X-PLOR

LUNAR EXPLORATION AND HABITATION ROVER

TECHNISCHE UNIVERSITÄT WIEN

DIPLOMARBEIT

X-PLOR

Lunar Exploration and Habitation Rover

ausgeführt zum Zwecke der Erlangung des akademischen Grades eines Diplom-Ingenieurs unter der Leitung von

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KURZBESCHREIBUNG

Seit Menschen in den Himmel blicken, steht der Mond im Mittelpunkt der Faszination. Das Artemis-Programm der NASA ist der erste Schritt in die nächste Ära der Erforschung durch die Menschen. Es hat weltweit für Aufregung gesorgt und neues Interesse an der Erforschung des Mondes geweckt, seit die NASA die Landung der Astronauten auf den Südpol des Mondes im Jahr 2024 angekündigt hat. Um AstronautInnen einen geeigneten Lebens- und Arbeitsraum auf dem Mond zu bieten, zielt das Artemis Base Camp-Konzept der NASA darauf ab, ein modernes Mondhabitat, einen Rover und ein mobiles Zuhause zu entwickeln, das als „bewohnbare Mobilitätsplattform“ bezeichnet wird.

X-plor ist ein Erkundungs- und Wohnfahrzeug, das als Vorschlag für das Artemis-Basislager konzipiert wurde. Es ist an die Sicherheit und Leistung von Astronauten während der Monderkundung zugeschnitten und kann die Aktivitäten von 2+2 Mitgliedern für mehrere kurzfristige Missionen auf extremen und komplexen Oberflächen unterstützen. Es zielt darauf ab, ein hohes Maß an Mobilität, Flexibilität und Bewohnbarkeit auf dem Mond zu erreichen, während das dynamische Design es Astronauten ermöglicht, den Mondsüdpol sicher und bequem zu erkunden, zu entdecken und zu beobachten. Diese Kombination von Leistungsmerkmalen zielt darauf ab, die Produktivität der Astronauten zu steigern und den Aufwand für die Rückkehr zur Mondstation oder zur Landefähre am Ende eines jeden Tages zu eliminieren, da der Rover in der Lage ist, mehrtägige oder wochenlange Missionen zu unterstützen.

X-plor begegnet den extremen Herausforderungen der Mondumgebung sowie den strukturellen, technischen und habitablen Anforderungen, indem es Autonomie und Modularität nutzt, um den Transport und die Lebensbedingungen auf dem Mond zu verbessern. Die fortschrittliche, autonom entfaltbare Architektur passt sich an die spezifischen Missionserfordernisse und die Missionsdauer an und ermöglicht eine revolutionäre Herangehensweise an die Erforschung der Planetenoberfläche durch Menschen. Dies wird durch das autonom entfaltbareTransit- und Wohnsystem erreicht, das den Rover für vier verschiedene Konfigurationen optimiert: Startkonfiguration, mobile Konfiguration, Wohnkonfiguration und getrennte Konfiguration.

ABSTRACT

Human space exploration assists in answering basic questions about where we fit in the Universe and the history of our solar system. For as long as humans have gazed skyward, the Moon has been a focus of fascination. The Artemis program by NASA represents the upcoming phase of human exploration. It has generated global enthusiasm and stimulated fresh curiosity in lunar exploration, especially following the agency's announcement of astronauts landing on the lunar South Pole in 2024. To give astronauts a place to live and work on the Moon, NASA's Artemis Base Camp concept aims to develop a contemporary lunar habitat, a rover and even a mobile home that is referred to as a habitable mobility platform.

X-plor is a self-deployable exploration and habitation vehicle designed as a proposal for Artemis Base Camp. It is adapted to optimize astronaut safety and performance during lunar exploration and can support crew operations of 2+2 members for multiple short term missions on extreme and complex surfaces. It seeks to achieve a high level of mobility, flexibility, and habitability on the Moon, while the dynamic design allows astronauts to extend exploration, discovery and observation of the lunar South Pole safely and comfortably. This combination of features is designed to enhance the efficiency of crew members in space suits and eliminate the need to return to the outpost or lander daily. This is possible because the rover can sustain missions spanning multiple days or even weeks.

To overcome the challenges posed by the harsh lunar environment and meet structural, technical, and habitability requirements, X-plor leverages autonomy and modularity to enhance performance and flexibility in lunar transportation and habitation. Its self-deployable architecture enables it to adapt its appearance and size according to mission requirements and duration, marking a significant leap forward in human planetary surface exploration. This is made possible through the use of a self-deployable transit and habitation system, which allows the rover to be optimized for four different configurations: launch, mobile, habitation, and separated configuration.

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ABBREVIATIONS

ALM - Apollo Lunar Module

ATHLETE - All-Terrain Hex-Limbed Extra-Terrestrial Explorer

ESA - European Space Agency

EVA - Extra Vehicular Activity

GCR - Galactic Cosmic Rays

ISRU - In Situ Resource Utilization

ISS - International Space Station

JAXA - Japan Aerospace Exploration Agency

LEO - Low Earth Orbit

LRO - Lunar Reconnaissance Orbiter

LSS - Life Support System

LTV - Lunar Terrain Vehicle

MMOD - Micrometeoroid and Orbital Debris

NASA - National Aeronautics and Space Administration

NBP - Neutral Body Posture

PSR - Permanently Shadowed Region

ROSA - Roll-Out Solar Arrays

SCR - Solar Cosmic Rays

SLS - Space Launch System

SPE - Solar Particle Event

01 EXPLORATION OF THE MOON

"We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too."

John F. Kennedy, 1962.

1.1 INTRODUCTION

The Moon, Earth's closest celestial companion, holds a significant role in both our planet's history and its future. For thousands of years, humanity has gazed at the Moon in wonder and admiration. The intrigue of Moon exploration has persisted across the ages, captivating people from ancient civilizations to contemporary science. The notion of uncovering the Moon's mysteries has continuously fascinated us. Despite its vastness comparable to an entire continent, human presence on the Moon has been rare. Regarded as a portal to the solar system, it offers a valuable terrain for testing deep space technologies and procedures, crucial for preparing human expeditions to other planets like Mars.

The lunar environment poses a range of challenges for human habitation and exploration. With no atmosphere, no magnetic field, and extreme temperature variations, the lunar surface is a hostile environment for human beings. However, despite these challenges, NASA's Apollo missions in the 1960s and '70s demonstrated that human exploration of the Moon is possible, and paved the way for the Artemis program, which aims to send humans back to the lunar surface.

In the coming decade, NASA's Artemis program will establish the groundwork for a consistent and extended stay on the Moon's surface. This lunar presence will serve as a platform to test and validate deep space technologies and procedures, ensuring readiness for the more extensive journey to Mars (NASA 2023). The global goal of space exploration is to ensure ongoing success for humanity by broadening our scope of activity and creating new knowledge. Our presence on the Moon will be a constant reminder of humanity's unlimited potential and will continue to inspire us as we explore more distant worlds. The technologies developed for lunar missions can then be used on Earth to improve transportation, develop sustainable technologies, and benefit society and the planet (National Space Council 2018).

