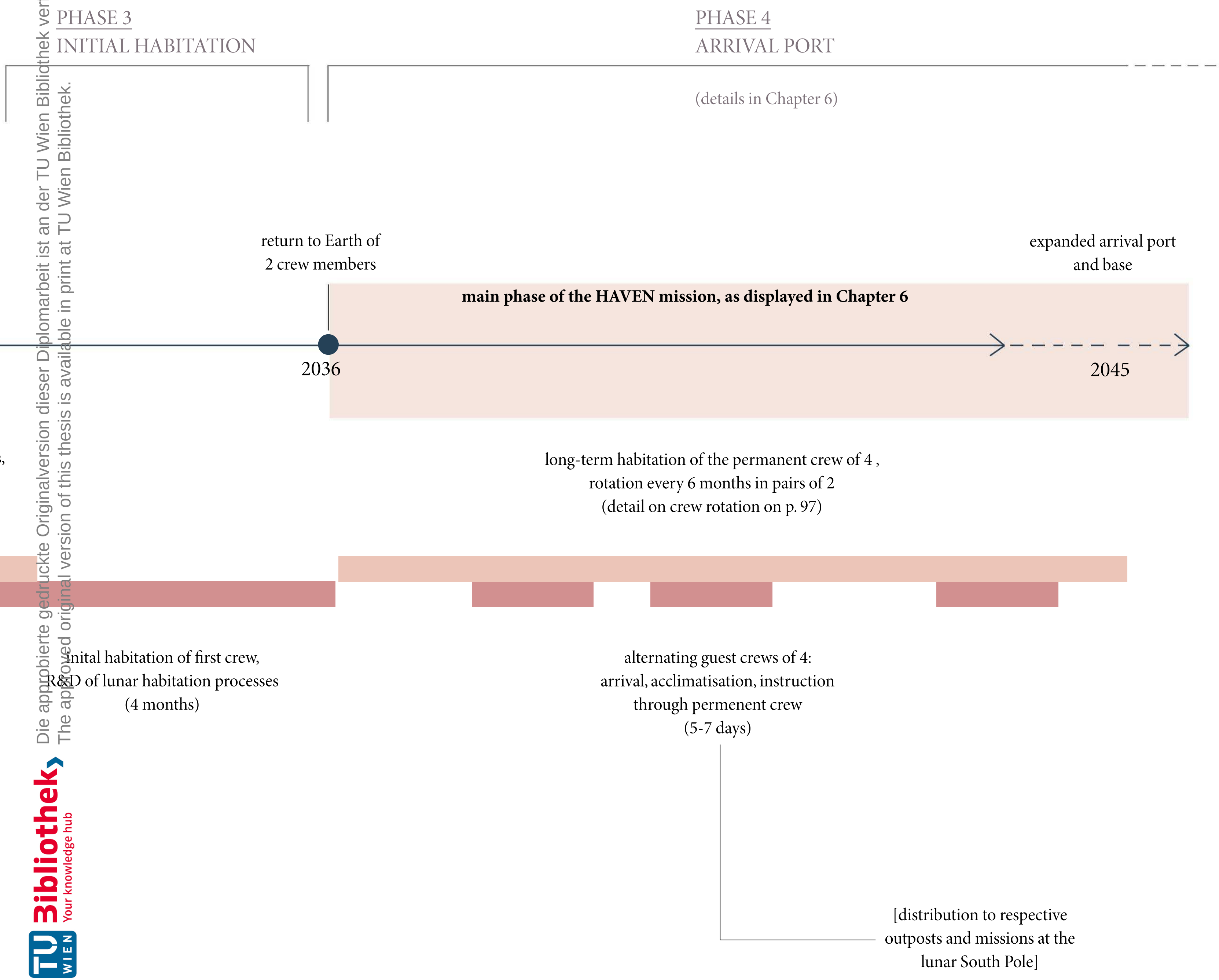


Fig. 4.16 | HAVEN mission timeline



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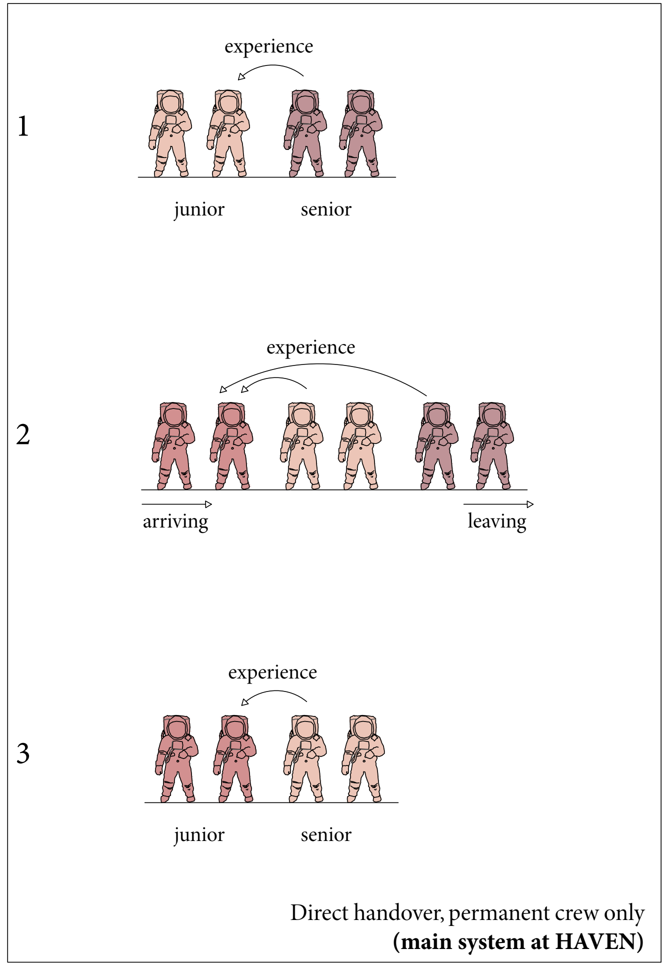
the whole six-person crew is never exchanged at the same time, but in two teams of three. The new arriving crew, the junior crew, learns from the senior crew for several months, before the senior crew returns to Earth, the junior crew turns into the new seniors, ready to train the newly arrived junior crew. (NASA 2017)

4.5.1.2 Crew Rotation at HAVEN

The crew rotation at HAVEN happens in a buddy-system, meaning that instead of rotating all four members of the permanent crew at the same time, they change in pairs of two and with a three month delay in between to enable a handover of experience and expertise.

The exchange itself can happen in both the direct and indirect mode, depending on the current HAVEN occupation. In general, it is intended to use a direct handover approach, with an overlap of the old and new crew of seven days. This should be scheduled at a time when there is not additional guest crew situated at HAVEN. As there won't be a permanent occupation of guest crews at HAVEN, it can be assumed that a direct handover between two guest crews is possible, upping the total inhabitants of HAVEN to six crew members.

However, in the case of no appropriate time space in between guest crews, the handover could either be done in an indirect mode, or in a shorter direct mode, which would leave HAVEN with ten inhabitants for five days. In that case, additional sleeping arrangements can be procured in the sickbay. This would allow the new part of the permanent crew to arrive on the same launch as the new guest crew.



1 - Junior crew learns from senior crew

2 - New crew arrives. Expertise exchange between junior, senior and new crew in a 14 days direct handover period. Old crew leaves.

3 - Old junior crew becomes new senior crew.

Fig. 4.17 | Possible HAVEN rotation schedules with experience transfer in buddy system

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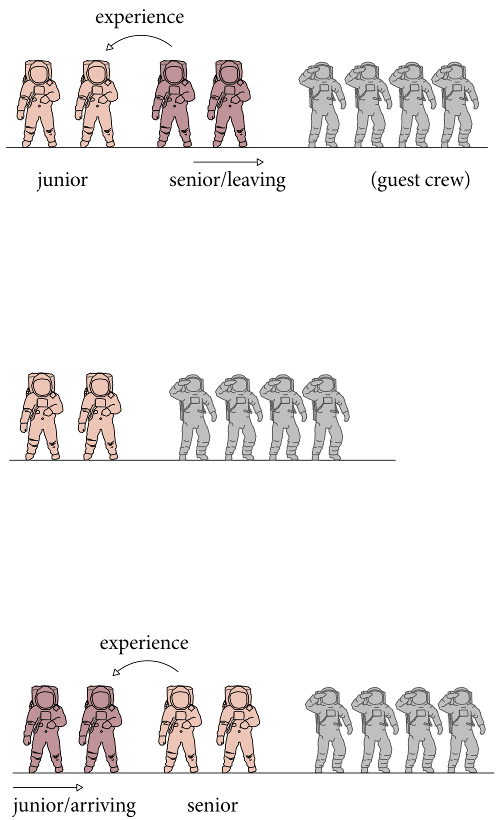
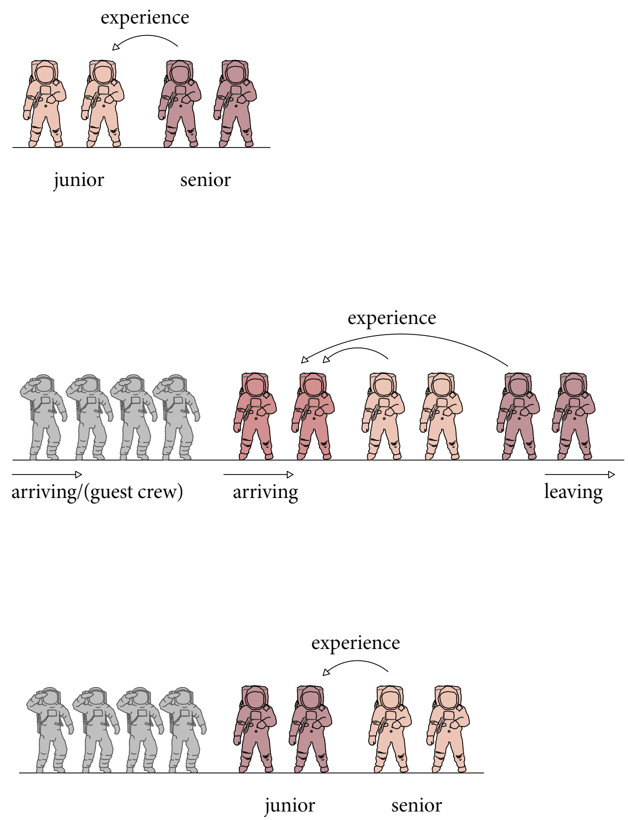


Indirect handover, permanent crew and guest crew



Direct handover, permanent crew and guest crew

1 - Junior crew learns from senior crew. (Guest crew learns from juniors and seniors.) Senior crew leaves.

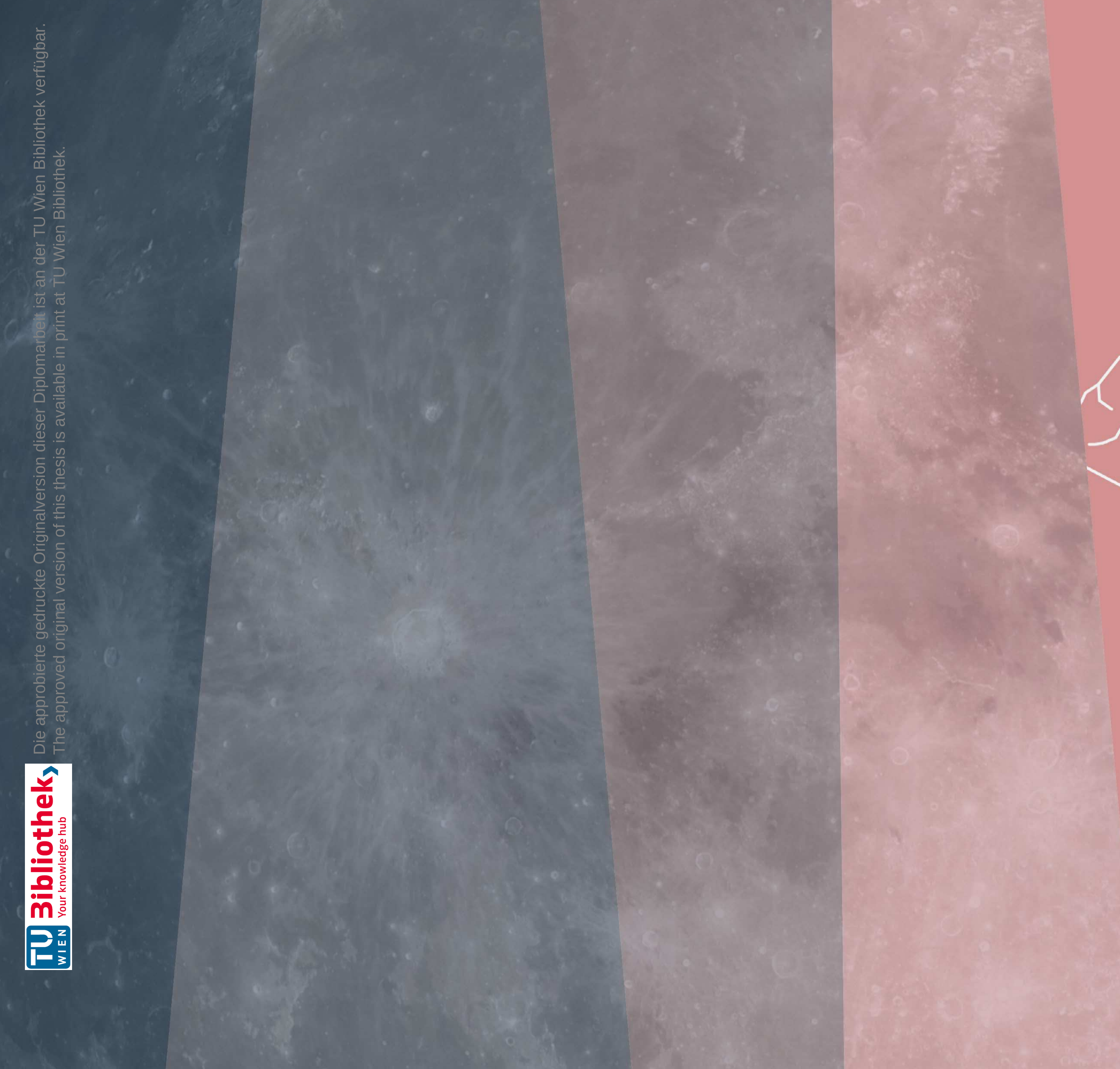
2 - Remaining permanent crew of two runs HAVEN with guest crew for 7 days until new crew arrives.

3 - New crew arrives. Old junior crew becomes new senior crew. (Guest crew learns from juniors and seniors.)

1 - Junior crew learns from senior crew.

2 - New crew arrives together with guest crew. Maximum habitation at HAVEN for five days. Expertise exchange between junior, senior, new crew, and guest crew in a direct handover period of 5 days.

3 - Old junior crew becomes new senior crew. (Guest crew learns from juniors and seniors.)



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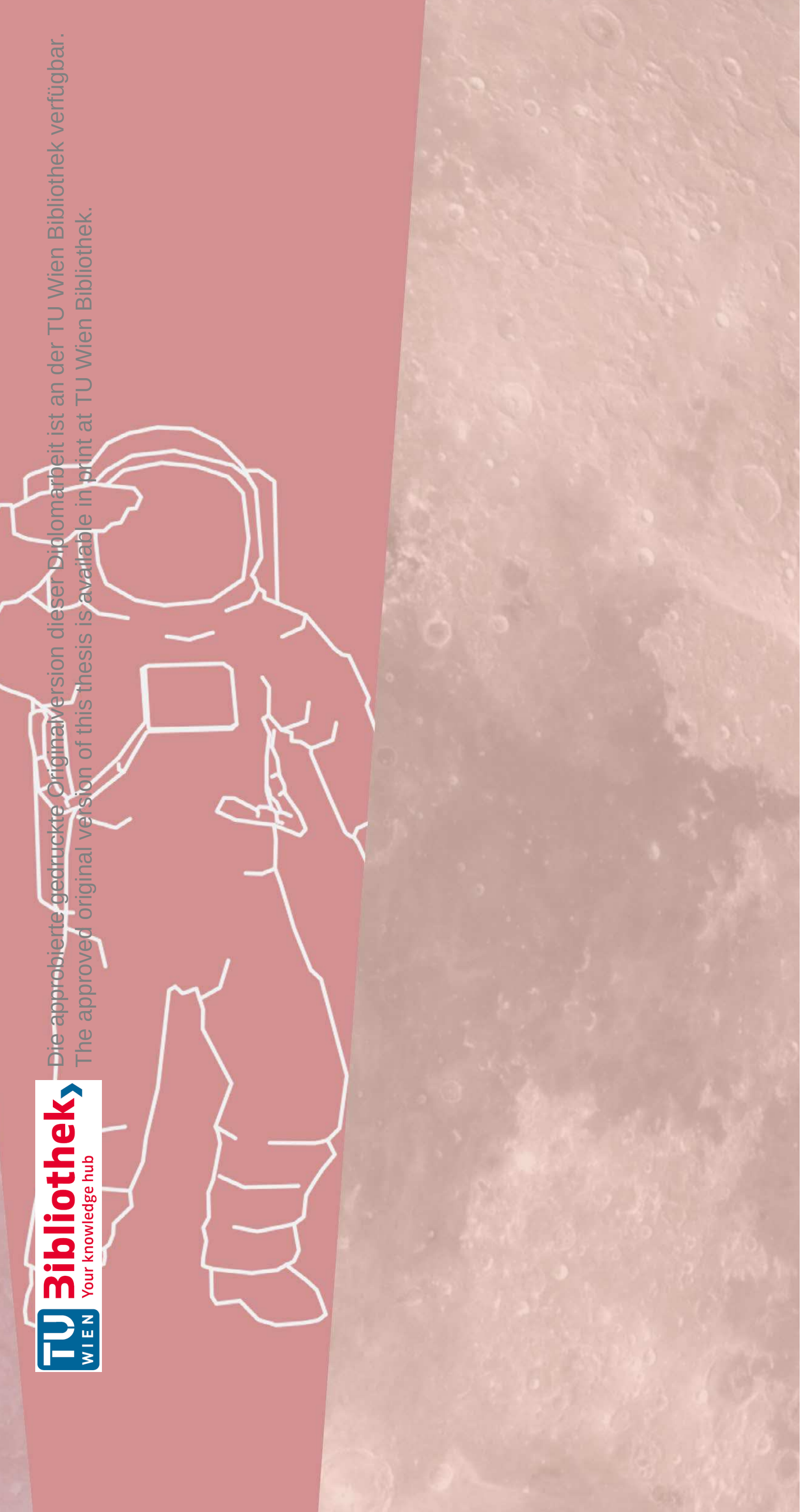

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CHAPTER 5
Interview with Apollo Astronaut Charlie Duke

During the progress of this thesis the author had the exceptional opportunity to conduct an interview with Apollo Astronaut Charles Duke, the youngest man to walk on the Moon.

Charles Moss Duke Jr. (Brigadier General, USAF, ret.) was born in North Carolina, on October 3, 1935.
On April 16-27 1972, Duke served as the lunar module pilot of the Apollo 16 mission, the fifth manned lunar landing. Apart from Duke, the Apollo 16 crew consisted of spacecraft commander John W. Young and command module pilot Thomas K. Mattingly II.
Apollo 16 was the first scientific expedition to inspect, survey, and sample materials and surface features in the Descartes region of the rugged lunar highlands. During their record setting lunar surface stay of 71 hours and 14 minutes Duke and Young each logged 20 hours and 15 minutes in extravehicular activities. Duke furthermore served as a member of the astronaut support crew for the Apollo 10 flight, acted as CAPCOM for the first Moonlanding with Apollo 11, and served as backup lunar module pilot on Apollo 13 and Apollo 17. He has logged 265 hours in space and over 21 hours of extra vehicular activity. (NASA 1994)

Astronaut Duke kindly agreed to talk to the author about his time on the lunar surface and the habitation conditions in the Moon's gravity of 1,62 m/s^2.

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5.1 Lessons Learned from an Apollo 16 Astronaut

Following selection of habitation and human factor requirements for a long duration mission on the lunar surface have been developed based on the interview with Apollo Astronaut Charlie Duke, as well as confirmed and used as guiding principles in the research, design, and development process.

Basic Requirements

Privacy: a certain amount of privacy is essential for a long-term mission; in particular for the use of lavatories, washrooms, and during rest periods

Technical requirements: technical requirements like thermal shielding and radiation shielding are of high priority

Landing site: a suitable landing site has to be selected carefully in regard to the mission's goals and requirements, such as daylight or exploration sites

Architectural Elements

Windows: windows are vital not solely to achieve natural lighting inside the habitat, but to give the crew a possibility to observe the exceptional lunar terrain, as well as the stars

Seating accommodations: pure physical requirement for conventional chairs or seats is marginal in lunar gravity; leaning onto curved walls or protruding objects provides satisfactory support. However, for long-duration missions it is necessary to provide seating accommodations, less for the physical and more for the psychological benefit of being seated; the seat design can benefit from the reduced gravity

Sleeping accommodations: while lunar gravity provides a comfortable environment for sleeping in a hammock, the restricted sleeping positions in hammocks demand actual bunk-like structures for a regenerating rest period. A soundproof environment is necessary to grant uninterrupted rest periods.