In order to establish a sustained human presence on the Moon, NASA is developing new technologies and vehicles that are capable of supporting human needs and scientific exploration in the challenging lunar environment. One of the key components of this effort is the development of a lunar habitation and exploration vehicle, which will serve as a home and workspace for astronauts on the lunar surface.

In this chapter, we delve into the harsh lunar environment and discuss the implications it has for designing a habitable lunar base and vehicles. We examine the challenges posed by extreme temperatures, radiation, and impact hazards, and explore the technologies and systems that are being developed to overcome these challenges and create a safe and sustainable human presence on the Moon. The lessons learned from the Apollo missions, as well as from research conducted on the Artemis program and other space missions, are helping to inform the design of the future lunar vehicle concept. To ensure that the lunar habitation and exploration vehicle meets the needs of human beings, it is necessary to take a multidisciplinary approach that addresses a range of factors, including physiological, sociocultural, and environmental considerations. Exploring ways to use local resources is crucial. The Moon is rich in resources such as water ice, which could be extracted and used to produce oxygen and rocket fuel. The lunar regolith, or soil, could be used as a building material for habitats and infrastructure.

The challenges of making a lunar base and habitation possible are many, but the potential rewards are equally significant. A permanent lunar presence would allow for sustained scientific research and exploration, as well as serve as a stepping stone for future missions to Mars and beyond. Through the Artemis program, NASA is laying the groundwork for a new era of lunar exploration and discovery.

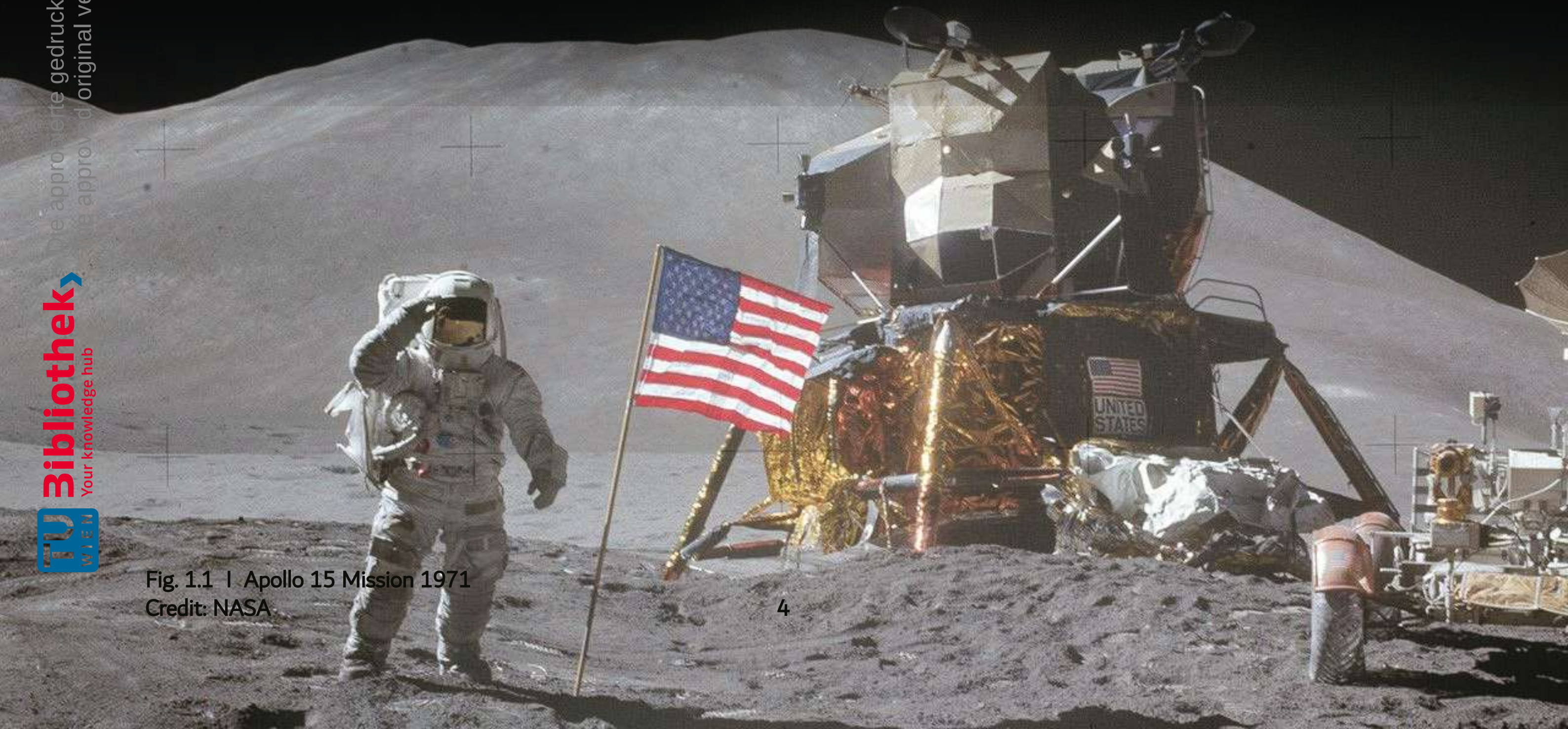


Fig. 1.1 I Apollo 15 Mission 1971
Credit: NASA

1.2 LUNAR ENVIRONMENT

As the Earth's nearest celestial neighbor, the moon has captivated human imagination for centuries. Its silver glow in the night sky, its waxing and waning phases, and its influence on the tides have all contributed to a rich tapestry of scientific inquiry. But the moon is more than just a pretty sight in the sky; it is a fascinating and complex world in its own right.

Over the past five decades, the Moon has taken on a dual significance in human perception. As evidenced by the Apollo missions, the Moon holds great scientific value as a planetary entity. It holds a distinctive record of planetary formation and early evolution, and it functions as a sentinel that has documented the space environment and cosmic radiation for billions of years. Given its proximity to Earth, the Moon is an evident candidate for extended human exploration beyond our planet. Understanding the Moon's attributes, particularly its potential resources and utility, has become indispensable in shaping our plans for humanity's journey into space (Heiken et al 1991).

In this chapter, we will explore the moon's history, geology, and environment, as well as some of its extreme conditions. We will delve into the latest scientific discoveries about the moon, including its composition, origins, and potential as a future destination for human exploration and settlement. Along the way, we will encounter stories of lunar exploration, both past and present, and gain a deeper appreciation for the role that the moon has played in shaping our understanding of the universe.

The moon has a number of extreme conditions that make it a challenging environment for human exploration, for example: extreme temperature variations, cosmic and solar radiation, vacuum, dust and low gravity (Heiken et al 1991).

Overall, the moon's extreme conditions require careful planning and preparation for any human exploration missions. Whether you are a casual stargazer, a seasoned astronomer, or simply curious about the world beyond our planet, this chapter will provide you with a comprehensive and engaging look at our nearest celestial companion.

Fig. 1.2 I Moon
Credit: Britannica

1.2.1 THE EARTH-MOON SYSTEM

The Moon is a natural satellite of the Earth. It is also the fifth largest moon in the solar system and the largest relative to its host planet, with a diameter of about 1/4 of that of Earth. Therefore, the Earth-Moon system is sometimes escribed as “Double Planet” to emhasize the importance and relative size of the Moon. The Moon is approximately 384.400 kilometers away and travel duration is around 2.5 to 4 days. The Moon orbits the Earth due to the gravitational force of attraction between the two objects where the Moon travels counterclockwise in a slightly elliptical path around the Earth. One orbit around Earth lasts 29.5 days (Eckart 1999, p. 113).

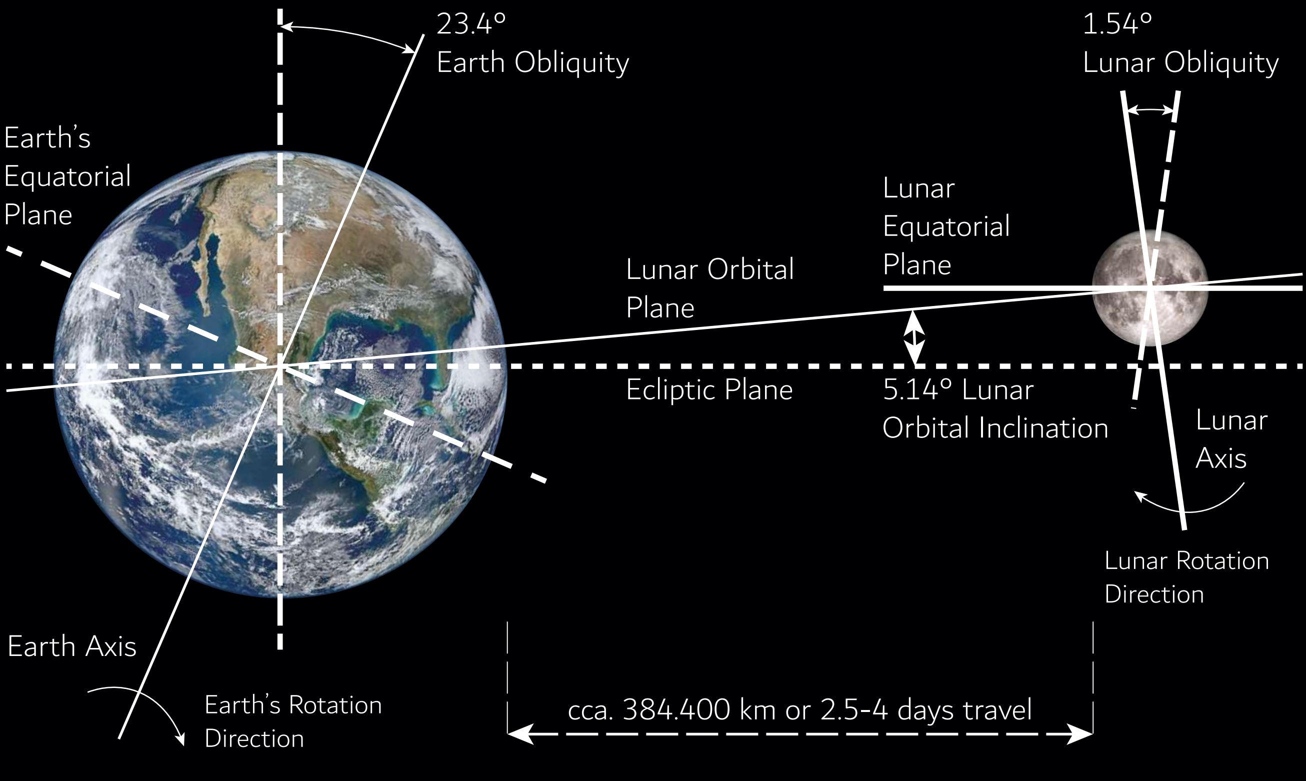


Fig. 1.3 I Lunar Orbital Characteristics (dimensions are not to scale)

PROPERTIES	MOON	EARTH
Mass	7.353×10^{22} kg	5.976×10^{24} kg
Mean Radius	1.738 km	6.371 km
Surface Area	3.80×10^{7} km^2	5.10×10^{8} km^2
Mean Density	3.34 g/cm^3	5.517 g/cm^3
Gravity at Equator	1.62 m/sec^2	9.81 m/sec^2
Escape Velocity at Equator	2.38 km/sec	11.2 km/sec
Atmosphere composition	3×10^{-12} Pa	101.325 kPa
Gravity	1.62 m/s^2 or 1/6 g	9.807 m/s^2 or 1 g
Average Temperature	-30 °C	13 °C
Radiation	60 µSv/hour	0.17-0.39 µSv/hour
Sidereal rotation time	29.5 days	24 hours

The Moon's orbit around the Earth is called synchronous rotation, and it occurs because the time it takes for the Moon to rotate on its axis once (a lunar day) is the same as the time it takes for the Moon to orbit around the Earth (a lunar month). As a result, the same side of the Moon always faces the Earth, while the far side of the Moon remains permanently hidden from view from Earth. When the Moon is on the side facing the Sun, that side experiences daylight for 14 days, while the side facing away from the Sun experiences darkness also for 14 days (Eckart 1999, p. 114). Some of the most impor-tanat parameters of Moon and Earth are compared in Table 1.1.

Table 1.1 I Moon and Earth Comparison List

1.2.2 LUNAR GEOGRAPHY AND GELOGY

From the surface to the core, the Moon can be divided into the following layers and seen on Fig. 1.4 (NASA Solar System Exploration 2022):

1. **REGOLITH:** This is the layer of loose, rocky material that covers the Moon's surface. It is made up of dust, rocks, and soil that were created by meteoroid impacts and other processes.
2. **CRUST:** Beneath the regolith is the Moon's crust, which is composed of different types of rock, including basalt, anorthosite, and breccia. The crust is thickest near the center of the near side and thinnest near the edges of the far side.
3. **MANTLE:** Beneath the crust is the Moon's mantle, which is made up of denser rock than the crust. The mantle extends to a depth of about 1,000 kilometers below the surface.
4. **CORE:** At the center of the Moon is a small, partially molten core made up of iron and other metals. The core is thought to be about 500 kilometers in diameter.