Airlocks: well designed airlocks avoid the tracking in of lunar dust into the habitat, as well as provide the crew with efficient charging systems, storage space, and possibilities for safe, methodical procedures for egress and ingress preparation

Food preparation facility: a well-equipped food preparation facility with the possibility to heat food and drinks and prepare a broad variety of meals is necessary for long-term habitation

Environmental and Spatial Components

Environmental Control System (ECS): a personalised ECS in the private quarters facilitates an adjustment of temperature and air supply to individual preferences

Adjustable illumination: personalised, dimmable illumination in the private quarters facilitates an adjustment of light intensity and colour to individual preferences

Headspace: ceiling height and wall curvature need to account for movement in 1/6 G and bulk of EVA suits and equipment

Storage space: storage facilities may be located in raised positions, as the lunar gravity enables an easy handling of heavy equipment

Waste management system: a well-designed waste management system is crucial to avoid the disposal of waste onto the lunar surface

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5.2 Five Questions for Astronaut Charlie Duke

Of your 71 hours on the Moon, you logged 20 hours of EVA, meaning that you spent around 50 hours inside the Lunar Module on the surface of the Moon. With a habitable volume of 6.6 m³ for two astronauts, this is a very confined living space. Can you describe your time inside the Lunar Module - did you have a favourite feature; was there something that affected the living conditions negatively?

Actually we didn't feel like it was so confided, except for several events. One of those is suiting up, getting ready to go outside for our moonwalks. When you started putting on your suit - and especially getting reading to put on your backpack - you had to move in towards one another and face one another because with the backpack on you could not straighten up and be right next to the right or left wall, the bulkhead. We found in training that it was best to face one another so you could help one another and check one another during the suit-up. (…) It is important to have the equipment in the same place that you had trained. In other words, if you put the gloves on the computer panel, then, when you got into the flight, you better do the same thing or you're going to lose stuff. "Where is my glove?" And you're looking around and it has fallen on the floor or something like that. You need to be conscious in doing things procedurally and regularly in order. (…)
Once we took the suits of again, we stored them behind the engine. There was a place back there that would get the suits out of your way. With the suits off there was like four of you in there, instead of two of you. With them stowed behind the ascent engine cover that wasn't a problem.
I think you can put up with a lot in two days. Of course in a two month stay on the Moon you need, I think, certainly a bigger volume, a place to sit down and relax, and a little bit more privacy in sleeping arrangements. But it was okay. You're motivated when you get on the Moon. So you put up with little inconveniences that would irritate you probably after a couple of months. But John and I never had a crosswords due to the volume in the Lunar Module. We'd trained and stood beside each other for a couple of hundred hours in training. So we knew how it was going to be. (…) We felt very comfortable in there. When we were out of our suits you could reach over and touch one another, but we felt like we had plenty of room.

I think probably my favourite feature in the Lunar Module was the big windows. We had a good view outside; and of course the unusual lunar terrain kept you glued to the window during some of the idle time.

One of the features that I didn't particular like in our Lunar Module was that we had no hot water. All the food we prepared - which was mostly dehydrated food - it was made with cold water. So some of the bags of food were not very appetizing with cold water. We weren't very hungry though, and we found that we didn't eat that much. But I think in a longer duration mission, having a cup of hot coffee and cup of hot soup (…) and something that would give you a variety of temperatures for your meals would be necessary.
The second was the environmental control system. Of course if both of you had the same likes and dislikes of heat and cold, everything was okay. John liked it colder than I did. (…) It didn't matter in the suit; in the suits I was comfortable. John might have been a little warm until we plugged into the suit environmental control system. But out of the suit the temperature was noticeable cooler for me. So I stayed in my liquid cool garment. When I took my suit off, I just left that on because it gave me a little bit more protection against the chilly lunar module environment. John just took everything off except for his lightweight underwear and then he put on a constant wear garment.

One thing, as I was reading your proposals on a future design - the idea of a (large) airlock was really nice. We tracked in a lot of lunar dust and on the Moon of course the dust stayed on the floor of the Lunar Module. But when we got into orbit all this dust floated up around - all over the cabin! We had to stay suited up and buttoned up and, if you will, enclosed to keep the

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lunar dust out. We were sort of closed loop with the environmental control system and the suits; and when we docked up with Mattingly, and he saw the dust, he wouldn't let us come in. He in fact closed the hatch after floating over one of these dust devil vacuum cleaners and we were able to vacuum up all the dust that was floating around in the spacecraft.
You also end up with trash and stuff in the Lunar Module from food bags and breaking out other equipment. We ended up with a big bag of trash, maybe even two bags of trash, that we kicked out on the lunar surface before we lifted off.

But I thought, overall, the Lunar Module was fairly comfortable.

Returning to the Lunar Module after an EVA, did you do so with a feeling of entering a safe space, maybe even some kind of homebase?

As we returned to the lunar module you did sort of feel like it was your homebase. In fact, one time I remember saying "Home again, home again!" as we topped a ridge and there was the lunar module about a quarter mile in front of us. (…)
As we climbed back in and stood up inside with our backpacks on, the suit was protecting us to that point. But as we closed the hatch and the lunar module pressurized you felt secure, you felt safe. It was a safe environment. We never thought once about 'what if the window popped out?' or 'what if we had a micrometeoroid puncture?'. Those things would be a disaster of course, but you never thought about it. You felt very secure in the lunar module and as I stood around in my liquid cool garment it was sort of homey.

The gravity on the Moon is one-sixth of what our bodies are used to from Earth. You are one of the few people who have actually experienced this very specific gravity. Footage of Apollo astronauts moving over the lunar surface has been seen all over the world, but how did the low gravity affect your activities inside the confinements of the lunar smodule? Was it a hindrance or did it make some things easier?

There were no seats in the lunar module. But in 1/6 G it's no problem. You don't really need a seat. I remember I would lean back, just lean back, against the environmental control system and sort of rest on that, but I never felt like I was missing out by not having a chair or seat of some sort. John felt the same way. (…)
The lunar gravity did affect us in our suit-ups. Though, it wasn't really the gravity; it was the small volume during the suit-ups and unsuiting, as I related earlier. The gravity actually was helpful. Down here, training in the Space Centre, we practiced getting in and out of the suit, putting on the backpacks –we did that over and over and over again. Well, the backpacks, the full weight ones, weigh 150 pounds down here. We had to have a light-weight one so we could even pick it up – it was maybe 80 or 90 pounds, had the same volume, same connectors and hoses as the real one. Up on the Moon 150 pounds become 25 pounds and you can pick it up with basically one hand. So moving the PLSS was easy. That gravity was a real advantage up there! Picking up the Moon boxes, the rock boxes, and the equipment that we had - the cameras and all that - everything was just real light.
Lunar gravity was a real advantage in operating on the Moon, expect you lost your balance a lot outside. Inside, 1/6 G was a help and not a hindrance.
So suiting up and unsuiting was easier than in training because of the light gravity. Moving equipment around, especially the heavy weight PLSSs… Overall 1/6 G is a big help.

Preparing the food was actually easier in the lunar module in 1/6 G than it was in zero gravity. You could put things down and they would stay where you lay them. (…)
The waste management system in the lunar module was also easier to use than up in space. Since with the urinal everything went into the tank, you didn't have to be very careful. We had a faecal bag that we used just like we did in zero gravity and of course that worked better because you had gravity and everything went to the bottom of the bag.

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Sleep is one of the most important factors on any mission. Inside the lunar module, hammocks were used instead of convectional beds. How did you experience this downtime in 1/6 G? Did comfort and privacy play any role in this?

The sleep was really important for us and it was difficult for me on our first sleep period to go to sleep. Stringing up the hammocks, preparing for a rest period was easy. The hammocks were comfortable. Mine went from starboard to port right and left; I was about 6 inches above the floor. John's was fore and aft and he was about three feet, two feet above me. Basically I could reach up and touch his hammock from my hammock on the floor.

Sleeping in the hammock is…you get used to it; you sleep on your back. It's impossible to sleep on your stomach because of the arch of the hammock (but) it was comfortable.

The problem was getting to sleep. First sleep period was just five or six hours, if I recall, after we landed. So you were so enthusiastic - "I'm on the Moon, I'm on the Moon!" Looking out of the window and looking at this fascinating, incredible lunar terrain was real exciting. So your mind was just rocketing along and then they tell you to go to sleep.

Well, John drifted off pretty easily but I was…almost impossible to go to sleep. There were two reasons – one, I was so excited about being on the Moon, but the second was that I had the communications cap on and was monitoring the radio. If they saw something unusual in the spacecraft – a system over-pressurizing or whatever – then they would give us a call and we would respond. So we had to have communications.

Anyway, about halfway through I decided to take a sleeping pill, so I called Houston and said "I'm taking a sleeping pill!" And this was right after we had a master alarm come on – which they had warned us about but, you know, in the quietness of the lunar module with the curtains over the windows and dark inside…the master alarm clang goes off and it's…you spring into action, to say the least. But I handled the situation and then after that I told Houston "Hey I can't get any sleep. I'm taking a sleeping pill!" and they approved it. We had a light one - not a knockout pill - but a pill that would just put your mind in idle so that you would drift off.

To answer the question about did comfort and privacy play a role - I didn't find it uncomfortable. 1/6 G g is really nice. You can relax and things are easy to move around and the hammocks were comfortable. For long duration stays on the Moon something probably a bit more substantial than a hammock would be nice – a soft bed, a sturdy bed. A chair, you know, something to sit around in. And of course privacy also was not important to us. Two guys in a small environment like that - we just didn't have any feeling of needing any privacy. We knew, when we used the faecal system or the urine system: "Your buddy is just there; there is not place for him to go." You just got used to it. We of course trained that way anyway.

I think in a long duration mission – in a co-ed mission – it's going be a little bit different. I think it would have been very unusual to try and make one of our lunar modules co-ed. I guess people could do it - of course they had co-ed crews ever since Apollo! But a bigger spacecraft with a bit more privacy is important. So a bigger living area in a long-duration mission would be important. To have some quiet time would be important in your design of a crew module on the lunar surface.

Just to summarize - sleep is important. After the first EVA we were exhausted when we got our hammocks up and got in, ready for our rest period. We slept really well and were refreshed. 1/6 G is a nice sleeping environment. We got it dark inside by getting up some curtains over the windows and turning off the lights. So for our little lunar module, John and I didn't have anything to complain about. We were excited about being there but after several weeks I wouldn't have liked to continue in there. You would do it and you could do it, but it would be nice on the longer duration missions to have a little bit more room and some privacy and a place to rest.

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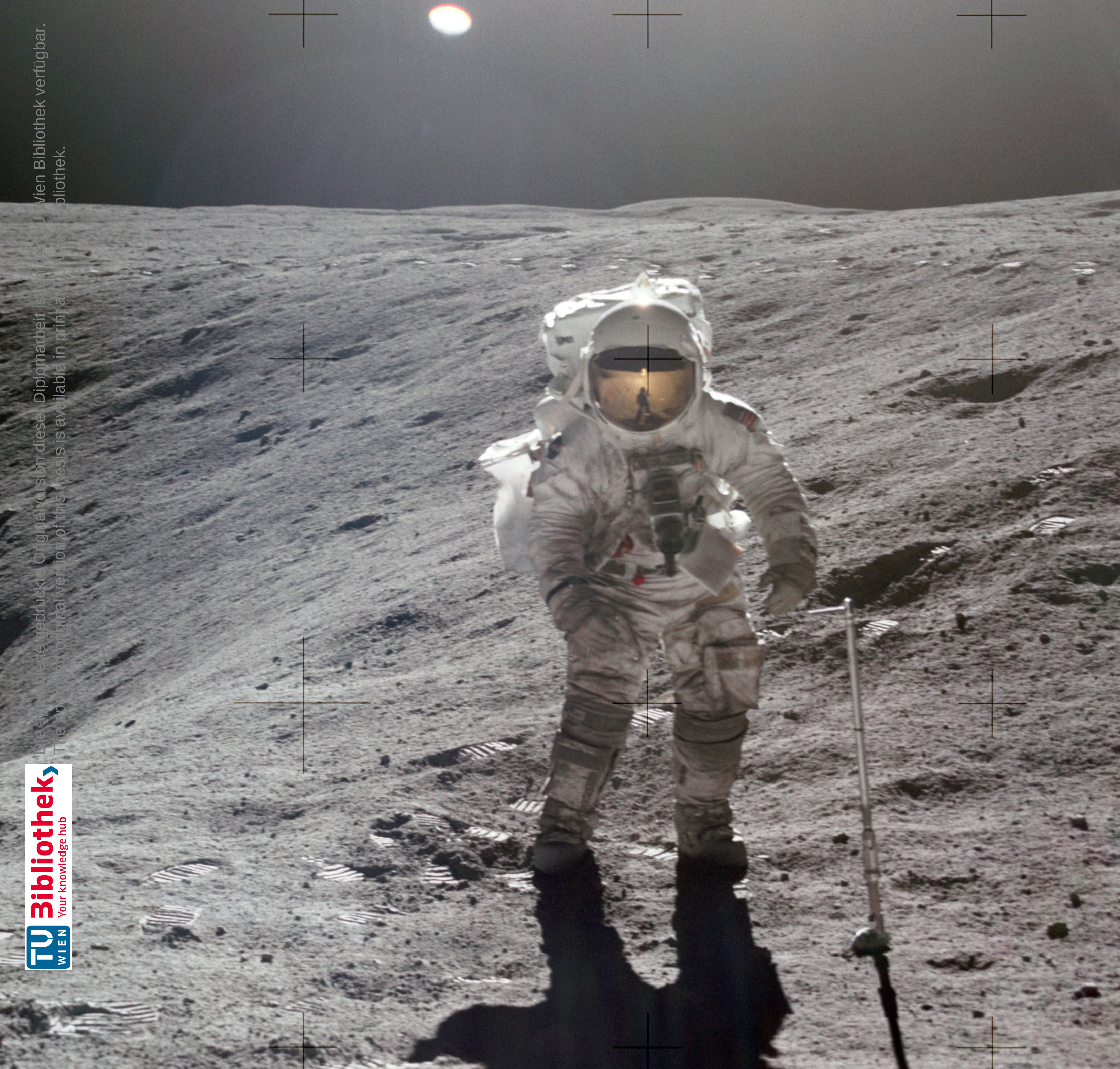
In regard to future habitation designs on the Moon - which are aiming for more space and comfort due to longer mission durations - is there anything you would wish for; any necessities that you would see in regard to lunar gravity?

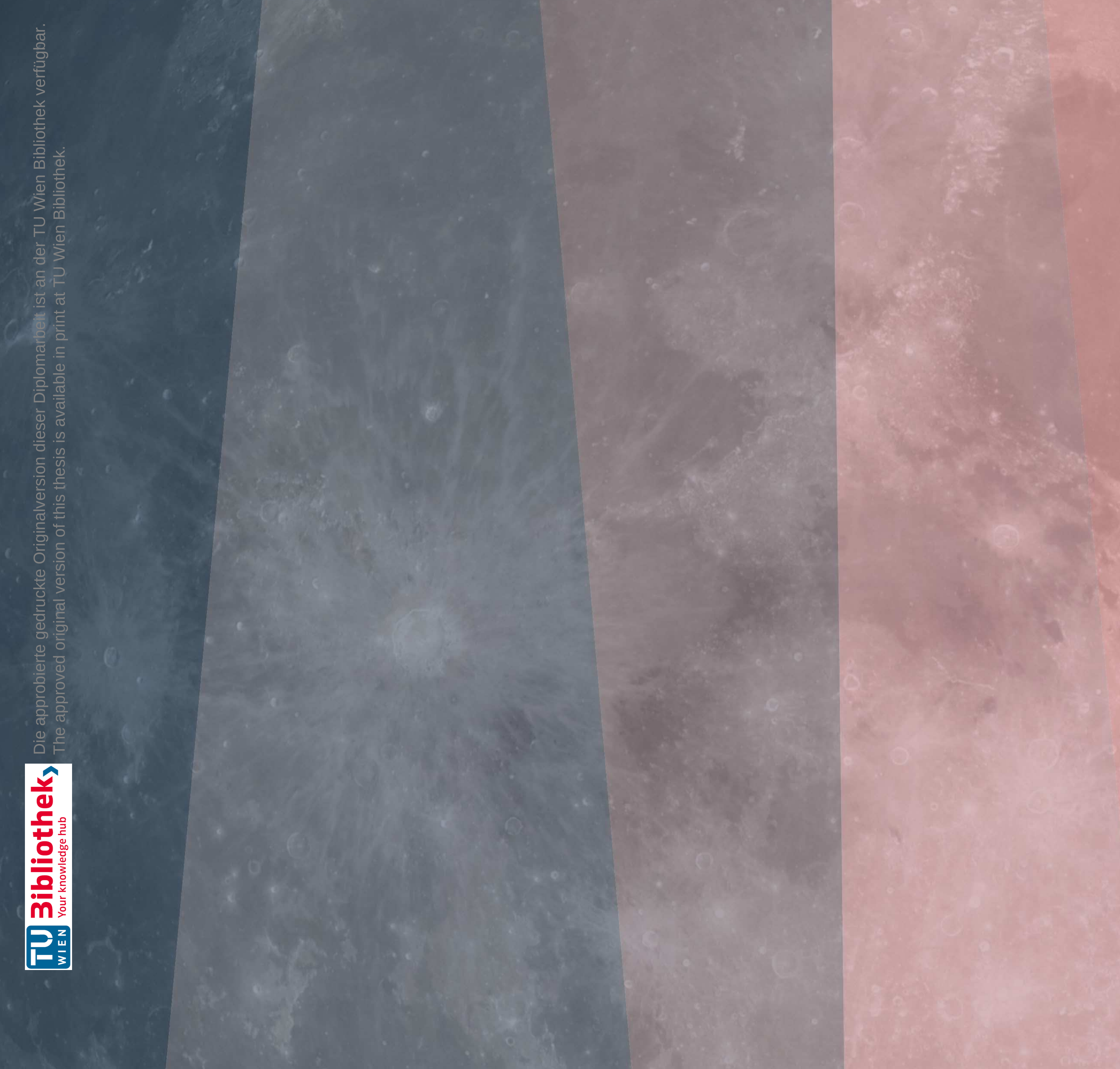
In long duration missions, airlocks are important. The charging station was quite adequate, by the way, in the lunar module – we could charge batteries and fill the water tanks and oxygen tanks easily; so that was well designed. New airlocks, longer mission airlocks, need a good design like that, where it is easy to recharge backpacks.
I'll say it again - one of the most important things, I think, for long duration stays is an airlock. You don't want to track all that moon dust into your habitation module like we had to do! (…)

And a good way to heat water for your food - microwaves, ovens, you know, hopefully a refrigerator, a freezer - that all would be nice to have too. I think you could get by with just a way to heat water; and during daylight that would be no problem up on the Moon (…). Nighttime is going to be a little bit different.
Of course you have to have some thermal protection, radiation protection. All of those kind of absolutely required parts of the habitation module.
The landing spots (have to be reviewed) in detail. Near the South Pole or near the Polar Regions you have longer daylight (...) but you're going to still have some night and being able to keep the environment in a reasonable 20-25 degrees is something that's going to be necessary.

The author would again like to thank Astronaut Charlie Duke for taking the time to answer the questions in such detail, for his kind words of encouragement, and the inspiring tales of Apollo 16.

Fig. 5.1 | Astronaut Charlie Duke on an EVA during Apollo 16





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CHAPTER 6

Concept Design for the HAVEN Lunar Port and Base

After a detailed research of local parameters, the decision-making in regard to structural composition and habitability, and the elaboration of the mission timeline and any necessary support equipment, the visualization of the design is the next logical step in the development of a lunar habitat.
This includes the depiction of the spatial layout in floor plans and sections, the elaboration of interior arrangements, the development of technical details, and of course the preparation of renderings or collages based on architectural models.
The drawing of architectural plans is a crucial process to review, validate, and refine the concept ideas; the plans themselves are the foundation of conveying the design to interested parties.