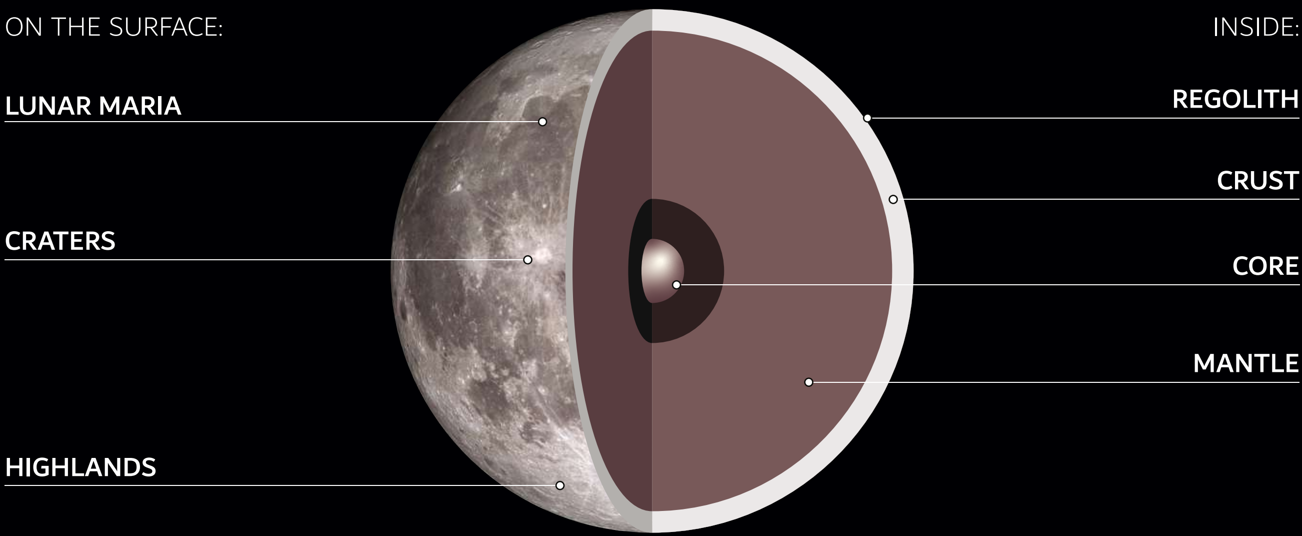


Fig. 1.4 I Internal and External Structure of the Moon

The moon's surface is covered with impact craters, highlands, and valleys. It also has dark, flat areas known as "maria," which are ancient basaltic lava flows (Eckart 1999, p. 118).

5. **CRATERS:** Circular depressions on the surface of the Moon, created by impacts from meteoroids and other space debris. They are one of the most common features on the Moon's surface and come in a wide range of sizes, from small bowl-shaped pits to large impact basins that can be hundreds of kilometers across.
6. **HIGHLANDS:** The light-colored highlands are often referred to as lunar highlands or terrae, and they are characterized by their light-colored appearance in contrast to the darker regions of the Moon, known as lunar maria. They are the original primordial crust of the Moon and have been continuously penetrated by meteoroids which created their very rough landscape.
7. **LUNAR MARIA:** Large, dark, flat areas on the surface of the Moon. The term "maria" is Latin for "seas", and the name was given to these features by early astronomers who thought they were actual bodies of water on the Moon. However, today is known that the maria are not seas, but rather vast regions of solidified lava that were formed by volcanic activity on the Moon. The lunar maria are generally located on the side of the Moon facing Earth, and they are more prominent in the Moon's northern hemisphere. They are characterized by their dark color and often marked by irregular-shaped craters (Eckart 1999, p. 119).

Various types of lunar rocks can be classified into groups such as basaltic volcanic rocks, pristine rocks, breccias, and impact melts. Basaltic volcanic rocks, located in the maria regions, boast high iron and titanium content, primarily in the mineral ilmenite. Conversely, pristine rocks found in the highlands contain potassium, phosphorus, and pyroxene. Breccias, commonly situated in craters, form due to micro-meteoroid impacts that fragment rocks or create impact melts. Lunar regolith encompasses a range of rock debris and volcanic ash and is often grouped with lunar soil, though the latter pertains only to the smaller fraction of sub-centimeter regolith. Regolith usually contains substantial iron, whereas lunar soil is predominantly composed of agglutinates featuring non-magnetic iron sulfide, known as troilite (Seedhouse 2008, p. 122).

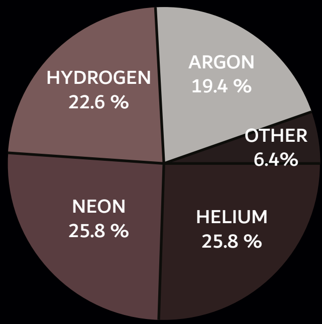
Lunar regolith refers to the layer of loose, fragmented materials that covers the surface of the Moon. It is a mixture of dust, rocks, and other particles that have been ground down over billions of years by meteoroid impacts and other geological processes. The regolith on the Moon is very different from the soil found on Earth, as it is made up of mostly fine-grained material, with larger rocks and boulders scattered throughout. The regolith layer can be several meters deep in some areas and is typically thicker in older regions of the Moon's surface (Eckart 1999, p. 125).

The lunar regolith contains around 45% oxygen by mass, although its composition changes based on the Moon's location. Generally, it comprises a blend of silicates, oxides, and diverse minerals, with trace amounts of metals like iron, nickel, and titanium. Past endeavors have demonstrated the feasibility of extracting oxygen from regolith using different methods. NASA is now focused on creating innovative oxygen extraction systems capable of efficiently processing substantial amounts of lunar regolith while minimizing resource consumption, mass, and energy usage (NASA SBIR/STTR 2022).

Fig. 1.5 I Lunar Near Side Map

1.2.3 LUNAR SURFACE ENVIRONMENT

Due to its small size, low gravity and low escape velocity, the Moon lacks the ability to retain much of its atmosphere, resulting in a significantly lower atmospheric presence compared to Earth. Its atmosphere is often described as "exospheric" because it is extremely thin and tenuous and the lack of a substantial atmosphere means that during the daylight hours, the sky from the moon appears black. The surface pressure of the lunar atmosphere is less than 10^-14 bar, which is almost a vacuum. The lunar atmosphere consists mainly of helium, neon, and argon, with trace amounts of methane, ammonia, and carbon dioxide (Eckart 1999, p. 145), (Hassan 2020).



1.2.3.1 Temperature

The Moon's thin atmosphere causes its temperature to fluctuate greatly, with the supersonic solar wind heating up and removing gas particles from its surface, resulting in boiling temperatures at the equator of up to 121 °C (250 °F) during the day and freezing temperatures of -133 °C (-208 °F) at night (Hassan 2020). The temperature at the lunar poles varies depending on the location and time of day, but it is generally much colder than at the equator. Some areas of the lunar poles are in permanent shadow and never receive direct sunlight, causing temperatures to drop to as low as -240 °C (-400 °F). However, there are also areas that receive sunlight and can warm up to temperatures as high as 38 °C (100 °F). The temperature at noon varies throughout the year because of varying distance from the Sun.

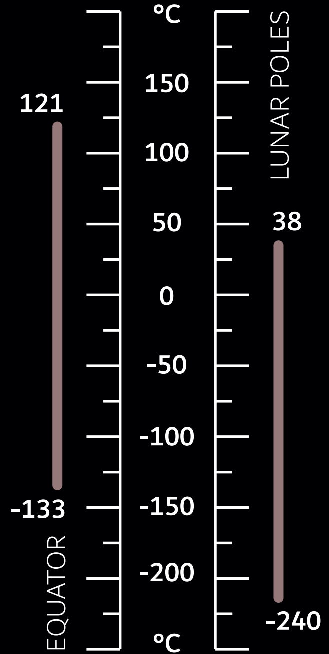


Fig 1.6 I Lunar atmosphere composition

Fig 1.7 I Surface equator and polar temperatures

1.2.3.2 Radiation

The radiation environment on the Moon differs significantly from that on Earth due to the absence of a protective magnetic field and atmosphere. As a result, the lunar surface is constantly bombarded by high-energy particles, including Galactic Cosmic Ray (GCR) particles and Solar Energetic Particles (SPEs). In addition to primary radiation from the Sun and deep space, secondary radiation is also produced by interactions of these particles with the lunar surface, contributing to the overall radiation environment on the Moon (Reitz et al 2012):

1. **Galactic cosmic rays** (**GCRs**): These are high-energy particles, mainly protons and nuclei, that originate outside the solar system and continuously bombard the Moon's surface. GCRs are a chronic source of radiation exposure that can increase the risk of cancer and other long-term health effects.

2. **Solar particle events** (**SPEs**): These are sudden and intense bursts of energetic particles from the Sun, such as protons and ions. The SPE can reach the Earth-Moon system within tens of minutes to tens of hours, and adequate protection of astronauts on lunar surface is needed.

3. **Secondary radiation**: When high-energy particles from space interact with the lunar surface, they can produce secondary radiation, such as neutrons, gamma rays, and other particles. These secondary radiations can contribute to the overall radiation exposure on the Moon.

4. **Electromagnetic radiation**: In addition to particle radiation, the Moon is also exposed to various forms of electromagnetic radiation, such as ultraviolet (UV) radiation and X-rays. UV radiation can cause skin damage and increase the risk of skin cancer, while X-rays can penetrate deeper into the body and cause damage to internal organs.

On Earth, cosmic radiation adds up to around 1/6 of the total annual natural ionizing radiation dose of 2.4 mSv. On the lunar surface, the yearly exposure due to Galactic Cosmic Rays (GCR) varies, being approximately 380 mSv during solar minimum and 110 mSv during solar maximum (Reitz et al 2012).

1.2.3.3 Micrometeorites

Meteoroids are naturally occurring solid bodies traveling through space that are too small to be called asteroids or comets. Those with diameters less than about 1 mm are commonly classified as micrometeoroids. Meteorites, on the other hand, are meteoroids that have fallen upon a planet and have been recovered. The lunar rock surfaces that were exposed to space contain numerous micro-craters.

The lack of an atmosphere on the Moon makes it vulnerable to meteoroid impacts. These impacts can range in size from small particles to large boulders, and they can leave visible craters on the Moon's surface. Upon impact, a meteoroid can kick up a cloud of dust and debris that can travel for hundreds of miles before settling back down. This creates a secondary impact, which can cause additional damage to the surrounding area. The severity of the impact depends on the size and speed of the meteoroid. Larger meteoroids can create craters several miles in diameter and hundreds of feet deep. These craters provide valuable information about the history of the Moon and the Solar System as a whole. The side of the Moon that is facing the Earth's direction of motion in its orbit around the Sun is more exposed to larger and more hazardous meteoroids. The distribution of meteoroids is fairly well defined based on spacecraft-collected data (Eckart 1999, p. 150).

1.2.3.4 Illuminated Environment

The extent of natural illumination on the lunar surface is highly contingent on its specific location. Each point on the lunar surface experiences an identical lighting progression throughout every lunar day. The angle at which light falls is contingent upon the latitude of the lunar surface site. In the absence of an atmosphere to disperse light, the overall luminosity on the Moon diminishes to the amount reflected by surfaces and objects (Eckart 1999, p. 144).

Some lunar locations defined by Sun illumination are: Permanently Shadowed Regions and Peaks of Eternal Light.

Permanently shadowed regions (PSR) on the Moon are areas that never receive direct sunlight, even during the lunar day. These areas are located near the lunar poles and are permanently shaded because the Moon's axial tilt is almost perpendicular to the plane of its orbit around the Earth, which means that the Sun's rays do not reach the bottoms of some of the polar craters. The temperatures in these permanently shadowed regions can drop to as low as -238 degrees Celsius, making them some of the coldest places in the solar system. These regions are of great interest to scientists because they may contain frozen water and other volatile compounds that have been preserved for billions of years.

The Peaks of Eternal Light on the Moon are regions near the lunar poles where sunlight never fades, due to the way the Moon is tilted and the way it orbits the Earth. These areas are located on the rims of craters near the lunar poles, and they receive almost continuous sunlight because they are situated at an angle that allows them to catch the rays of the Sun even when the rest of the lunar surface is in darkness. Because these regions never experience prolonged periods of darkness, they are of particular interest to scientists and potential future lunar explorers as they may provide a source of constant solar power that could be used to sustain a lunar base or colony (NASA 2021).

1.2.4 LUNAR GRAVITY

Since the mass of a celestial object is directly proportional to the gravity it exerts on other objects or molecules in its atmosphere, the smaller the celestial object, the lower the gravity (or smaller the gravitational field) and the lower the escape velocity. This makes it harder for the celestial object with a relatively small mass to retain an atmosphere (Hassan 2022).

The acceleration due to gravity on the surface of the Moon is approximately 1.625 m/s^2, whereas on Earth is approximately 9.81 m/s^2; only about one-sixth that of Earth and can cause a number of physical challenges for astronauts, such as muscle and bone loss, and difficulties with balance and movement. A person who weighs 45 kg on the Earth would only weigh 7.7 kg on the surface of the Moon (NASA 2021-I). In broad terms, any construction on the lunar surface will exhibit a structural weight-bearing capacity that is six times greater than that on Earth (Seedhouse 2008).

1.2.5 LUNAR RESOURCES AND ISRU

The aim of In-Situ Resource Utilization (ISRU) or "living off the land" is to utilize resources present in space to develop goods and services that can facilitate and significantly decrease the weight, expenses, and risks of both short and long-term space exploration. ISRU holds the potential to enable a sustainable and affordable program for human and robotic space exploration while reducing the cost and risk of lunar exploration and beyond. Although lacking some common resources found on Earth, the moon does offer potentially useful resources that could be useful for future human exploration and settlement, including regolith, solar power, oxygen, and metals, as well as subsurface resources such as water ice, hydrogen, and other volatiles that are located in permanently shadowed regions near the lunar poles (Schrunk et al 2007).