Fig. 6.3 (p. 111-112)| Visualisation of the HAVEN habitat and moonscape

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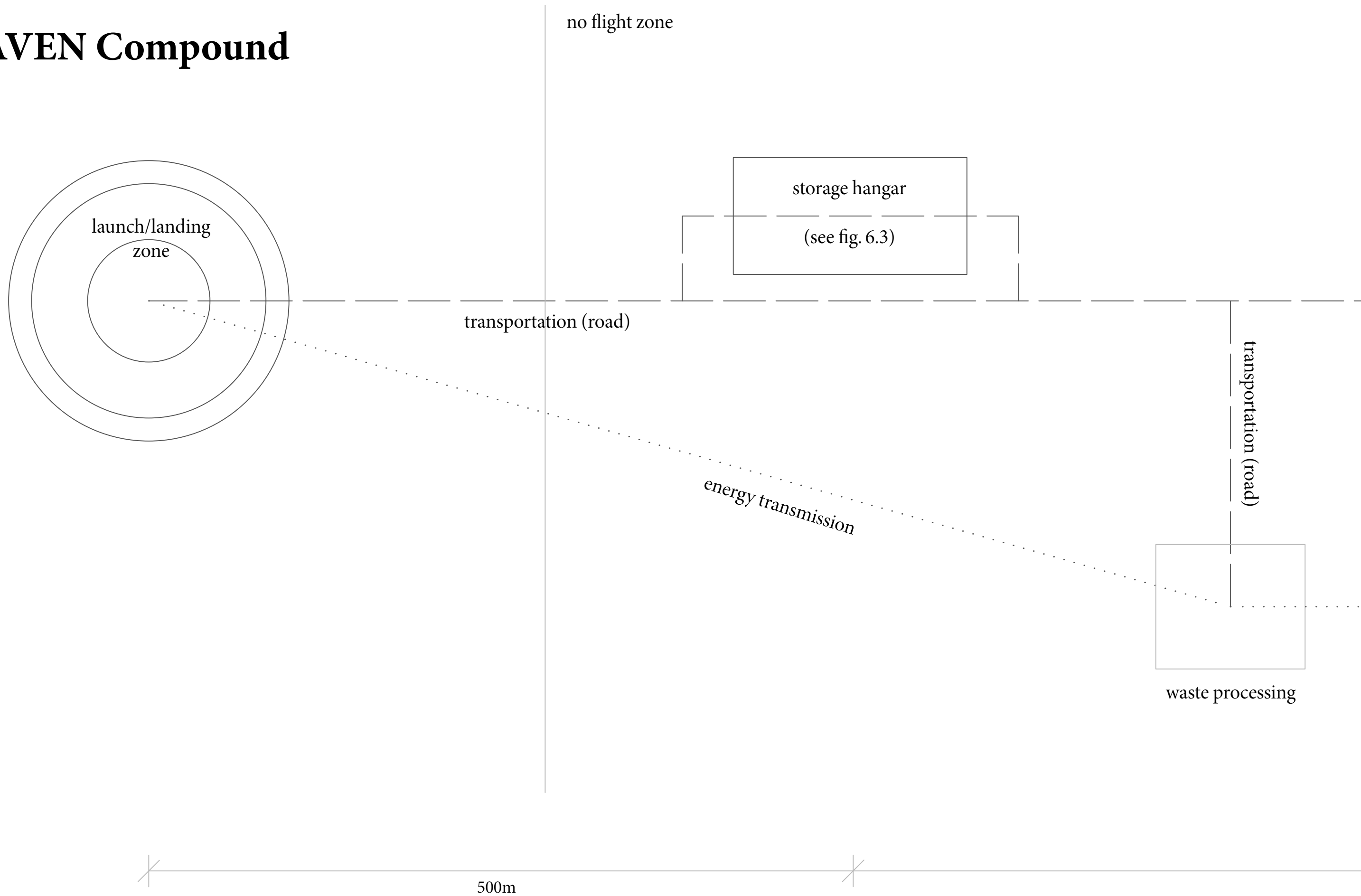
6.1 HAVEN Compound



The HAVEN compound contains separate areas for habitation, energy generation, launch and landing, and component storage.
A no-flight zone protects the habitation area from any hazards caused by launching and landing spacecraft.
Farthest from the habitat, at 2 kilometers distance, lies the multi-zoned launch and landing pad.
The storage hangar and ISRU zones (energy, water and oxygen, and waste processing zones) lie between the habitation and launch/landing areas, equally at a safe distance to the habitat.

The relatively close proximity of the hangar to the pad enables a fast transfer of landers between the two areas.

The hangar, which is a simple, unpressurized shelter construction shielded by regolith filled bags, is separated into three lanes, the middle of which allows a transport vehicle to pass through and place/pick-up the stored components and landers. Landers will be placed here during the crew's stay on the Moon, until the ascent module is needed for departure. Furthermore, both, discarded descent stages of crewed landers and cargo

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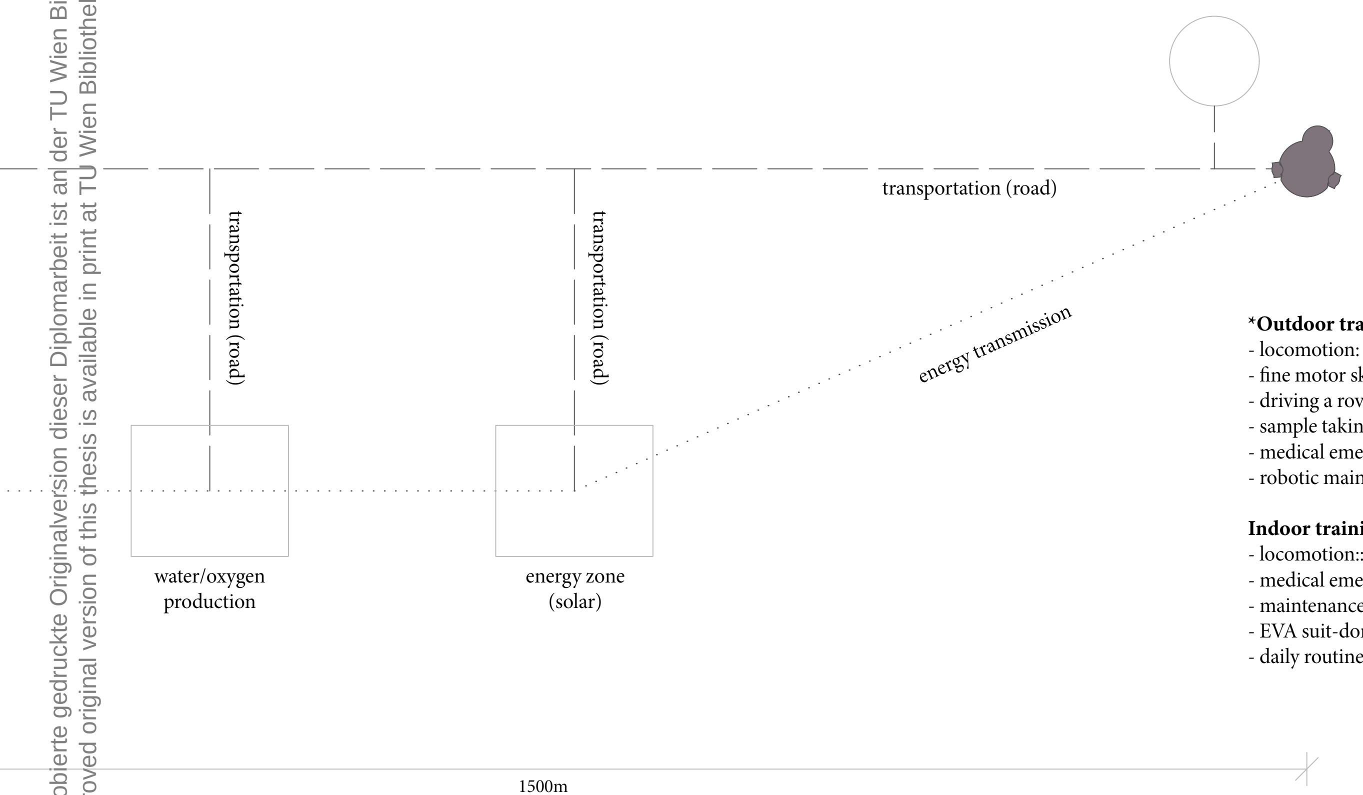


***Outdoor training subjects**
- locomotion: slow, fast
- fine motor skills
- driving a rover
- sample taking
- medical emergency protocols
- robotic maintenance/tool handling

Indoor training subjects
- locomotion:: slow
- medical emergency protocols
- maintenance
- EVA suit-donning
- daily routines

landers, are stored in the hanger to protect the components and valuable materials.
This enables the use of these parts for future constructions, such as the use of the tanks for habitat shielding, as well as prevents the further expansion of the lunar junkyard.

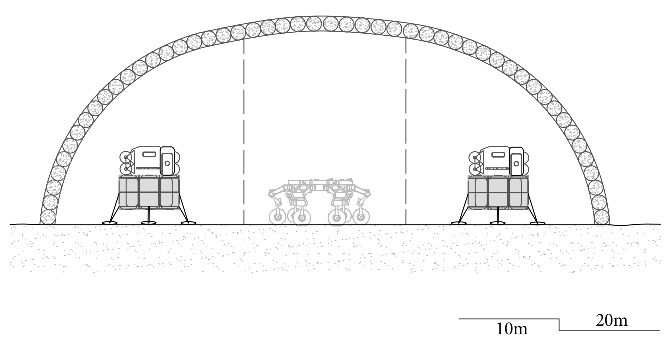
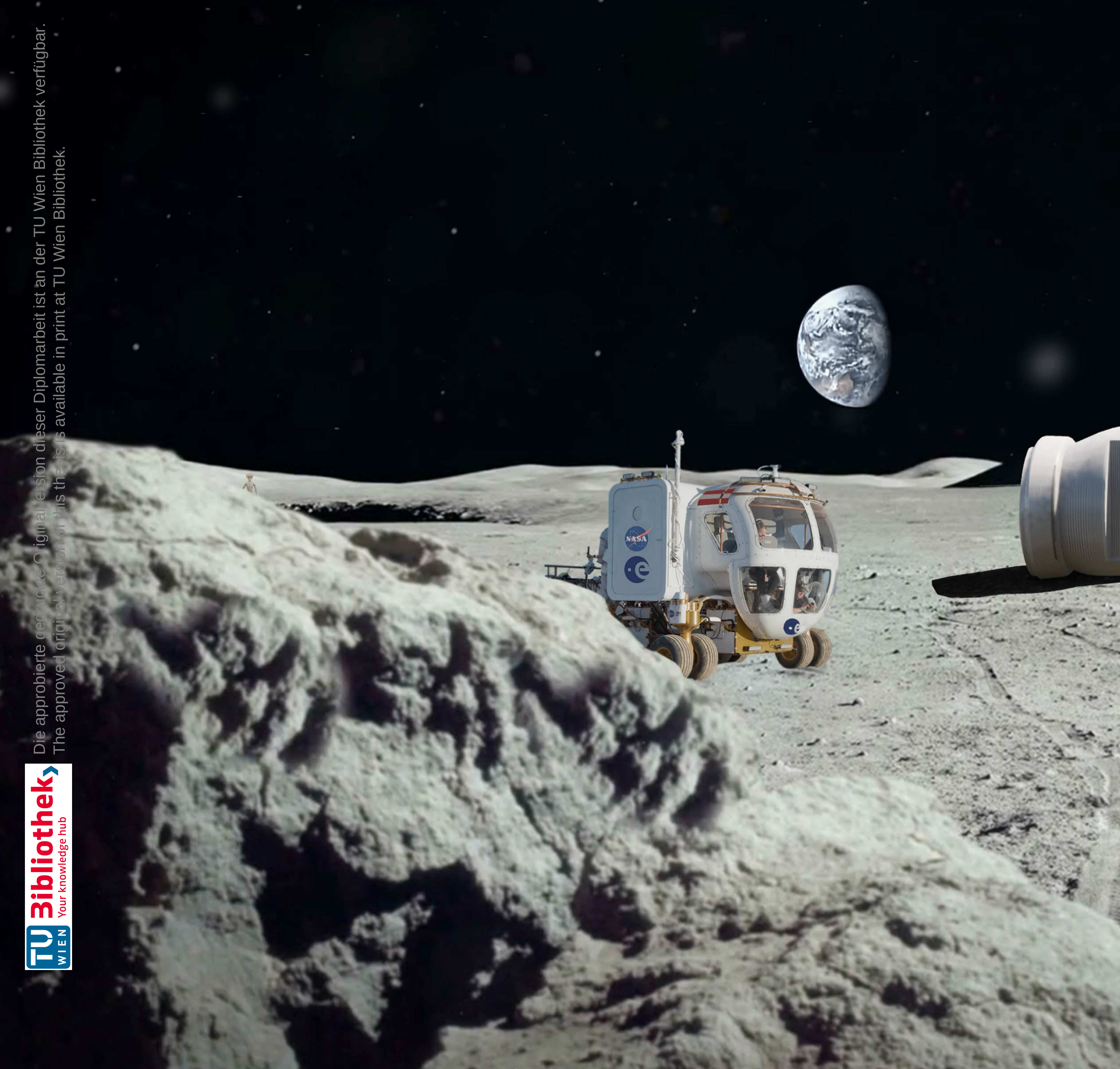


Fig. 6.1 | Sitemap, HAVEN compound layout

Fig. 6.2 | Schematic section, Lander and Component Storage Hangar



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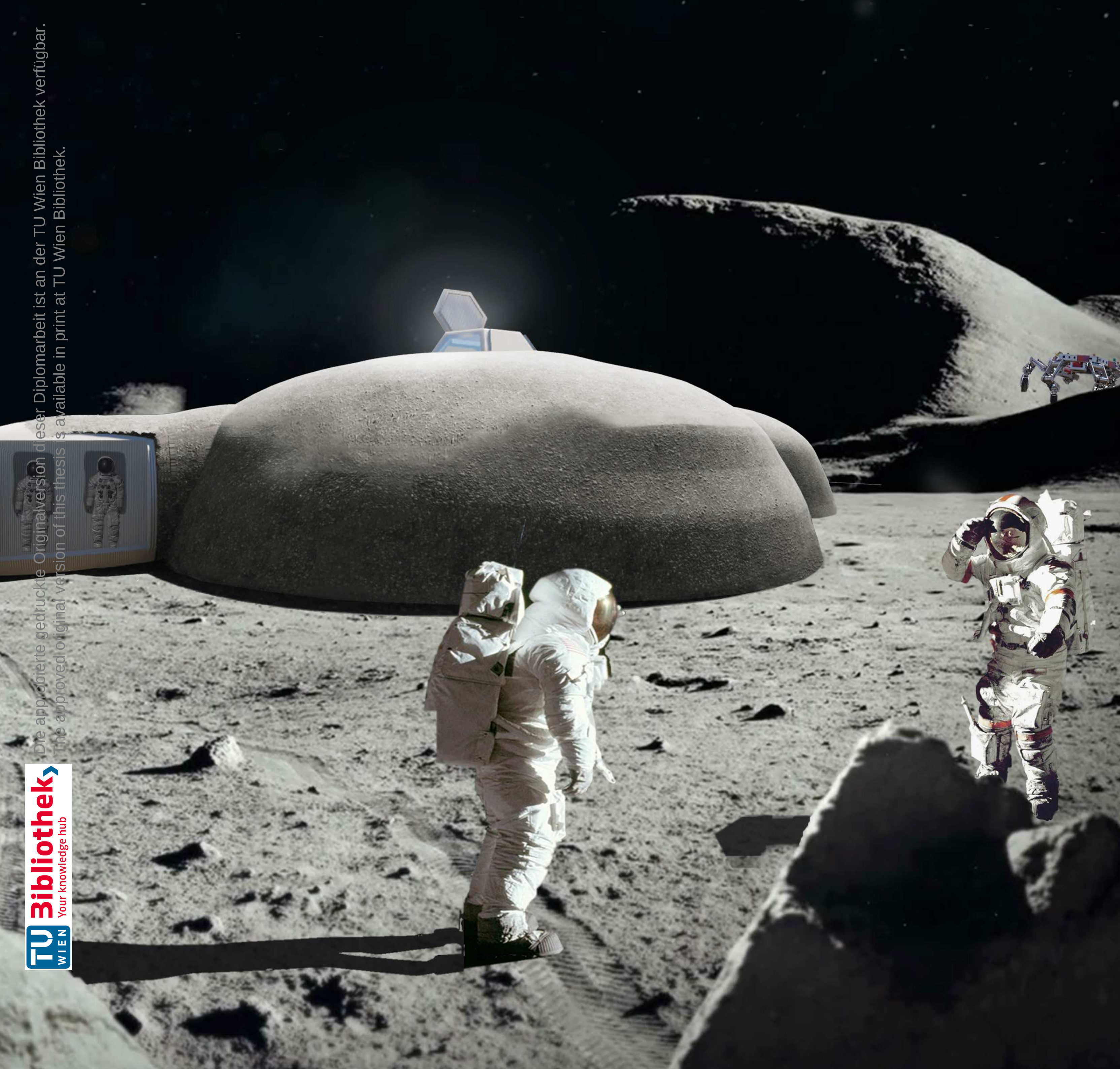

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6.2 HAVEN Habitat Construction

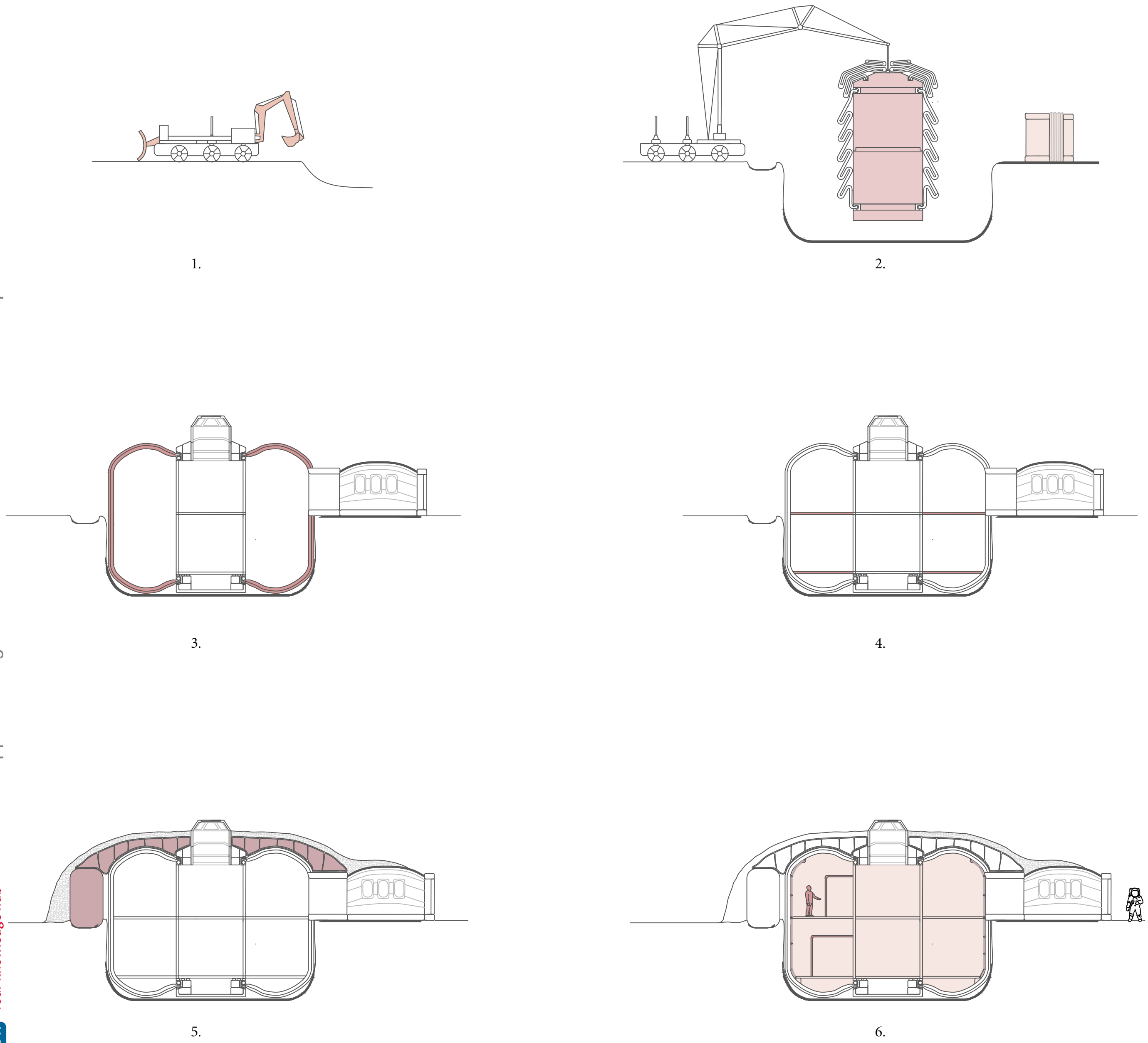

Fig. 6.4 | Construction process of the HAVEN habitat

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robotic construction phase

1. Excavation of the deployment site (490 m³), using percussive and pneumatic excavators mounted on a CMC.
Time requirement: 15 days

2. Placement of the undeployed habitat and airlock modules.

3. Deployment of the habitat. Deployment of the airlock(s) and airtight connection with the habitat.

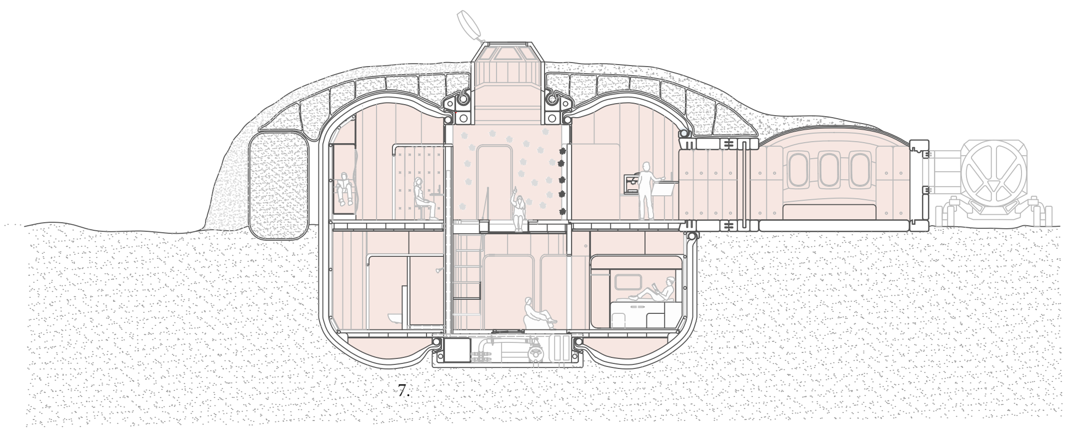
4. Automatic inflation of floors. Preliminary fixture to inflatable wall.