1. **Oxygen:** Oxygen is primarily found on the Moon in the form of oxides, such as silicon dioxide and iron oxide, and in the regolith (soil). This oxygen can potentially be extracted and used for life support systems, propulsion, and the production of water, which can be split into hydrogen and oxygen for rocket fuel (Eckart 1999, p. 591).

2. **Water ice:** Recent scientific studies and data from several spacecraft have indicated the presence of water ice in the polar regions of the Moon. The water ice is thought to be located in permanently shadowed regions on the floors of some of the Moon's polar craters, where temperatures are low enough to keep the ice stable. The presence of water ice on the Moon is of great interest to scientists and space exploration enthusiasts, as it could potentially be used

as a resource for future lunar missions and even for human colonization efforts. Water is a critical resource for sustaining human life, as well as for producing rocket fuel and other materials needed for space exploration (Eckart 1999, p. 127).

3

Solar power: Moon receives abundant sunlight that can be converted into electrical power using solar panels. The lunar surface is illuminated by the Sun for about 14 Earth days during the lunar daytime, followed by about 14 Earth days of darkness during the lunar nighttime. This presents a challenge for continuous power generation, but it can be overcome by using energy storage systems or by placing solar panels in areas that receive near-constant sunlight, such as the polar regions where certain crater rims are exposed to near-constant solar illumination.

4

Regolith: Regolith on the Moon contains various resources, including oxygen, silicon, iron, aluminum, titanium, and helium-3, among others. Oxygen, which is present in high concentrations and estimated to be 45% by weight, can be extracted from the regolith and utilized for purposes such as life support and rocket fuel. Regolith has versatile uses as a building material including shielding for habitats, support for structures and as sintered bricks or construction materials (lunar concrete or glass) (NASA SBIR/STTR 2022).

5

Metals: The moon's crust contains various metals that can be used for building materials or spacecraft components. Iron can be used for manufacturing building materials and machinery, as well as lightweight aluminum and corrosion-resistant titanium for constructing spacecraft and equipment.

6

Other: Although helium-3 is not abundant in the regolith, it is a rare isotope that can be used in fusion reactors to generate clean energy.
The moon also contains various rare minerals, such as ilmenite, which could be used in the production of high-tech devices and electronics (Eckart 1999, p. 592).

1.3 LUNAR MISSIONS

For centuries, the Moon has captivated our imagination. However, it wasn't until modern times that we were able to explore it, using both robotic machines and astronauts. This chapter explores the historical significance, benefits, and potential of lunar exploration, highlighting past, present, and future endeavors and the profound impact they can have on humanity, as lunar exploration remains an important part of human space exploration with endless possibilities. Lunar missions refer to any space exploration mission that involves sending spacecraft to the Moon. These missions can be either robotic or crewed, and they may involve landing on the Moon's surface, orbiting the Moon, or a combination of both.

The history of lunar exploration dates back to the 1950s and 1960s, when the United States and the Soviet Union were in the midst of a space race. The first successful lunar mission was the Soviet Union's Luna 1, which was launched in 1959. Luna 1 was the first spacecraft to reach the Moon's vicinity, and it helped pave the way for future lunar missions. It was followed by Luna 3, which captured the first images of the far side of the moon later that year. These images revealed that the far side had fewer smooth plains than the near side, which was unexpected.

In 1961, the Soviet Union launched the first human into space, Yuri Gagarin. This event marked a turning point in the space race, and it spurred the United States to step up its efforts in space exploration. President John F. Kennedy committed the United States to landing a man on the Moon by the end of the decade. In 1969, the United States successfully sent the first humans to the Moon as part of the Apollo 11 mission. This mission was a landmark achievement in human history, and it demonstrated the incredible capabilities of human ingenuity and technology (National Research Council 2007).

Currently, preparations are underway for humanity's return to the Moon, under the NASA's Artemis Program. There are several international robotic missions set to orbit the moon over the next few years and soft landings planned in the polar regions to map the surface, examine volatile deposits and characterize the unusual environment, ultimately with the goal of learning how to use the moon to support a new and growing spacefaring capability, developing technologies and skills required to live and work on other worlds and opening the solar system for human exploration (Moon NASA 2021).

1.3.1 WHY THE MOON?

The Moon poses a range of captivating challenges, and humanity is gearing up to return to it for the sake of scientific discovery, economic advantages, and inspiring the next generation of explorers. To succeed in our endeavor to reach the Moon and go beyond, meticulous preparation and the participation of various experts are essential. These experts include planetary scientists, engineers, medical researchers, physicists, chemists, mathematicians, mechanics, materials scientists, architects, doctors, communications and safety specialists, computer programmers, and many more. Exploring the Moon is a collaborative global effort, requiring investments from multiple nations to tackle a shared challenge. A vast realm of the unknown awaits our investigation (NASA's Artemis Program 2023).

DISCOVERY

- The Moon will offer scientists new insights into the early Earth, the formation of the Earth-Moon system and the solar system, and how asteroid impacts have affected Earth's past and could shape its future.

- By conducting scientific observations of the cosmos from the Moon and establishing outposts on its surface to adapt to lunar conditions, adventurers and explorers are empowered to expand their exploratory and settlement endeavors to planets and moons that lie beyond Earth.

- A wealth of technological innovation, advancements in robotics, and the creation of methods for utilizing local resources and life support systems (including bacteria, plants, animals, humans, and the biosphere) will decrease potential risks and pave the way for upcoming missions.

ECONOMIC OPPORTUNITY

- Enables significant development of global partnerships, based on international collaborations and challenges to develop a peaceful lunar society
- Moon exploration results in a growing lunar economy by fueling new industries, supporting job growth, and furthering the demand for a skilled workforce that benefit the Earth

INSPIRATION FOR NEW GENERATIONS

- Engaging the public and inspiring the next generation to innovate, to undertake and fulfil our destiny as explorers.
- The Moon serves as a valuable testing ground for technologies, flight capabilities, life support systems, and exploration techniques, reducing risks and improving future missions. Our lunar journey provides a unique opportunity to experience life and work on another world, testing advanced materials and equipment in extreme space conditions. We'll also refine robotic assistance, exploring remote areas and hazardous regions. Establishing a Moon presence enhances life on Earth and prepares us to explore beyond our solar system (Badescu 2012).

1.3.2 APOLLO MISSION

“We choose to go to the moon. We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too” (John F. Kennedy, 1962).

The "We choose to go to the Moon" speech was delivered by President John F. Kennedy on September 12, 1962, at Rice University in Houston, Texas. The speech is considered one of the most famous and influential speeches of the 20th century, as it set the goal of landing a man on the Moon and returning him safely to Earth by the end of the 1960s. In the speech, Kennedy emphasized the importance of space exploration and acknowledged the difficulty and risks of such a mission, but he argued that the benefits of space exploration and technological advancements would be worth the effort.