5. Installation of radiation shielding. (regolith filled propulsion tanks: detail p.115)
Time requirement: 2 days

human construction phase

6. Installation of structural cage and mounting of floors. Inflation and rigidization of interior walls. (detail on p.157)
Time requirement: 2 days

7. Interior outfitting: Adding of internal installations, such as sanitation elements, sliding walls and doors, and furnishings: Finalisation of the habitation spaces.
Time requirement: 2 days



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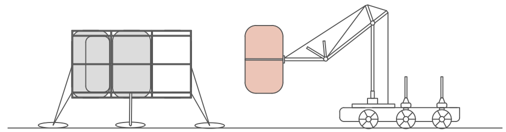

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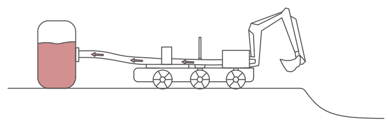

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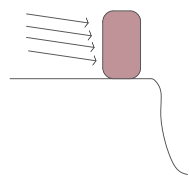

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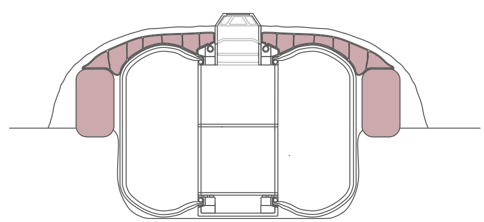

Fig. 6.5 | Radiation shielding: Re-use of empty propulsion tanks

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Radiation Shielding

1. Empty propulsion tanks are removed from the lander with the LMS mounted on the CMC.

2. Regolith is filled into the tanks during the pneumatic excavation process: thus, the excavated material is immediately safely disposed off, no additional machinery is needed, and the process can run simultaneously to the excavation process, saving time, payload, and money.

3. Regolith filled tanks act as horizontal radiation shielding for the habitat. The HAVEN deployment site at the lunar South Pole requires special attention on this horizontal shielding, due to the incidence angle of the sunlight.

4. The tanks are placed around the habitat as horizontal shielding. On top of the habitat, regolith filled bags act as shielding.
   An additional layer of lose regolith creates a barrier between the main part of the shielding and the lunar environment. This layer can easily be banked up with CMC-mounted machinery.

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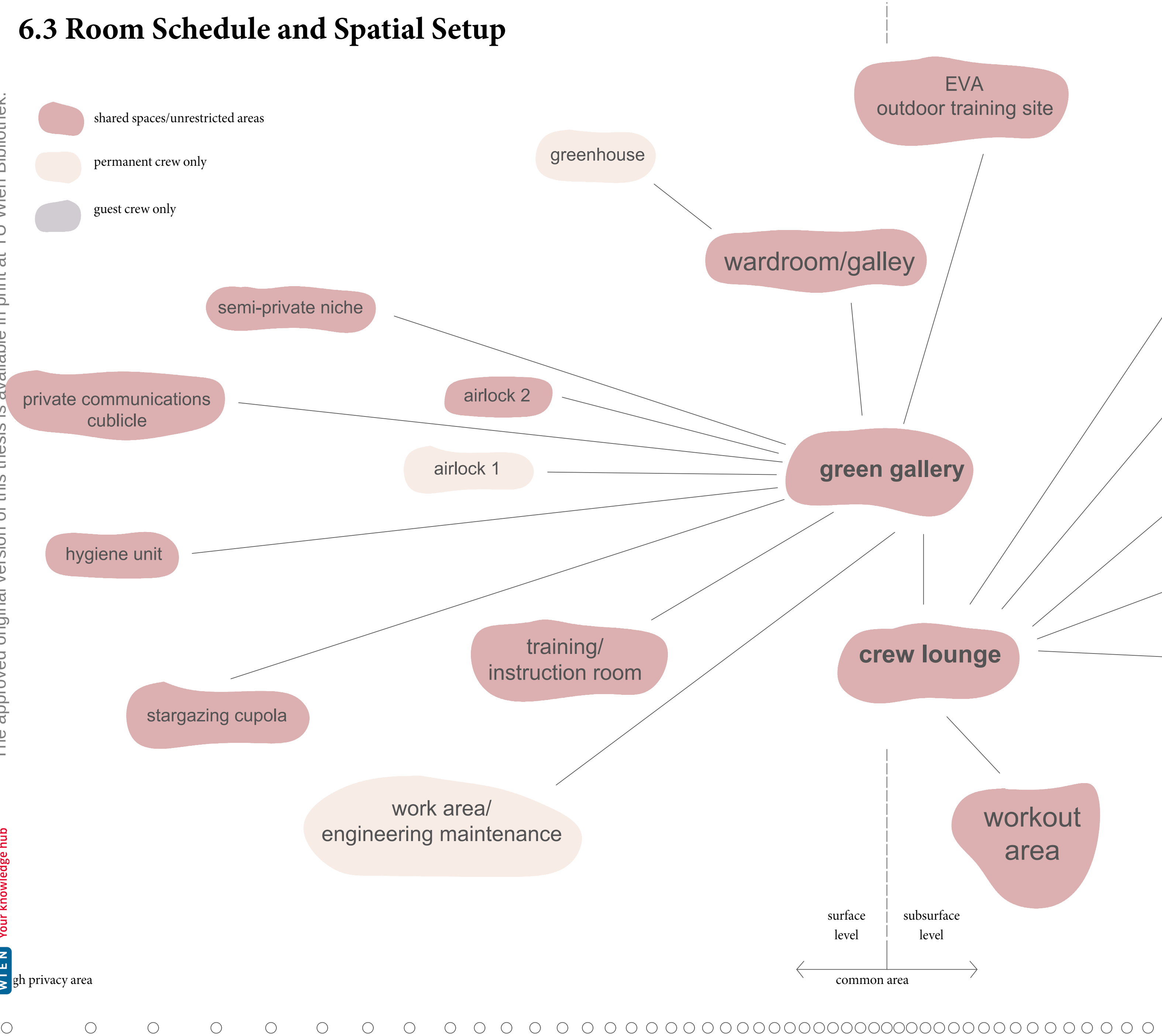
6.3 Room Schedule and Spatial Setup



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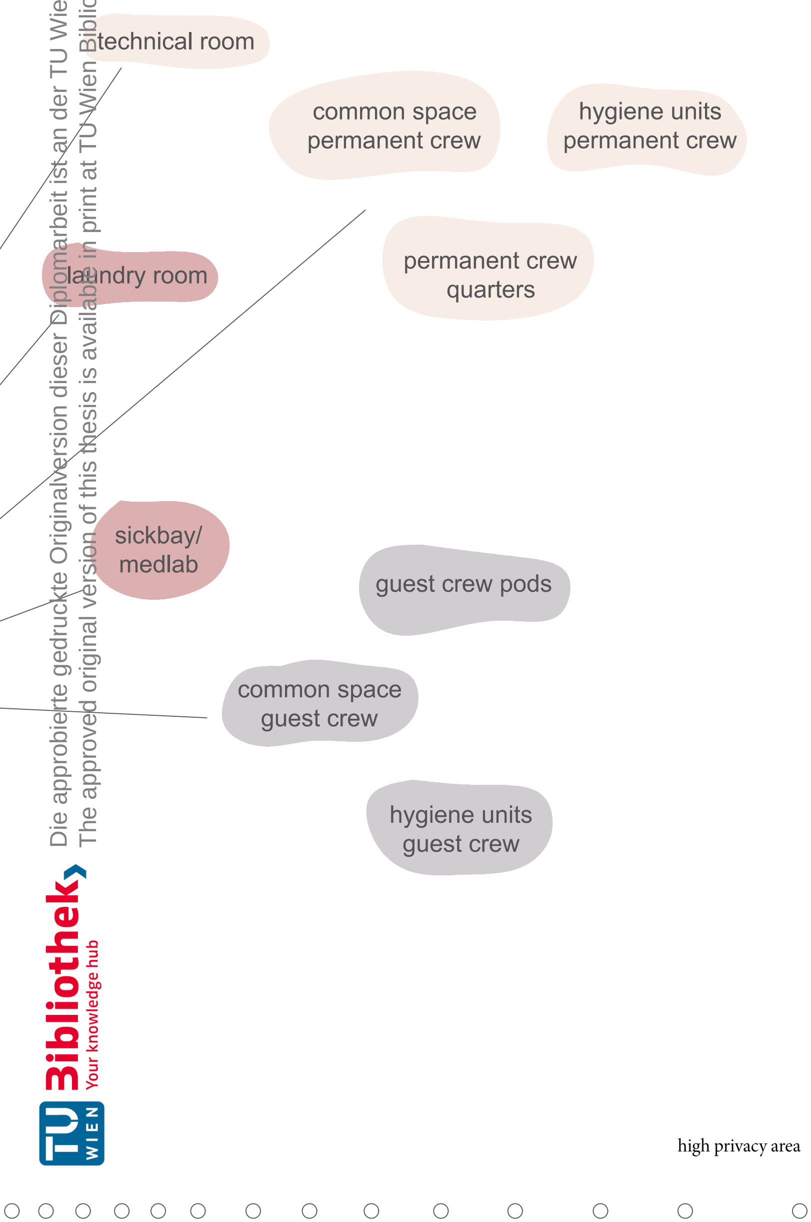

Access Restriction

The different areas inside the HAVEN habitat underlie different access restrictions. This is necessary to optimise the co-habitation of the permanent crew and the guest crew.
While there are many shared areas where both crews are encouraged to mix and participate in common activities, certain spaces are accessible only to the permanent crew. These include not only crew quarters and hygiene units, but also areas with critical systems, like the technical room or the greenhouse, and the workspace of the permanent crew. This ensures undisturbed working processes and the necessary amount of privacy. In contrast, the central crew lounge, which is open to both crews, as well as the open wardroom and galley, encourage the two crews to spend time with each other outside the work and training hours. Thus, the very limited social circle of the permanent crew is enriched with a changing number of individuals and their experiences.

Privacy

The HAVEN habitat offers a variety of different privacy situations. These are not necessarily dependent on the area restriction between crews, but often a result of these.
Open common areas with little privacy, such as the crew lounge and wardroom, are opposed by high privacy spaces like private crew quarters, the private communication cubicle, or hygiene units. However, as it is also important to offer areas in-between total privacy and common spaces, the HAVEN habitat has a number of semi-private areas or areas with flexible privacy, such as the workout area, the semi-private niche, or the stargazing cupola.

Fig. 6.6| Room schedule: area restriction and privacy situation

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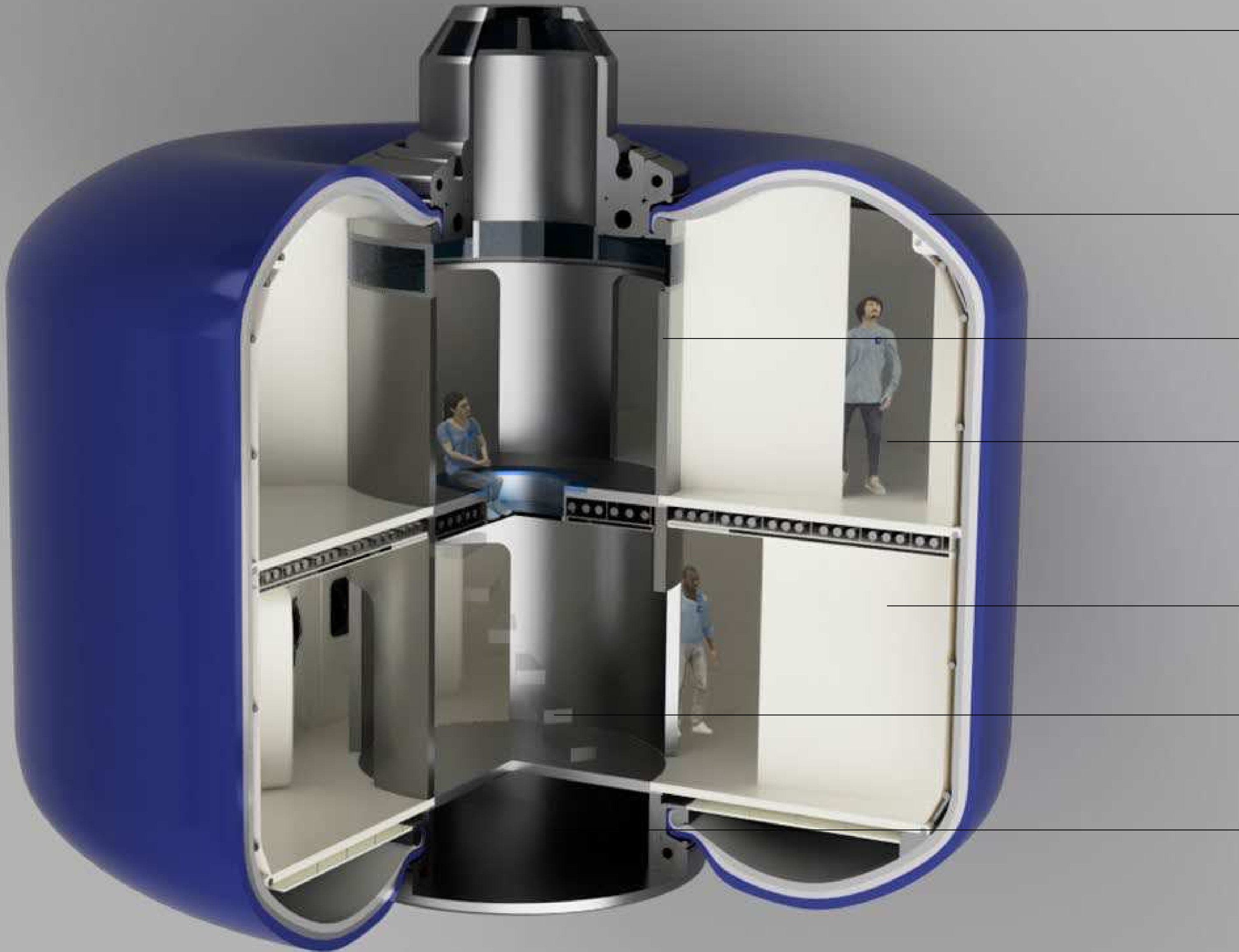

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stargazing window: Cupola

multi-layer inflatable

rigid centre module

surface level: work areas

subsurface level: leisure areas

lunar staircase: 42/22

technical room

Fig. 6.7 | HAVEN spatial setup

Spatial Setup

The HAVEN habitat consists of a rigid centre component of cylindrical shape, which is extended by a multilayer inflatable torus with oblate sides. Together, these two parts create a habitable volume of 73.5 m^3 per crew member, distributed over two levels. For launch, flight, and landing the inflatable is stored externally around the rigid centre (fig. 2.18, p.44), allowing the interior to be used as logistics storage space during transportation from Earth to the Moon.

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6.4 Surface Level

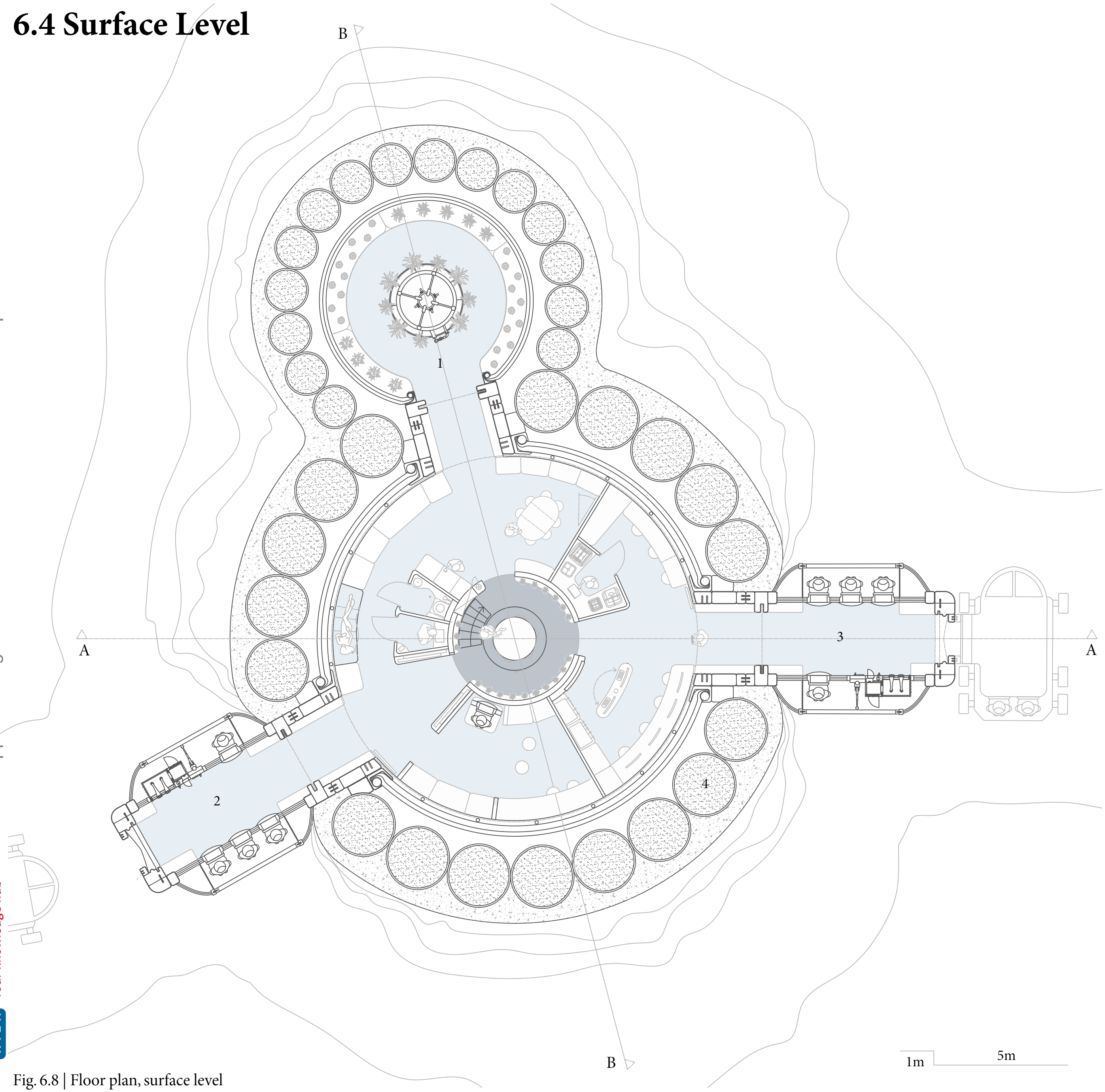

Fig. 6.8 | Floor plan, surface level

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1 - greenhouse
2 - airlock 1 (rover undocked)
3 - airlock 2 (rover docked)
4 - regolith-filled propulsion tanks

rigid modul

inflatable modul

add ons (airlock, greenhouse)

The surface level is where various working areas, as well as the wardroom, galley, and greenhouse (detail on p.125), are set. This is also the point of entrance via two airlocks (detail on p. 127).

To shield this upper level, regolith-filled lunar lander propulsion tanks are placed around the habitat and covered with a thin layer of sintered regolith. This process does not only make use of the otherwise discarded propulsion tanks, but is also a time and energy efficient version of creating regolith shielding: by using a mixture of percussive and pneumatic digging (see Chapter 4), the excavated regolith can directly be filled into the empty lander tanks, thus preventing the need for an external placement of the excavated material (which could prove harmful to the equipment), the need for sending additional bags or other habitat covers to the Moon, and the energy-consuming task of placing regolith around and on the habitat with special machinery.

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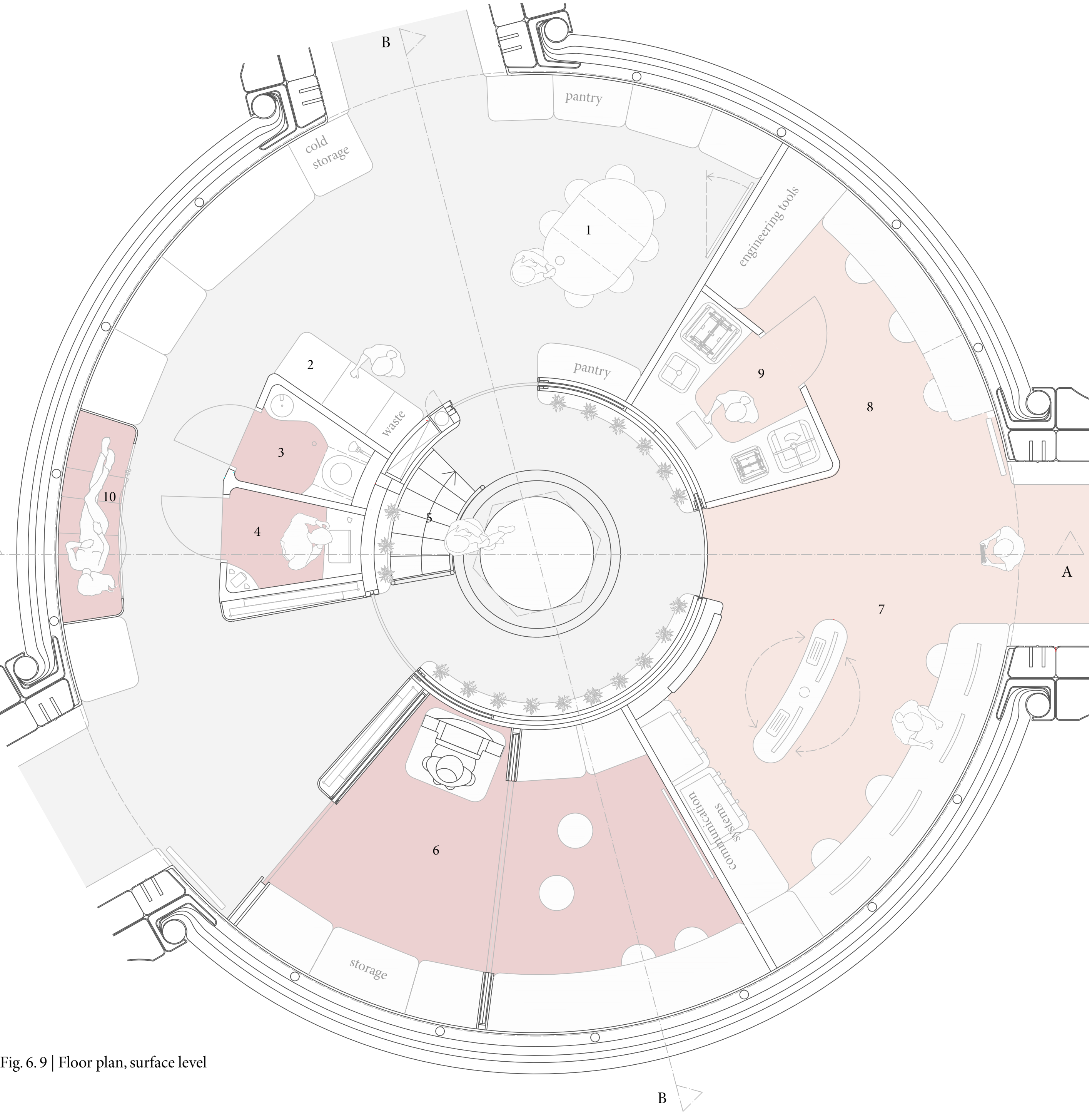

Fig. 6. 9 | Floor plan, surface level

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1 - wardroom (detail on p. 129)
2 - galley
3 - hygiene unit
4 - private communications room
5 - green gallery
6 - instruction area/workspace for guest crew
7 - communications and control centre/workspace for permanent crew
8 - engineering/maintenance
9 - additive manufacturing cubicle
10 - semi-private niche (detail on p.141)

permanent crew only

shared space

shared space, high privacy area during use

1m 5m

The centre of the surface level is the central green gallery (5), which connects the different work areas on this level, as well as the two levels themselves, and the stargazing cupola above. The gallery's floor breakthrough towards the crew lounge below allows view relations and the transmission of light from the stargazing window above. A green wall enhances the livability in the habitat by acting as a buffer between the work areas and by allowing the crew to interact with the plants.
The galley (2) and wardroom (1) offer room for different crew sizes due to flexible furniture systems. A media screen can be rotated and adjusted to personal crew preferences.
A bio-waste grinder attached to a chute next to the galley allows the crew to immediately dispose of their waste, which is then lead to a composting module in the subsurface level. Non-decomposable waste (eg. packaging material) is collected and transferred to a separate waste facility on the HAVEN compound for processing (eg. additive manufacturing resources).
From a communication and control centre (7), which also acts as the permanent crew's main work area, the launch and landing processes, as well as any communication with Earth or other outposts, can be managed from. This is adjacent to an engineering and maintenance area with a soundproof additive manufacturing chamber.
The instruction and training room (6) can also act as a private workspace for the guest crew. This large, open space can be divided into two smaller ones, depending on current needs, and offers enough free space for various kinds of trainings, including indoor 1/6 G exercises or 1/6 G medical training.
Certain areas in HAVEN underlie various degrees of access restrictions: to ensure smooth working processes the permanent crew's work areas are off-limits to the guest crews. The shared wardroom and green gallery, on the other hand, encourage interactions between the two crews.
A small separated room (4) with noise insulation offers the possibility for private communications with Earth and a niche with privacy curtain (10) allows the astronauts to temporarily withdraw from the busy workspaces.

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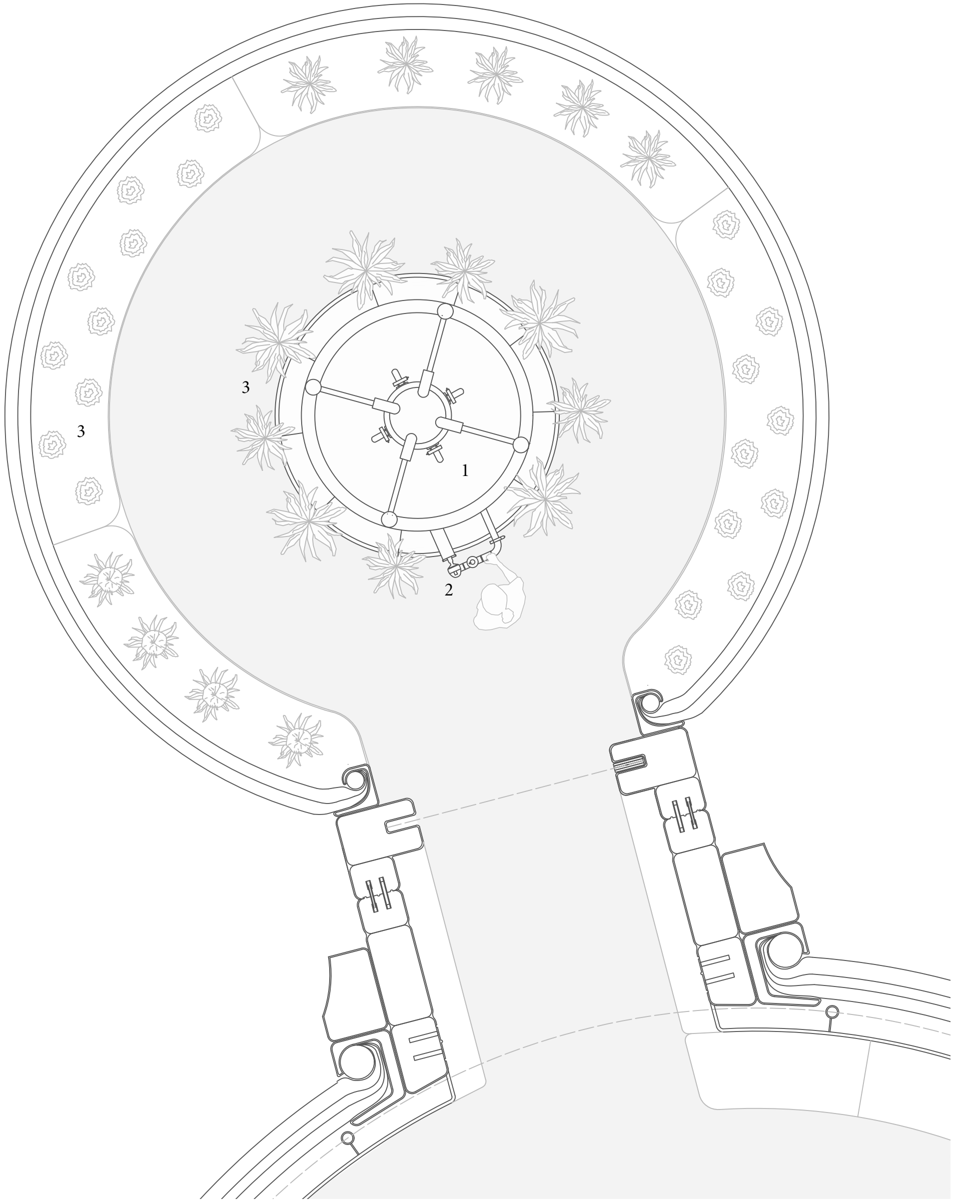

Fig. 6.10 | Floor plan, greenhouse

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1 - automated irrigation and harvesting system
2 - manual controls
3 - vertical farm

Greenhouse

The HAVEN greenhouse is an inflatable structure that is connected to the main habitat with an airlock. This allows the closing-off of the greenhouse, to keep the atmospheric conditions ideal for farming purposes.
The greenhouse is not meant for the astronauts to interact with the plants or to use as a means of improving habitability. Its sole purpose is to grow enough fresh produce to sustain the HAVEN crew. Therefore, the conditions in the greenhouse are precisely monitored and all processes are automated.
Manual controls allow the crew to access and maintain the systems.

1m 5m

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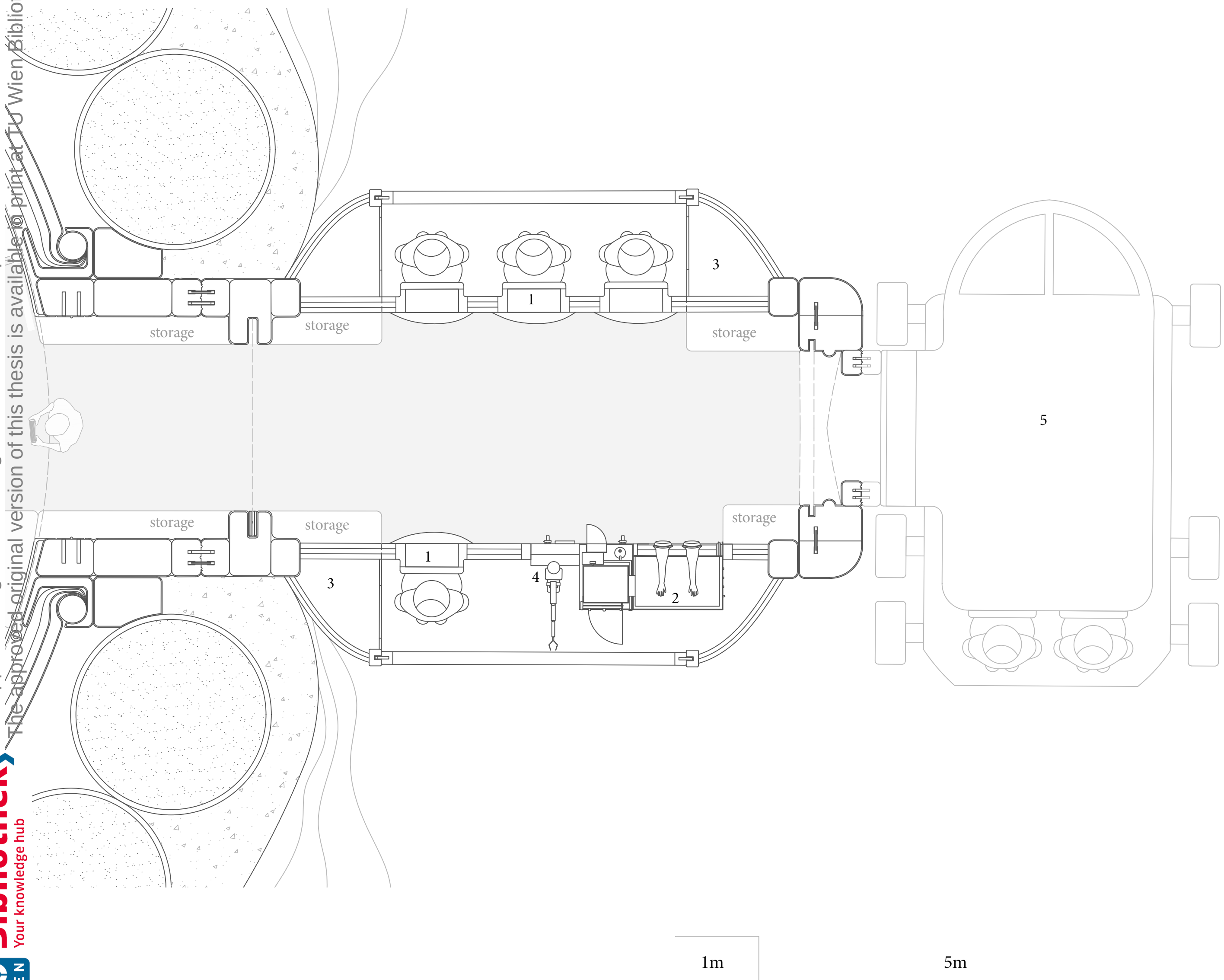

Fig. 6.11 | Floor plan, airlock

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1 - suitports
2 - glovebox
3 - external EVA locker
4 - robotic arm (telescopic)
5 - SPR

Airlocks

The HAVEN habitat is outfitted with two egress/ingress airlocks.
Both provide four suitports each, as well as a docking opportunity for an SPR with another two suitports.
The airlocks also include a glovebox system, with the possibility to blow out dust and bring samples inside, or work on them directly in the glovebox. An extensible (telescopic) robotic arm supports the work directly outside the habitat.
Apart from plenty of internal storage space and charging stations, external EVA lockers hold all necessary equipment for a successful EVA.
Airlock 1, next to the instruction and training room is used as main egress/ingress route for non-scientific EVAs and arriving crews. Airlock 2, located in the restricted area next to the permanent crew's working and communications area, is only accessible to the permanent crew. This airlock is mainly used for research and exploration EVAs, as well as maintenance tasks.

One of the merits of having two separate airlocks, is the aspect of redundancy in emergencies, which should be kept in mind during any space mission.

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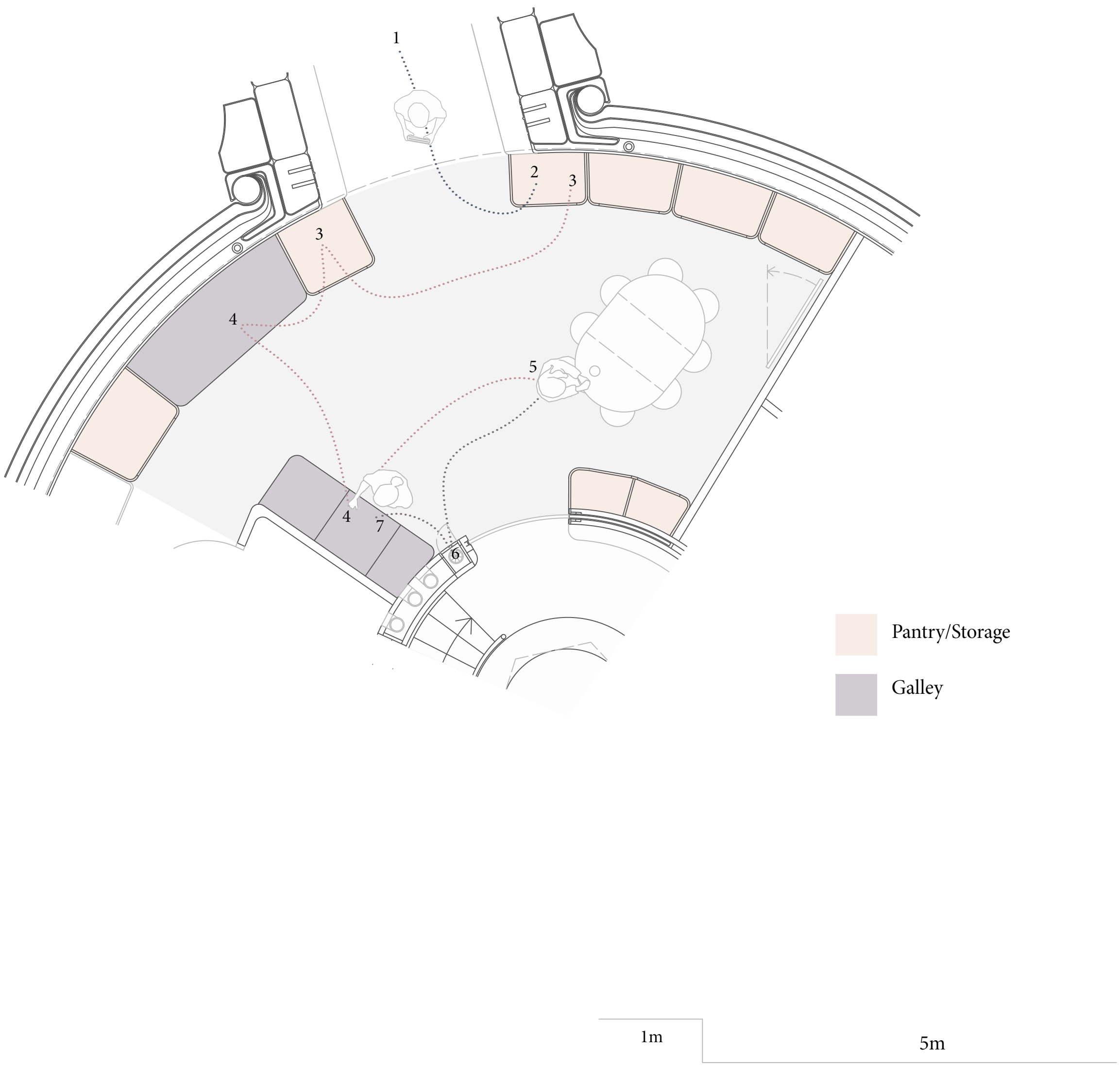

Fig. 6.12 | Wardroom and galley processes

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Wardroom and Galley Processes at HAVEN

1 - Crewman 1 brings fresh produce from the greenhouse
2 - Crewman 1 stores the produce in the pantry
3 - Crewman 2 gathers ingredients
4 - Crewman 2 prepares and cooks the ingredients
5 - The crew enjoys their shared meal
6 - Crewman 3 disposes of the bio-waste
7 - Crewman 3 loads the dirty dishes in the dishwasher

The large wardroom encourages an interaction of all crew members during mealtimes. A rotation schedule determines who is responsible for preparing the food; all the astronauts eat their meal together as one HAVEN crew. These shared mealtimes allow for a more relaxed exchange of experience and are crucial moments of crew bonding. Thus, sharing meals plays an important role in keeping a healthy social environment, despite the fast-changing crew members at HAVEN.

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6.5 Subsurface Level

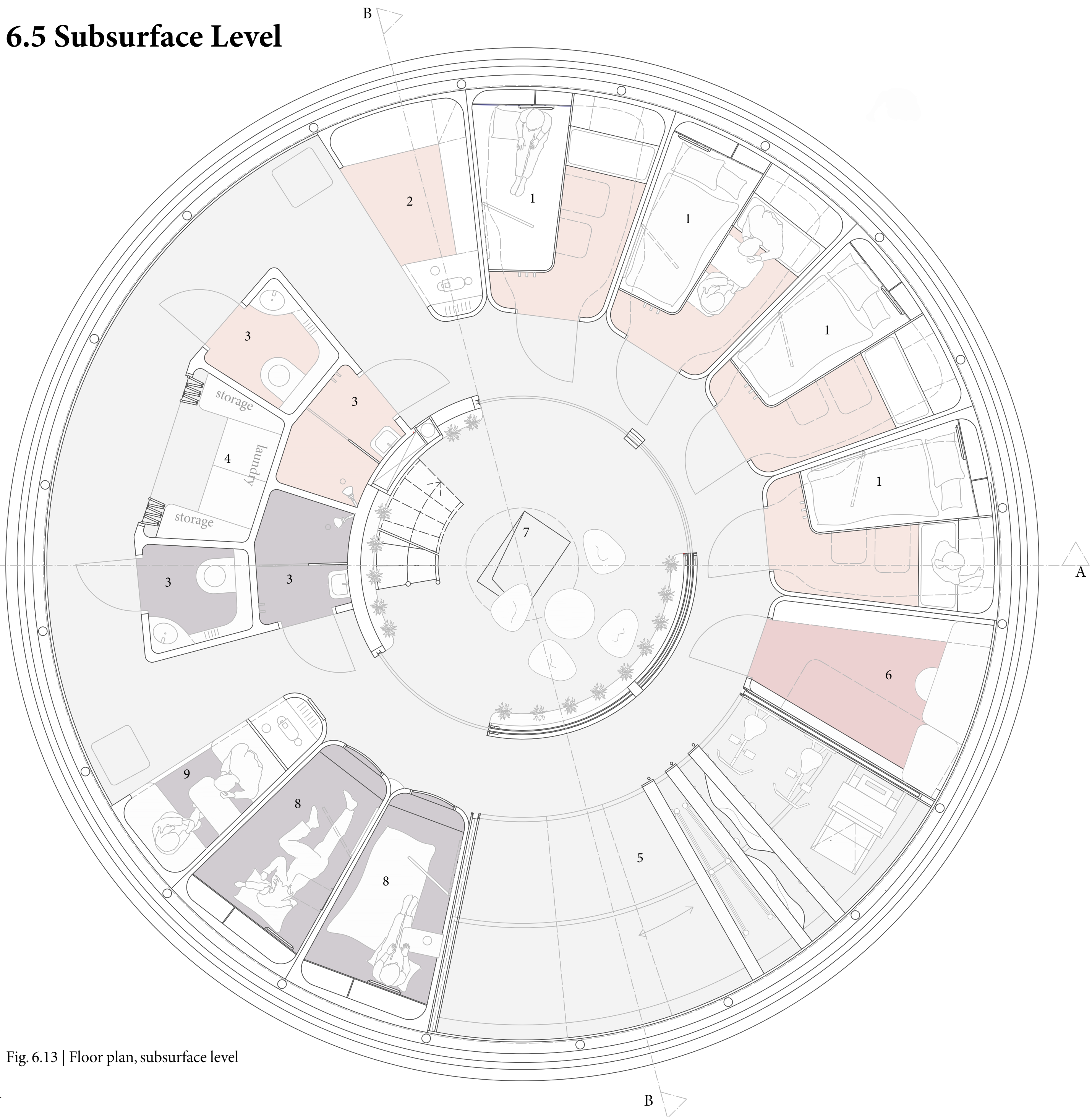

Fig. 6.13 | Floor plan, subsurface level

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1 - permanent crew quarter (detail on p.136)
2 - common space, permanent crew
3 - hygiene unit
4 - laundry and storage room
5 - workout area with movable walls (detail on p.152)
6 - sickbay/medlab
7 - crew lounge
8 - guest crew pods (detail on p.134)
9 - common space and storage lockers, guest crew

permanent crew only

guest crew only

shared space

shared space, high privacy area during use

1m 5m

As the subsurface location of this level makes it especially well shielded, this part of the habitat contains the private quarters and leisure time areas. This also includes the workout space.
A common crew lounge (7), which is open towards the green gallery and the stargazing window above, forms the centre of the living quarters.
The quarters of the permanent crew and guest crew, as well as the hygiene units of the two crews, are spatially separated to allow for more privacy between the permanent crew and the visitors.
Four crew quarters (1) offer individual living space to the members of the permanent crew. If desired, the private quarters can be opened towards the lounge, windows in doors allow view relations but can be toned at the inhabitant's leisure for maximum privacy. These permanent quarters are larger and offer more spatial variations than those of the guest crew. (details on p. 133-136)
On the other side of the habitat, four stacked pods act as quarters for the guest crew (8). These tiny, but comfortable, spaces offer privacy, personal storage and a feeling of home during the guest astronauts' short stays. An additional pod provides a small common space (9) with coffee-niche for the guest crew to interact amongst each other. On top of this, a locker-pod offers storage for bulkier and infrequently needed items, to be stored during the guest crew's stay.
Similar as with the quarters themselves, the common space for the permanent crew (2) is somewhat more spacious but serves the same objectives of creating a space where the permanent crew can spend their leisure time amongst each other, if they feel the need to withdraw from the shared lounge.