Apollo missions included the first—and so far only—times that humans have driven on another world. From 1969 to 1972, six Apollo missions successfully landed on the Moon and returned astronauts safely to Earth.

The Apollo 8 flight during Christmas of 1968 marked a significant achievement as it was the first time humans departed low Earth orbit and reached the moon. The crew spent almost a day orbiting the moon and became the first humans to observe it from orbit. Although the moon appeared barren and colorless, they saw no obstacles in the way of a future landing on its surface. In May of 1969, Apollo 10 completed a lunar orbit and tested the lunar lander in a simulation of the upcoming manned landing, serving as a rehearsal for the event.

The first human landing on the moon was the Apollo 11 mission on July 20, 1969. The mission saw the crew of Neil Armstrong, Buzz Aldrin and Michael Collins enter lunar orbit and then land on the Moon's surface in the Mare Tranquillitatis (Sea of Tranquility), close to lunar equtor. Armstrong famously uttered the words "That's one small step for man, one giant leap for mankind" as he became the first human to set foot on the Moon. During their two-hour walk on the Moon, they collected samples of rocks and soil and deployed experiment packages. The mission successfully returned all three astronauts to Earth on July 24 (NASA 2023).

Following the success of Apollo 11, the remaining Apollo missions continued to push the limits of human space exploration. Each mission aimed to explore different regions of the moon and conduct experiments. Apollo 13 faced a major crisis when an explosion in one of the oxygen tanks caused the mission to be aborted, but the crew was able to safely return to Earth. Apollo 14 brought back the largest single rock ever collected from the moon. The final three Apollo missions used the Lunar Roving Vehicle (LRV) to explore farther distances on the lunar surface. LRV was a 4-wheeled electric vehicle designed to carry two astronauts and equipment up to a distance of about 5 miles from the Lunar Module.

Apollo 17 was the final manned mission to the moon, launched in December 1972. Astronauts Eugene Cernan and Harrison Schmitt spent three days on the moon, conducting experiments and exploring the Taurus-Littrow Valley, and Cernan famously left the last footprints on the moon before departing (National Research Council 2007).

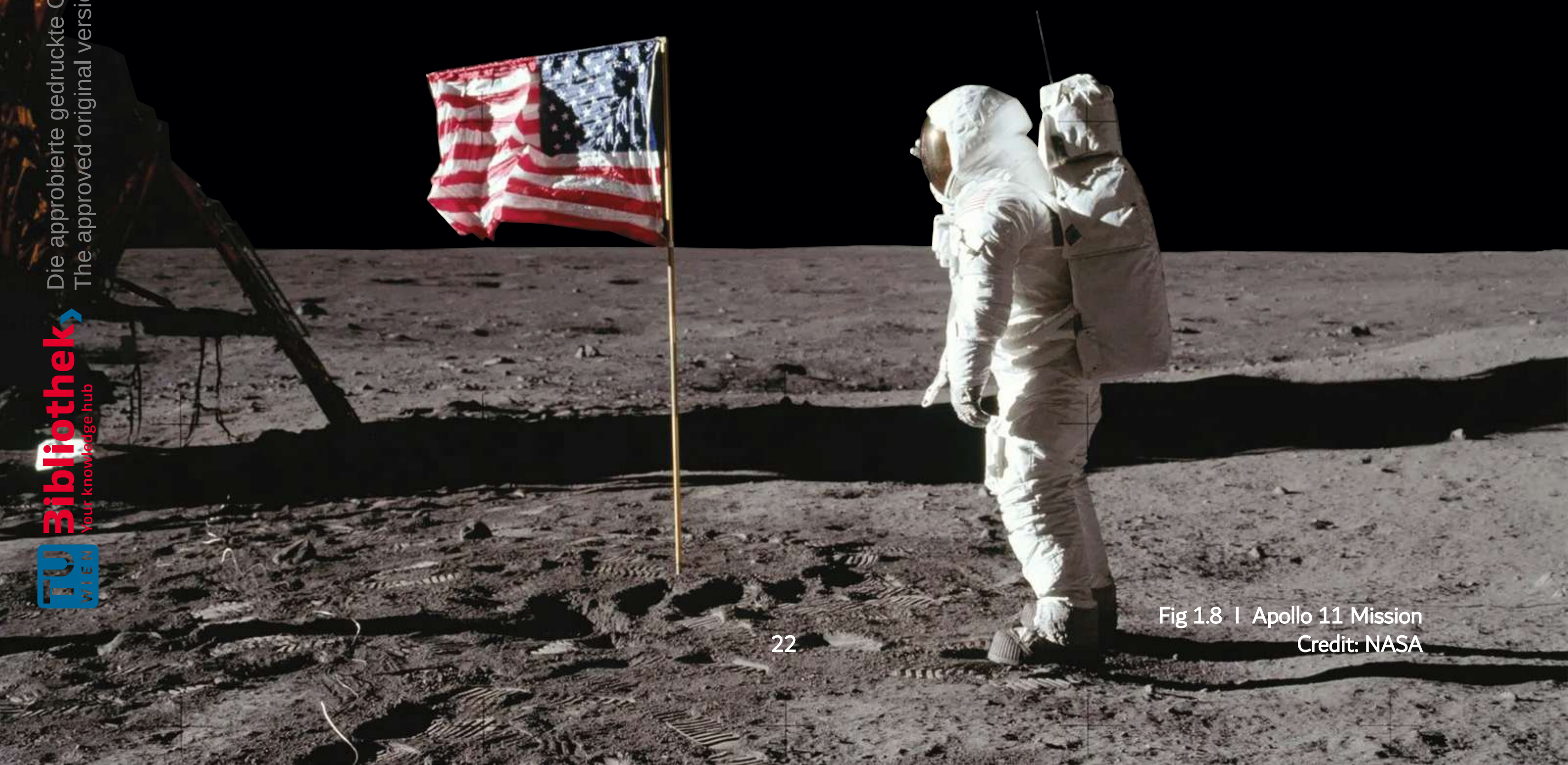


Fig 1.8 I Apollo 11 Mission
Credit: NASA

1.3.2.1 Apollo Mission Timeline

APOLLO 1
January 27, 1967
Astronauts Virgil Grissom, Edward White and Roger Chaffee were killed in a test for the first Apollo mission. This mission was originally called Apollo-Saturn 204, but was redesigned Apollo 1 as a tribute

APOLLO 9
March 3-13, 1969
Test of Lunar Module in Earth orbit
Astronauts: James McDivitt
David Scott
Russell Schweickart
Duration in space: 10:01:00:54
Distance traveled: 4 214 543 miles
Nr. of orbits: 151