The workout area allows a flexible adaption by sliding 'workout-walls' along a floor-rail system. The area offers bouldering, wall bars, battle ropes, and various work out machines. This system enables the crew to create several smaller or one bigger workout area, adapted to the individual needs. It also allows the interim use of the area for other functions, when no workout takes place.

The subsurface level furthermore contains laundry facilities (4) and the sickbay (6), which can double as a medical lab.

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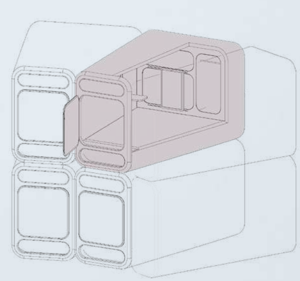

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storage for personal items

control panel for ventilation and lighting

sliding backrest

foldout table

rotating media screen

entry hatch, tonable glass

external storage

Fig. 6.14 | Guest crew pod

Guest Crew Pods

Guest crews stay at the HAVEN habitat for five to ten days after arriving on the Moon, to acclimatise and learn how to safely navigate the lunar gravity, before moving on to their own long-term habitats and research outposts.
Hence, the personal quarters of the guest crew differ from those of the permanent crew in shape, size and function. The guest crew is accommodated in private pods of 150 centimeters height. Two pods are stacked on top of each other for maximal spatial efficiency, the upper being easily accessible due to the low lunar gravity.
The pods' entry hatches are made from glass that can be toned at the inhabitant's choice, thus allowing both a visual connection with the central lounge area or complete privacy inside the pod.
A small external storage niche enables the astronauts to place their house shoes or quick-access items during the day. Inside, the pod offers additional storage for objects the guest crew will need during their stay at HAVEN. A separate locker pod provides storage for luggage and larger items that are needed less frequently.
A small foldout table and a rotating media screen complete the interior of the cozy pod. Over a control panel in the wall, the astronauts can individually control the ventilation and lighting situation of their pods. Comfort and privacy during a short-term stay on minimal space are the main objectives of the guest pods.

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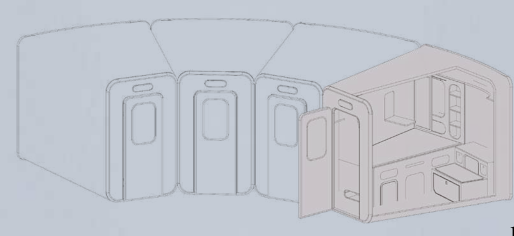

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privacy lamp

high situated shelf (easy access due to 1/6G)

sliding backrest in front of open storage

control panel for ventilation and lighting

door with tonable glass window

platform1: storage, desk, nightstand

pull-out profile 1: desk

platform 2: storage, two-directional

pull-out profile 2: chair

Permanent Crew Quarters

The personal quarters of the permanent crew differ from those of the guest crew in shape, size and function. Their somewhat larger volume allows the inhabitants to move around in a standing position. A high-situated shelf of various width lines the whole room; open storage at the back and the foot of the bed allows quick access; spacious drawers under the bed and desk, as well as an open hanging rail at the entrance, complete the generous storage possibilities.
The astronauts can personalise their quarter to individual preferences; there is plenty of room for personal items and decorations.
Similar as in the guest pods, a rotating screen and a control panel for ventilation and lighting are set within easy reach above the bed. Additionally, the permanent crew can control 'privacy lamps' outside their doors, which can give indication to their fellow crewmen of their mood, privacy needs, or availability.
The permanent crew quarters offer a flexible room schedule: simple pull-out profiles in the bed structure allow the flexible creation of a intimate space for two crew members.
Thus, the crew quarters can be used as fully private area during the night (1), as a small private work area (2), or as space for intimate gatherings between two crew members (3) during the day. If the need arises, the bed can be extended to accommodate a couple (4).

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2


3


4

Fig. 6.15 - 18 | Permanent crew quarter, version 1- 4

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6.6 Sections

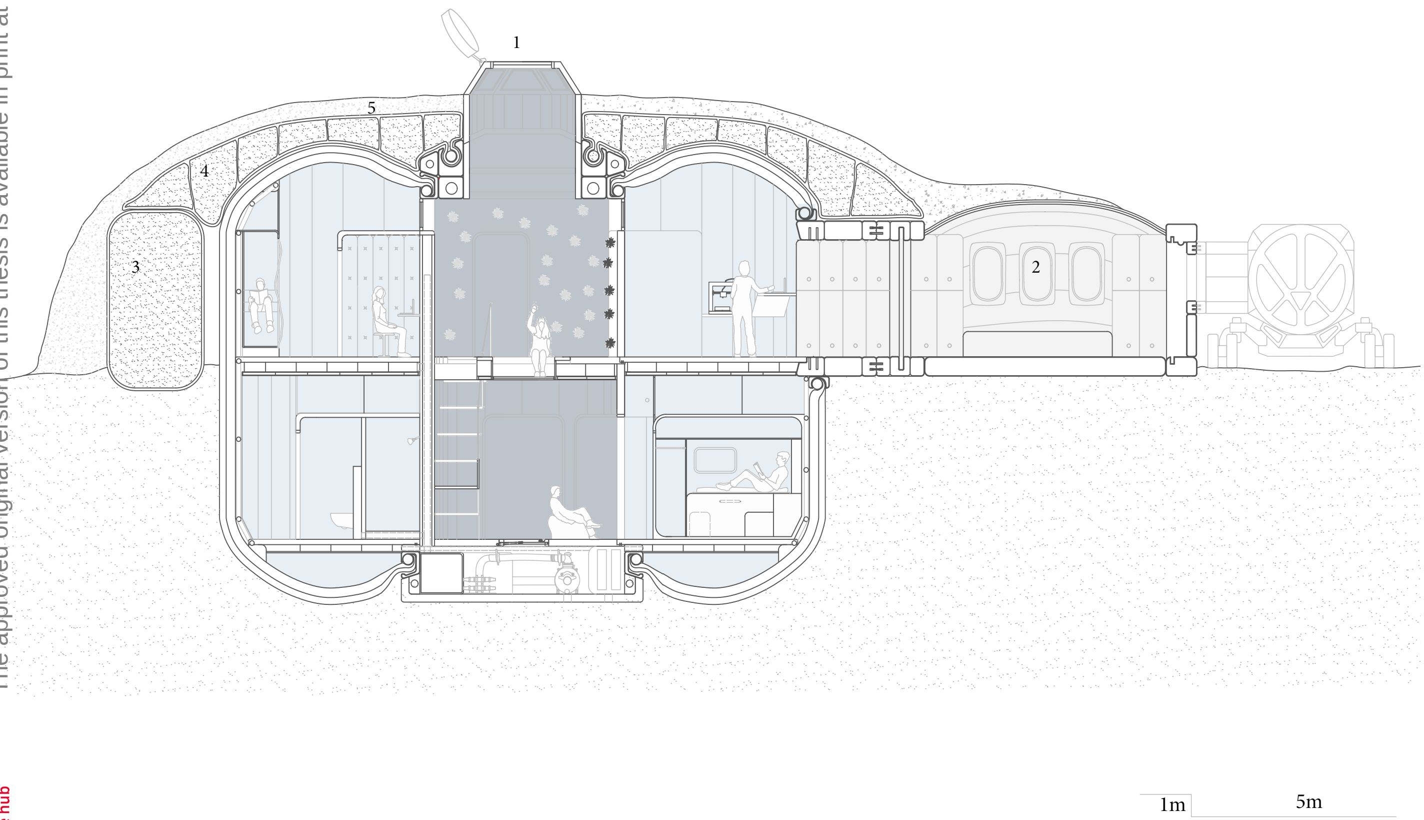

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Fig. 6.19 | Section A

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1 - stargazing window
2 - airlock 2
3 - regolith-filled propulsion tank
4 - regolith-filled bags
5 - additional, lose regolith layer:
protection of tanks and bags

rigid module

inflatable module

add-ons (airlock, greenhouse)

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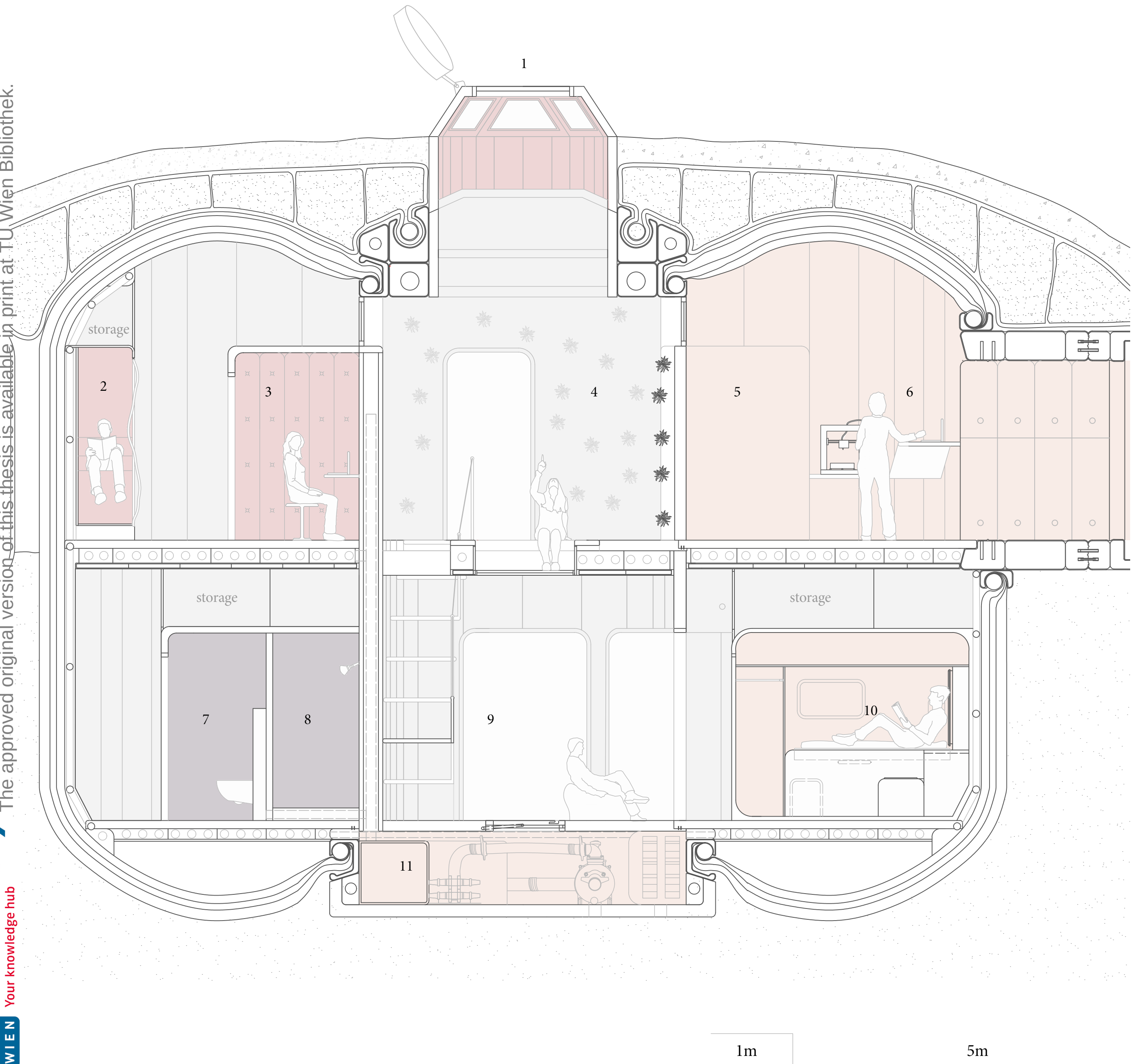

Fig. 6.20 | Section A

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1 - stargazing window
2 - semi-private niche (detail on p. 141)
3 - private communications area
4 - green gallery (detail green wall on p.142)
5 - additive manufacturing cubicle (extra-controlled environment)
6 - engineering and maintenance
7 - hygiene unit (toilet)
8 - hygiene unit (shower)
9 - crew lounge
10 - crew quarter permanent crew (detail on p.136)
11 - technical room

permanent crew only

guest crew only

shared space

shared space, high privacy area during use

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Semi-Private Niche

Fig. 6.21 | Semi-private niche

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Aeroponic Greenwall in Green Gallery

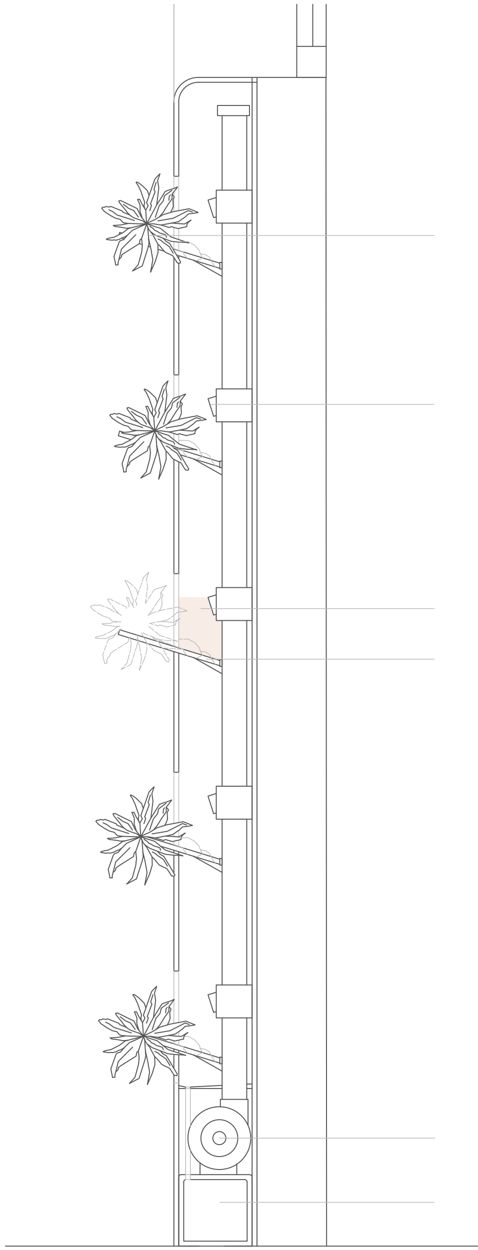

Fig. 6.22 | Technical detail, aeroponic greenwall

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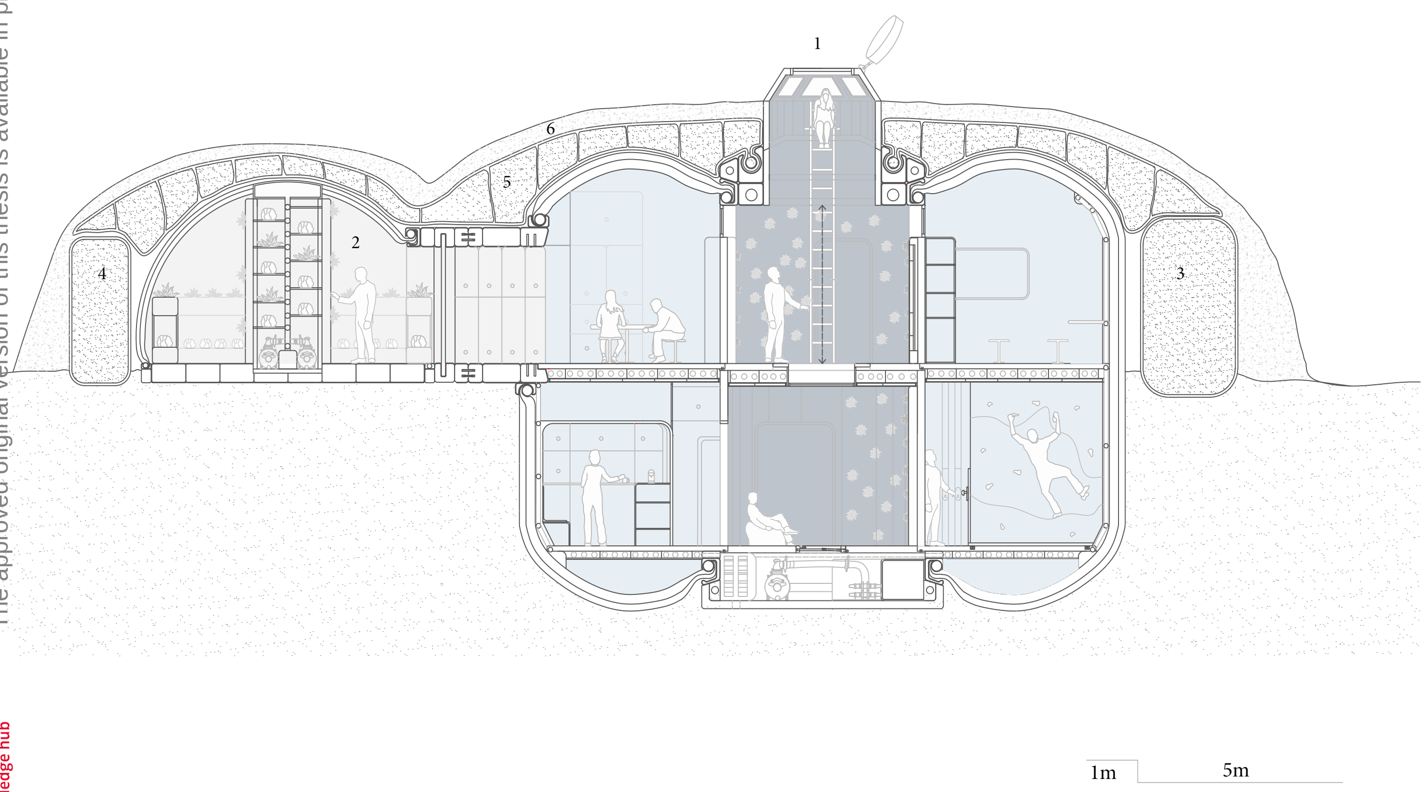

Fig. 6.23 | Section B

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1 - stargazing window
2 - greenhouse
3 - regolith-filled propulsion tank, big
4 - regolith-filled propulsion tank, small
5 - regolith-filled bags
6 - additional, lose regolith layer:
protection of tanks and bags

rigid module

inflatable module

add ons (airlock, greenhouse)

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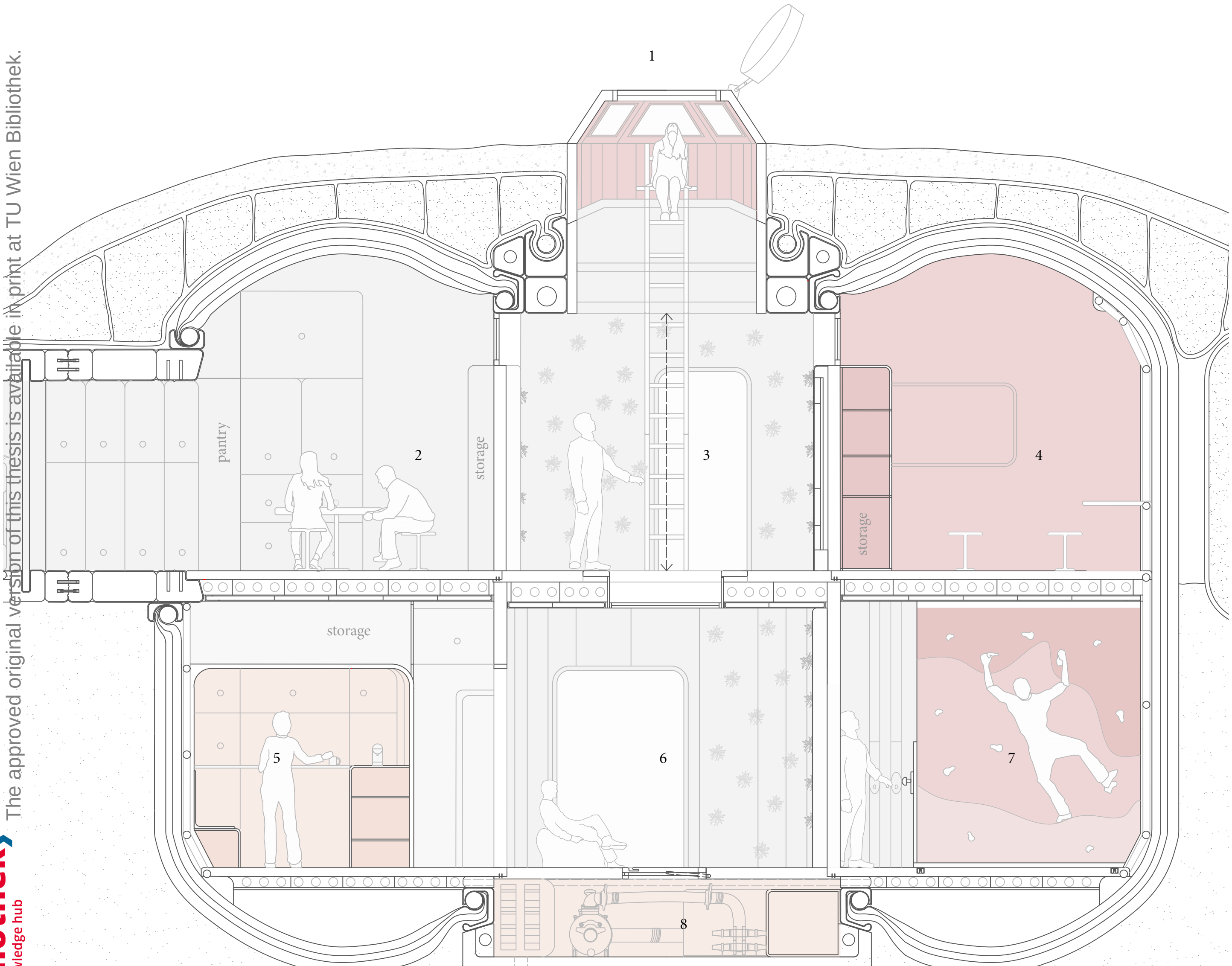

Fig. 6.24 | Section B

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1 - stargazing window (access via retractable ladder) (detail on p. 147)
2 - galley
3 - green gallery
4 - instruction area/workspace for guest crew
5 - common space, permanent crew
6 - crew lounge
7 - flexible workout area (detail on p.152)
8 - technical room

permanent crew only

shared space

shared space, high privacy area during use

1m 5m

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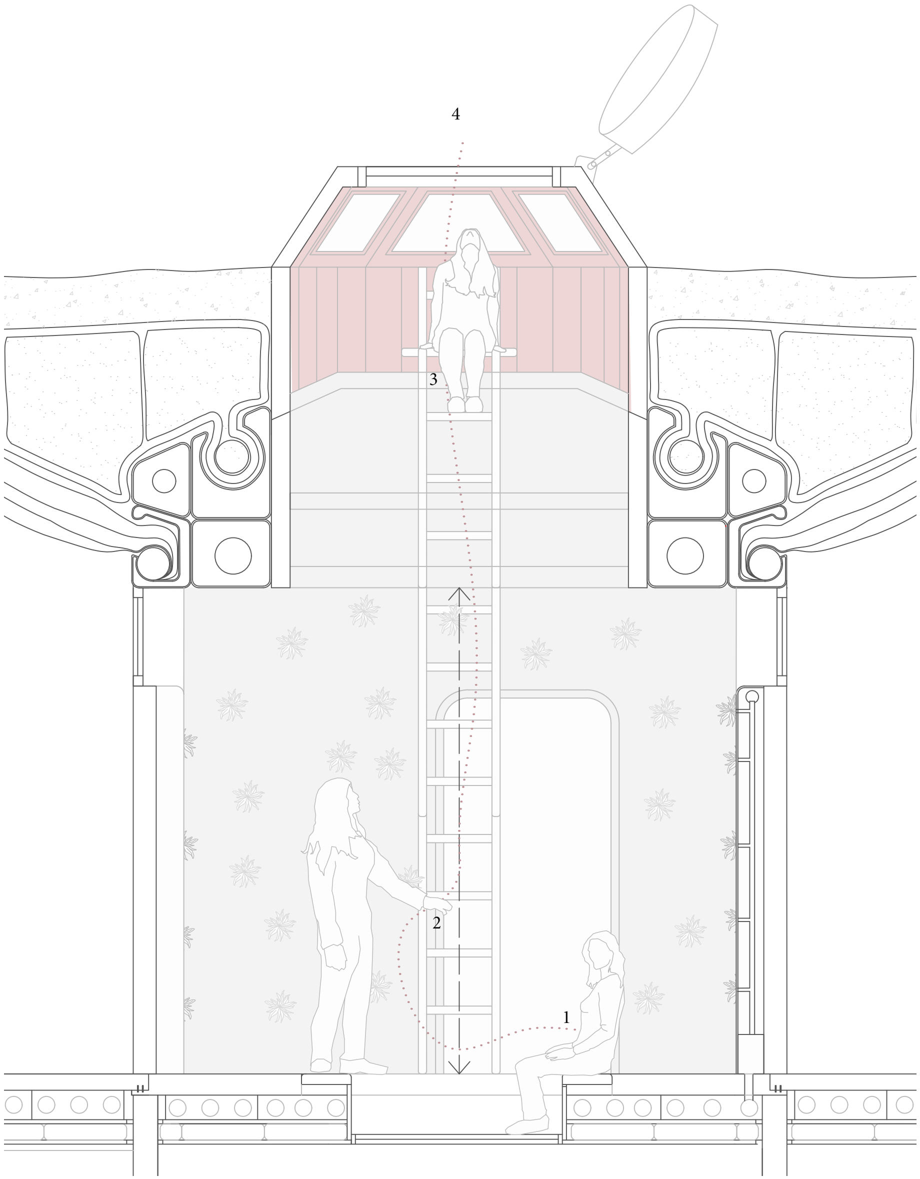

Fig. 6.25 | Stargazing in the HAVEN Cupola: process

Fig. 6.26 (following page)| Stargazing in the HAVEN Cupola: visualisation

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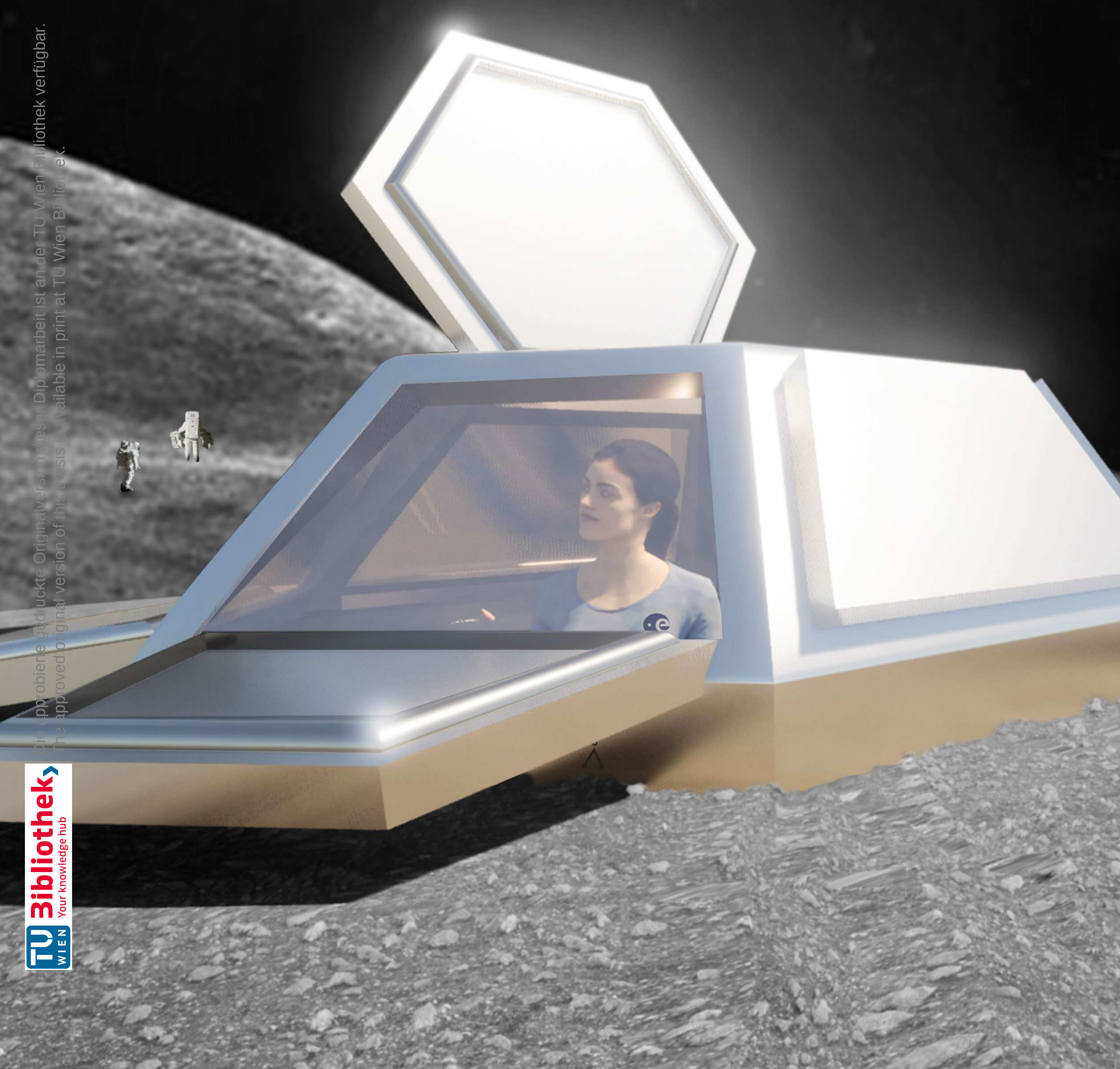
Stargazing at the HAVEN Cupola

1 - Crewman 1 sits in the green gallery underneath the stargazing Cupola.
2 - Crewman 1 decides to get a closer look at the stars and the lunar landscape: she pulls down the retractable ladder.
3 - Crewman 1 climbs into the Cupola. That's really easy thanks to 1/6 G! She sits onto the stargazing platform.
4 - Crewman 1 enjoys the stunning view of the lunar landscape and even gets a glimpse of Earth.

1m

5m



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Overhead Storage

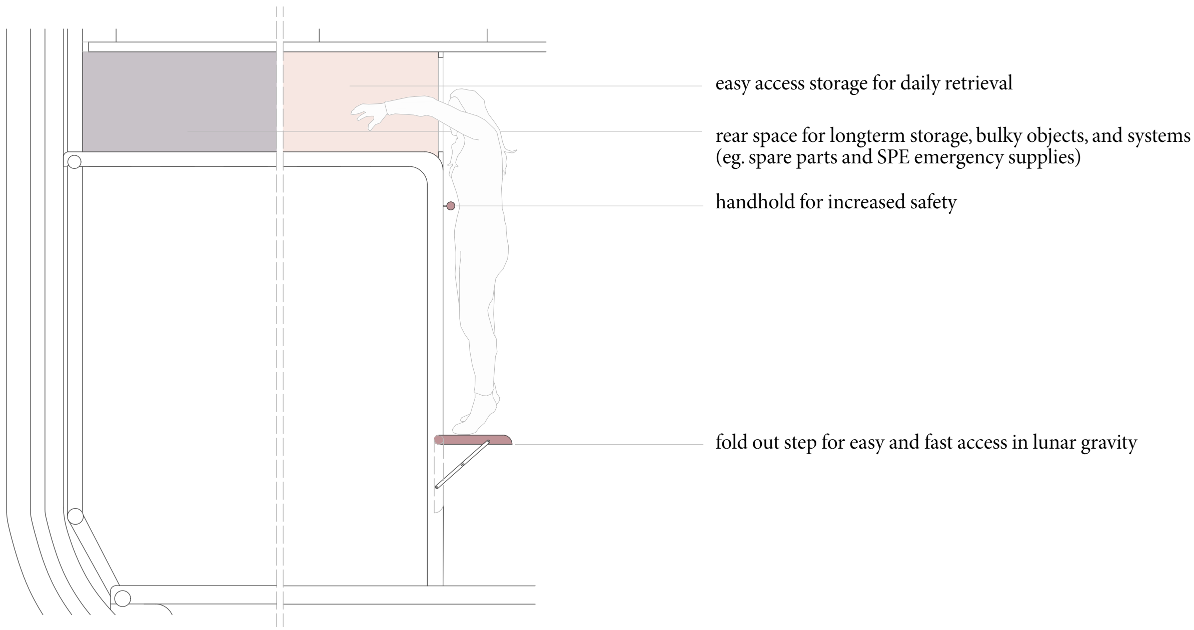

Fig. 6.27 | Overhead storage on top of all rooms of < 3 m height.

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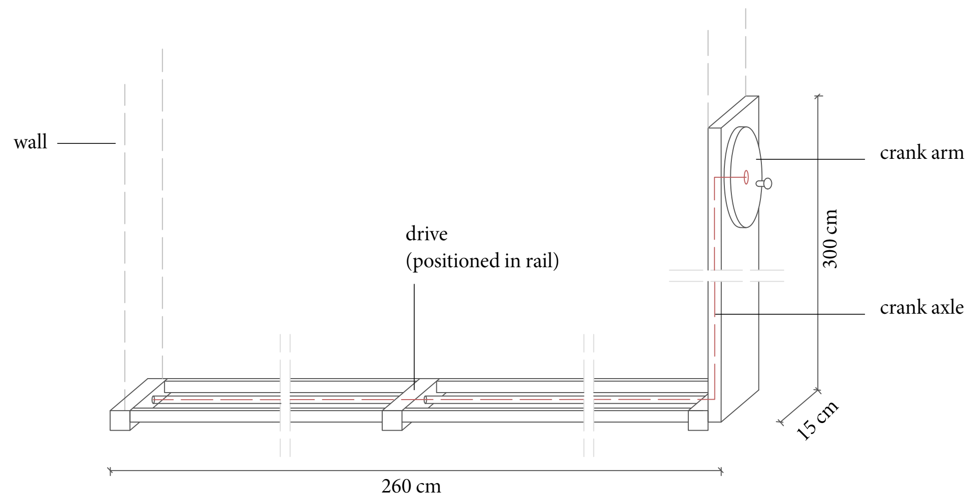
Flexible Work-Out Walls



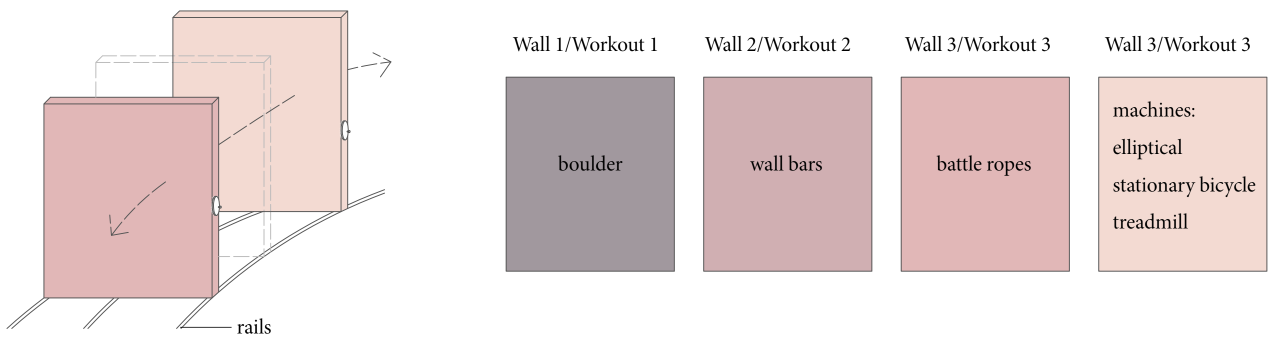


Fig. 6.28 | System, mobile wall on floor-integrated rails

Fig. 6.29 | 3D, mobile walls with different workout options

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6.7 SPE Procedures and Safe Haven

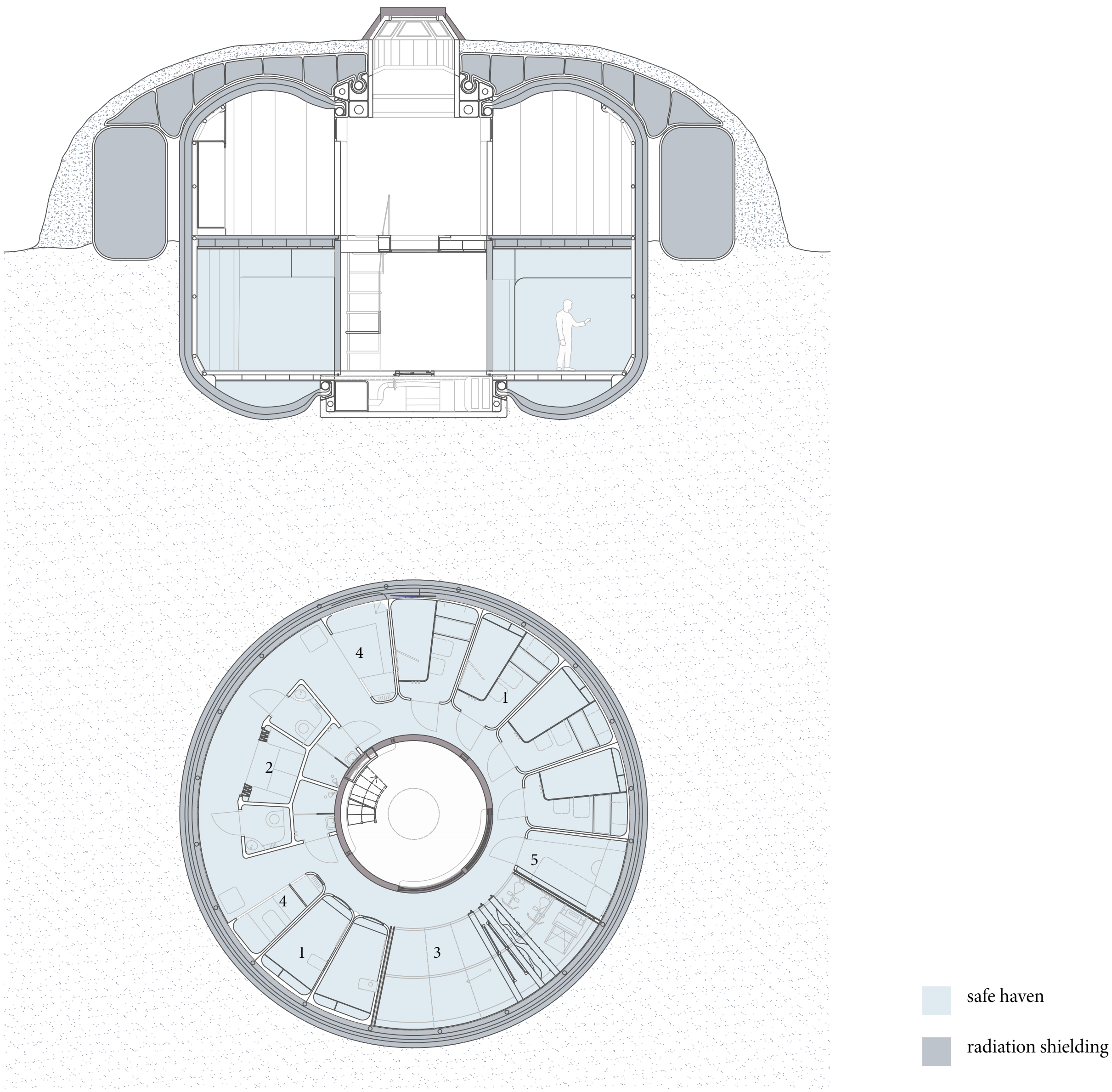

Fig. 6.30 | SPE safe haven zones in the HAVEN habitat

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1. SPE Forecasts

In the case of a threatening SPE, HAVEN is alerted through early warning systems based on technology such as the Solar Orbiter. As additional safety measure in case of a communication failure, the habitat is equipped with two radiation detectors (RD1: subsurface, level RD2: surface level).
If a SPE is forecast, the HAVEN crew activates the SPE emergency protocols.

2. SPE Preparation

Any crew members on EVA are recalled. Supplies and equipment in the safe haven is retrieved and double-checked. Communications are relocated from the control centre on the surface level to the sickbay, where a small interim communications centre is set up. (Note that an SPE could interfere with most communication between the Moon and Earth.)
As a last step, the crew retreats into the subsurface safe haven and closes the shielded doors of the rigid module.

3. SPE Isolation

SPEs can last from several hours to several days. The HAVEN safe haven consists of the inflatable module at the subsurface level (fig.6.30).[7]
This area is especially well shielded due to the subsurface location, as well as through the additional radiation shielding capacities of the Radiation Shield Water Tank (RSWT) (Almlie et al 1999), which is integrated in the ceiling.
The safe haven includes all necessary areas for an SPE isolation of several days for the maximum crew capacity, such as sleeping areas (1), hygiene units, (2) communal space (3) (and even workout space in case of a duration of several days). Basic meals from dehydrated food packages can be prepared at the communal space coffee niches (4), which offer the ability to heat water. Access to medical attention is possible through the sickbay (5), which also doubles as emergency communications centre.
The usual access restrictions are somewhat lifted during SPE isolation; however the personal crew quarters still offer enough privacy during this emergency situation.

7 - In addition, the two rovers docked at the airlocks (SPR configured CMCs) can also function as SPE radiation-hard emergency shelters in special emergency situations. (NASA 2008)

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6.8 Topview and Elevation

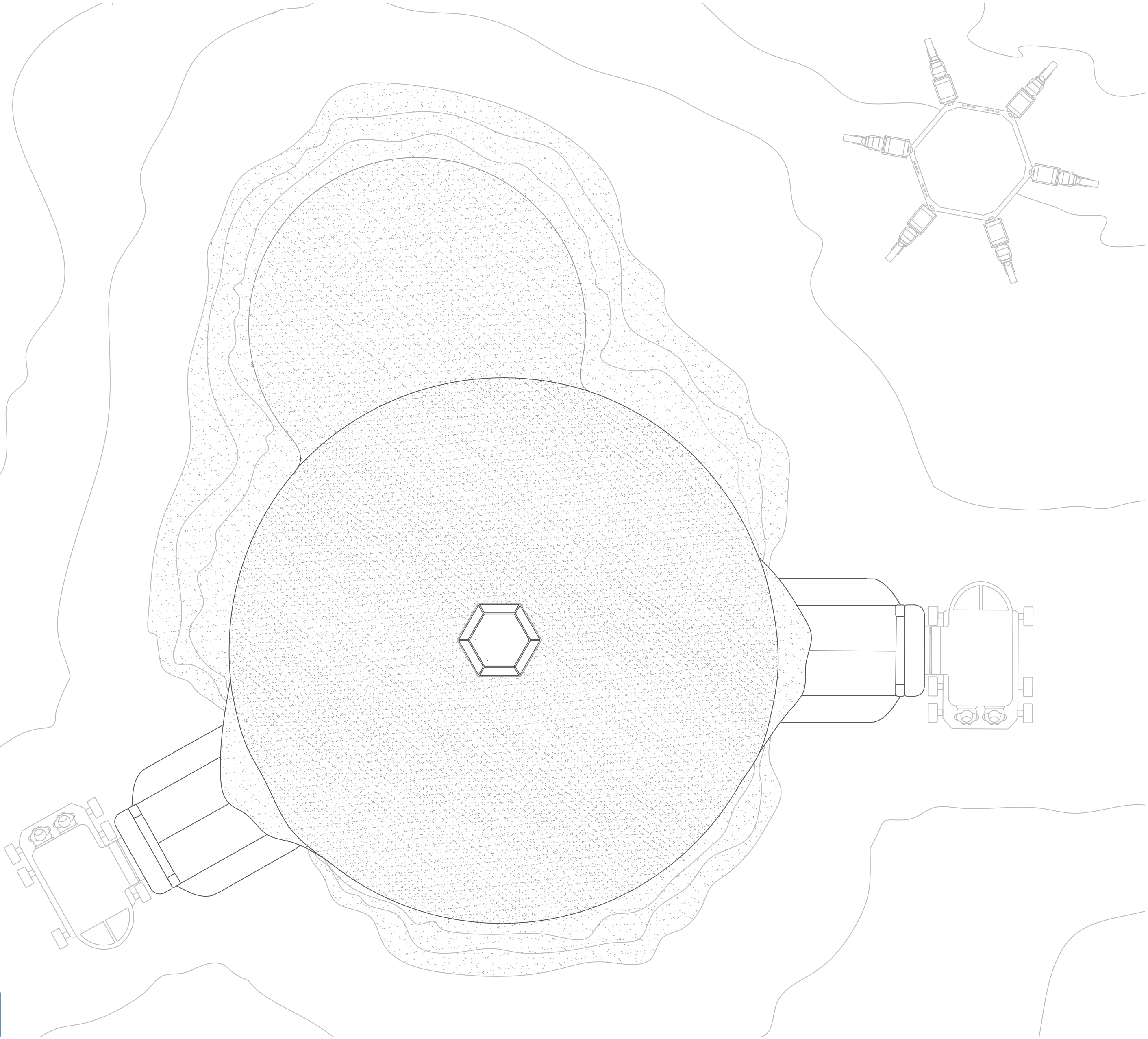

Fig. 6.31 | Topview of HAVEN with two docked SPRs and an ATHLETE rover

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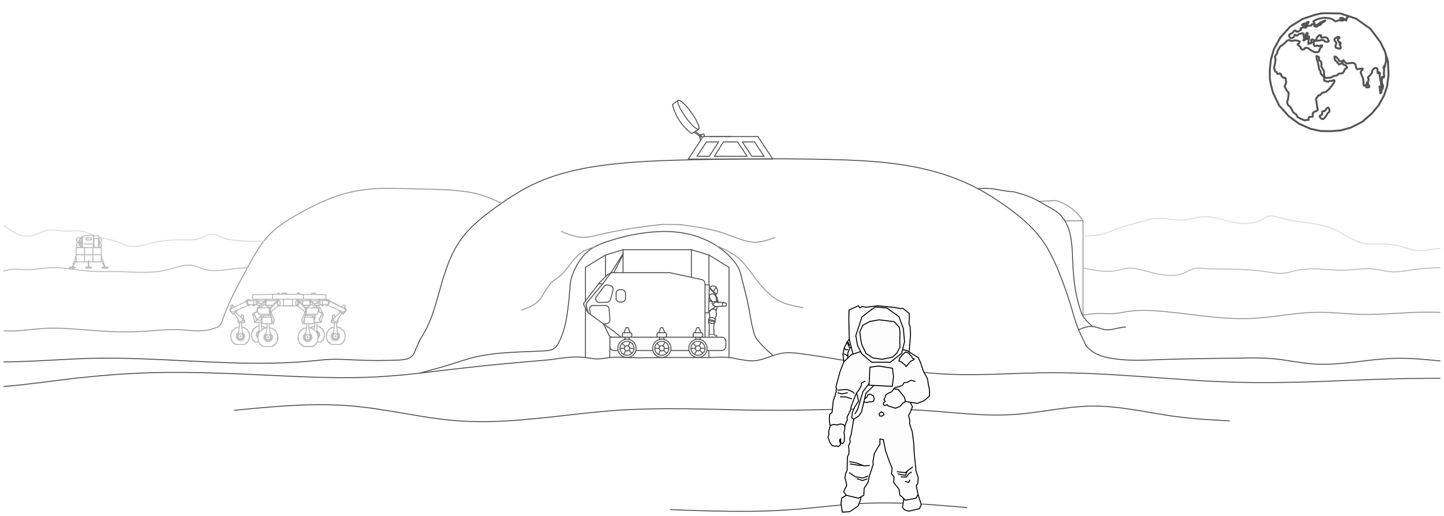

Fig. 6.32 | Elevation

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6.9 Wall and Ceiling Structure

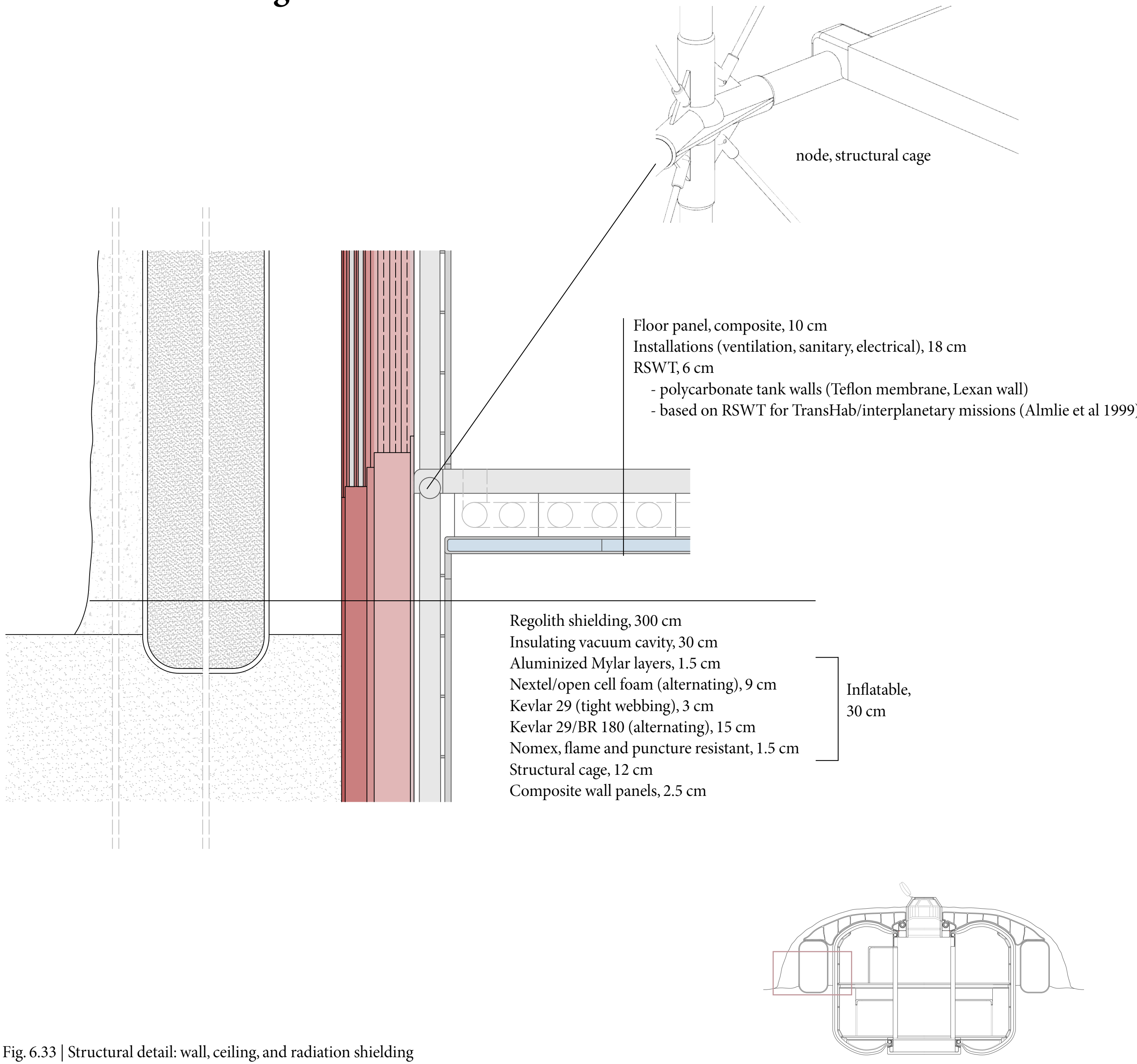

Fig. 6.33 | Structural detail: wall, ceiling, and radiation shielding

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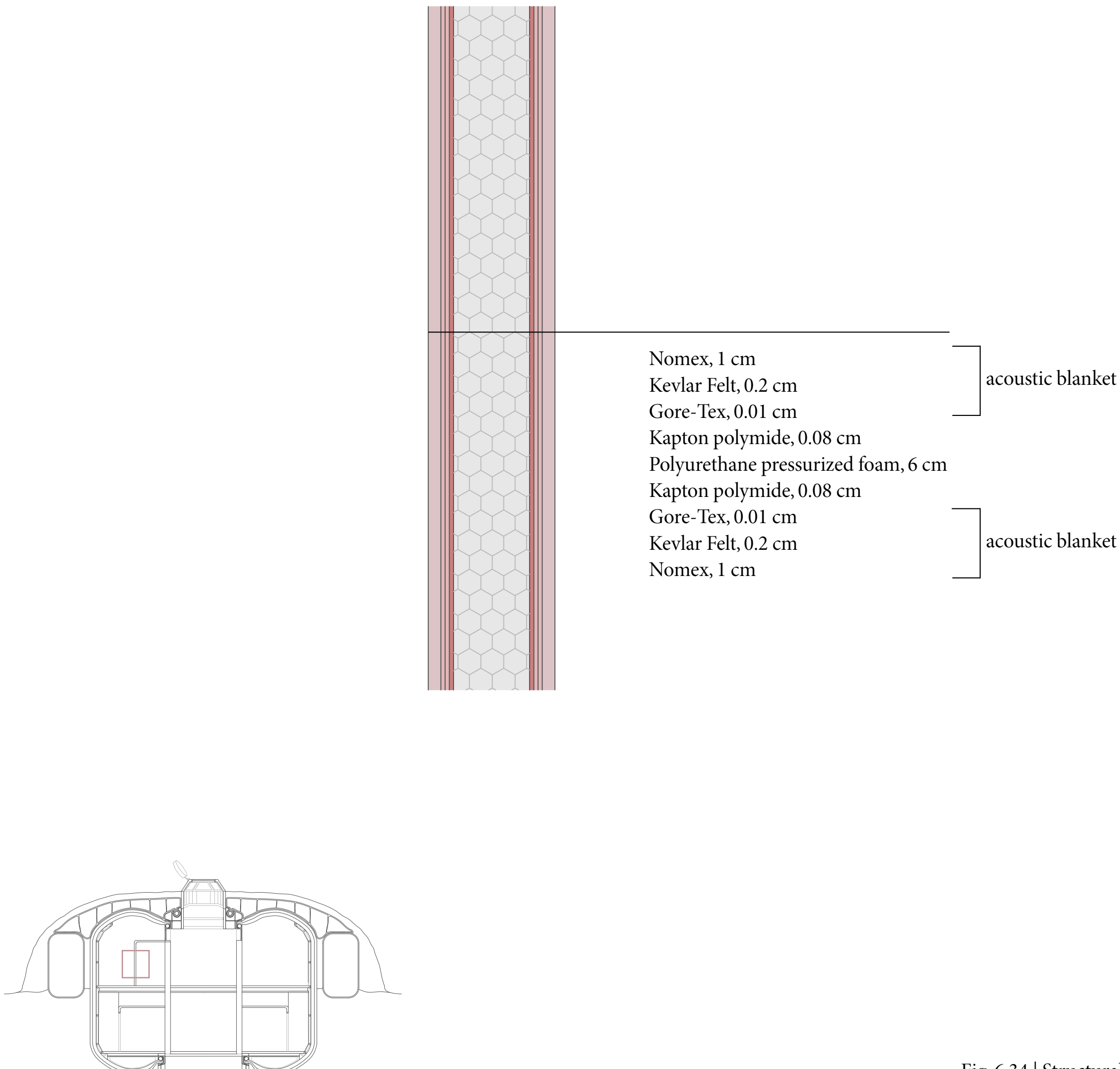

Fig. 6.34 | Structural detail: foam rigidized walls

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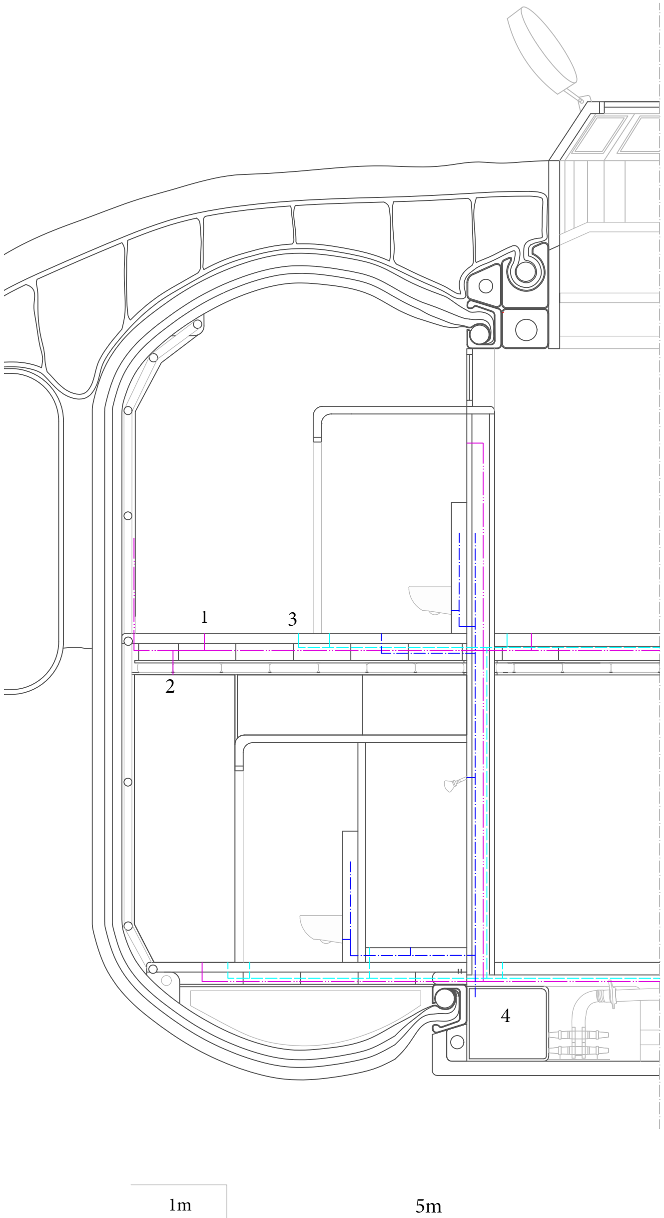
6.10 Installations



The installations at the HAVEN habitat are located in the rigid module. This allows the pre-installation of most systems before launch.
A subsurface technical room contains systems like the water treatment facility with the greywater and freshwater tanks, the fuse box and a small backup generator, and the air filtration system.
(detail on p. 158)

1 - outlet floor socket
2 - outlet illumination
3 - floor vent
4 - greywater tank and treatment

electrical installations
ventilation (Ø 17cm)
water installations: feeder, downcomer (Ø 10cm)

Fig. 6.35 | Installations

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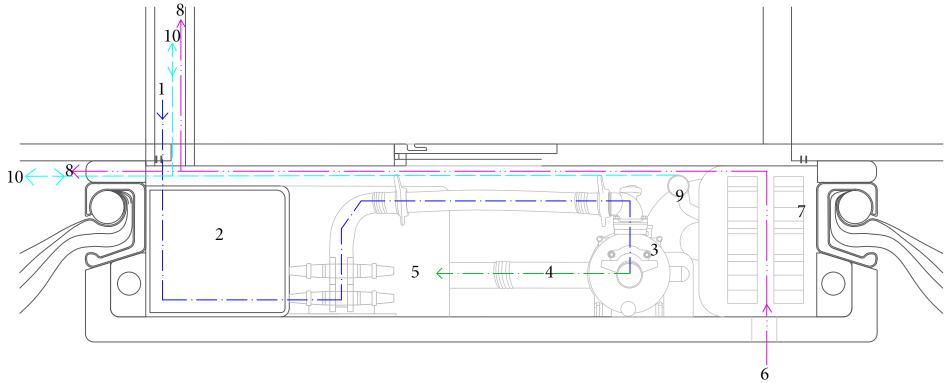

1 - waste water drain

2 - waste water collection tank

3 - greywater treatment

4 - treated, clean water

5 - fresh water collection tank (2500l)

6 - connection to energy zone: energy inlet (solar)

7 - fuse box, backup generator (bio gas)

8 - energy distribution

9 - air filtration

10 - ventilation

Fig. 6.36 | Processes in the technical room

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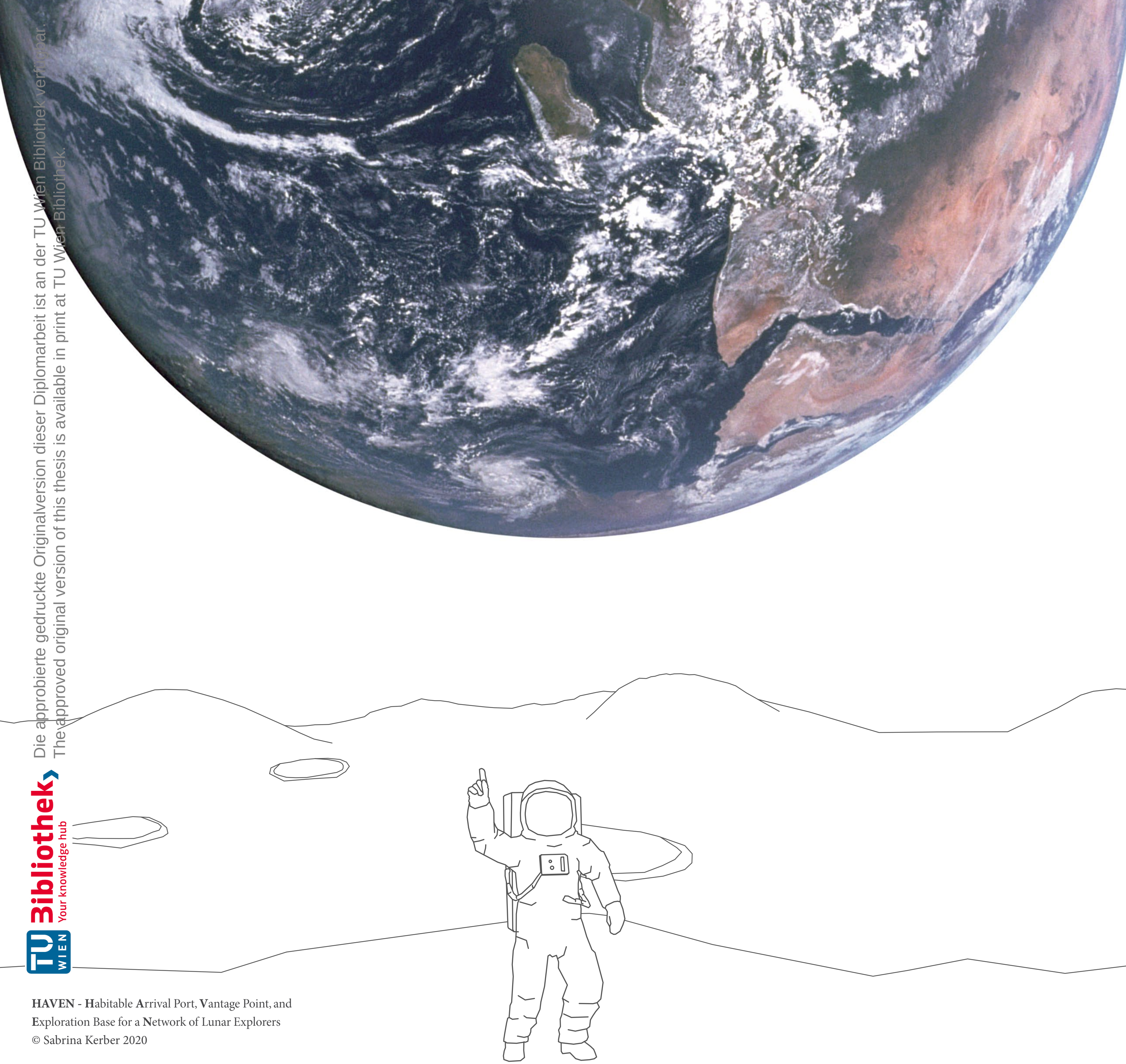

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HAVEN - **H**abitable **A**rrival Port, **V**antage Point, and
Exploration Base for a **N**etwork of Lunar Explorers

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