APOLLO 11
July 16-24, 1969
First to land and walk on the Moon
Astronauts: Neil Armstrong
Edwin "Buzz" Aldrin
Michael Collins
Time spent on the Moon: 02:32
Duration in space: 08:03:18:35
Distance traveled: 953 054 miles

1967 **1968** **1969** **1970**

APOLLO 7
October 11-22, 1968
First crewed Apollo space mission
Astronauts: Walter Schirra, Jr.
Donn Eisele
Walter Cunningham
Duration in space: 10:20:09:03
Distance traveled: 4 546 918.3 miles
Nr. of orbits: 163

APOLLO 8
December 21-27, 1968
First to fly around the Moon
Astronauts: William Anders
Frank Borman
James Lovell, Jr.
Duration in space: 06:03:00:42
Distance traveled: 579 606.9 miles
Nr. of orbits: 10

APOLLO 10
May 18-26, 1969
Rehearsal for the first Moon landing
Astronauts: Thomas Stafford
John Young
Eugene Cernan
Duration in space: 08:00:23:23
Distance traveled: 829 437.5 miles
Nr. of orbits: 31

APOLLO 13
April 11-17, 1970
Survived oxygen tank explosion
Astronauts: James Lovell, Jr.
Fred Haise, Jr.
Jack Swigert
Duration in space: 05:22:54:41
Distance traveled: 622 268 miles
Nr. of orbits: 1.5

APOLLO 15
July 26- Aug. 7, 1971
First to use lunar rover
Astronauts: David Scott
James Irwin
Alfred Worden
Duration in space: 12:17:12:00
Time spent on the Moon: 18:40
Distance traveled: 1 274 137 miles

APOLLO 17
December 7- 19, 1972
Last to walk on the Moon
Astronauts: Eugene Carnan
Harrison Schmitt
Ron Evans
Duration in space: 12:13:52:00
Time spent on the Moon: 22:05
Distance traveled: 1 484 933.8 miles

1971 1972 1973

APOLLO 12
November 14-24, 1969
First precision landing on Moon
Astronauts: Charles Conrad
Alan Bean
Richard Gordon
Time spent on the Moon: 07:27
Duration in space: 10:04:36:25
Distance traveled: 952 354 miles

APOLLO 14
Jan. 31- Feb. 9, 1971
First landing in lunar Highlands
Astronauts: Alan B. Shepard, Jr.
Edgar D. Mitchell
Stuart A. Roosa
Duration in space: 09:00:00:02
Time spent on the Moon: 09:35
Distance traveled: 1 150 321 miles

APOLLO 16
April 16- 27, 1972
Exploring the lunar highlands
Astronauts: John Young
Charles Duke
Thomas Mattingly
Duration in space: 11:01:51:00
Time spent on the Moon: 20:15
Distance traveled: 1 391 550 miles

Fig. 1.9 I Apollo Mission Timeline

1.3.3 ARTEMIS MISSION

Artemis mission is NASA's program to return astronauts to the lunar surface by 2024, for the first time since the Apollo 17 mission (in 1972). It is a program led by the United States' National Aeronautics and Space Administration (NASA) along with three partner agencies: European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and Canadian Space Agency (CSA) (NASA's Artemis Program 2023).

Artemis seeks to broaden the nation's geopolitical and economic reach by involving international collaborators and private companies in lunar activities. NASA's goal encompasses landing the first woman and individual of color on the Moon, establishing the foundation for a robust, persistent lunar presence that facilitates future missions to Mars. Named after Apollo's twin sister, Artemis plans to create a lasting and strategic foothold at the lunar South Pole, designated as the Artemis Base Camp. Positioned near the Shackleton Crater, this significant installation will serve as a permanent outpost with favorable access to resources such as ice and minerals, contributing to its strategic importance (National Space Council 2018). As part of the Lunar Surface Innovation Initiative, NASA intends to develop technologies that will allow robot and human exploration and in particular by (NASA 2020):

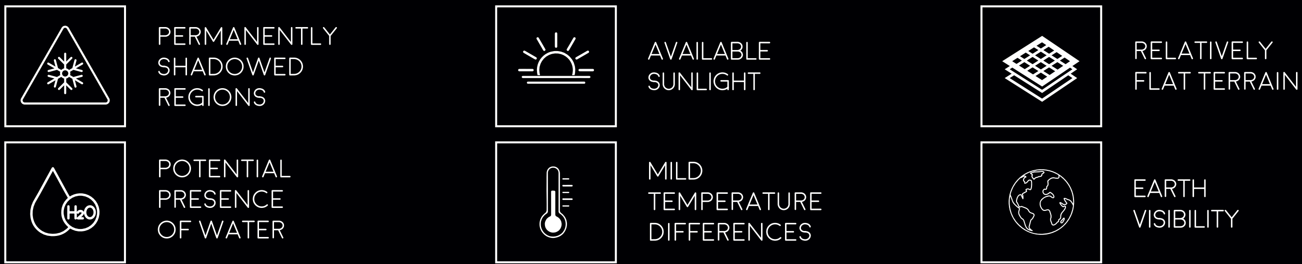
- Utilizing the Moon's resources, known as In Situ Resource Utilisation (ISRU)
- Establishing sustainable power during lunar day/night cycles
- Building machinery and electronics that work in extreme environments
- Mitigating lunar dust
- Carrying out surface excavation, manufacturing and construction duties
- Extreme access which includes navigating and exploring the surface/subsurface

Fig. 1.10 I Partner Agency Logos
Credit: NASA, ESA, JAXA, CSA

1.3.3.1 Artemis Location

NASA aims to explore the uncharted territory of the lunar South Pole, a prime candidate for a future human mission due to its extensively examined robotic assessments. The Lunar Reconnaissance Orbiter (LRO), orbiting elliptically and polarly, approaches the Moon's closest point during its traversal over the South Pole. Over the past ten years and numerous orbits, the LRO has amassed the most accurate data concerning the South Pole area, surpassing all others in terms of insights into its terrain, temperature, and potential icy water deposits (NASA 2019).

A designated South Pole landing site has not been finalized; however, Figure 1.11 displays potential sites near areas of continuous shadow. These locations are significant due to potential mission-enhancing volatile presence. They offer advantages over other lunar spots, including extended sunlight exposure, direct Earth communication, and manageable surface slopes and roughness for landers and astronauts (National Space Council 2018).



The floors of polar craters stay extremely cold due to being in constant shadow, caused by the shallow angle of sunlight in the Moon's polar regions. The Moon's lack of atmosphere also contributes to this coldness. Close to Shackleton crater, there are areas that receive uninterrupted sunlight for over 200 Earth days. If an astronaut stood near the South Pole, the Sun would always be on the horizon, casting light sideways and primarily illuminating the edges of deep craters, while leaving their interiors in darkness. These permanently shadowed craters have some of the solar system's lowest temperatures, reaching around -248 degrees Celsius. Water ice remains stable at these temperatures, and it's believed that these craters contain significant ice deposits (NASA 2019).

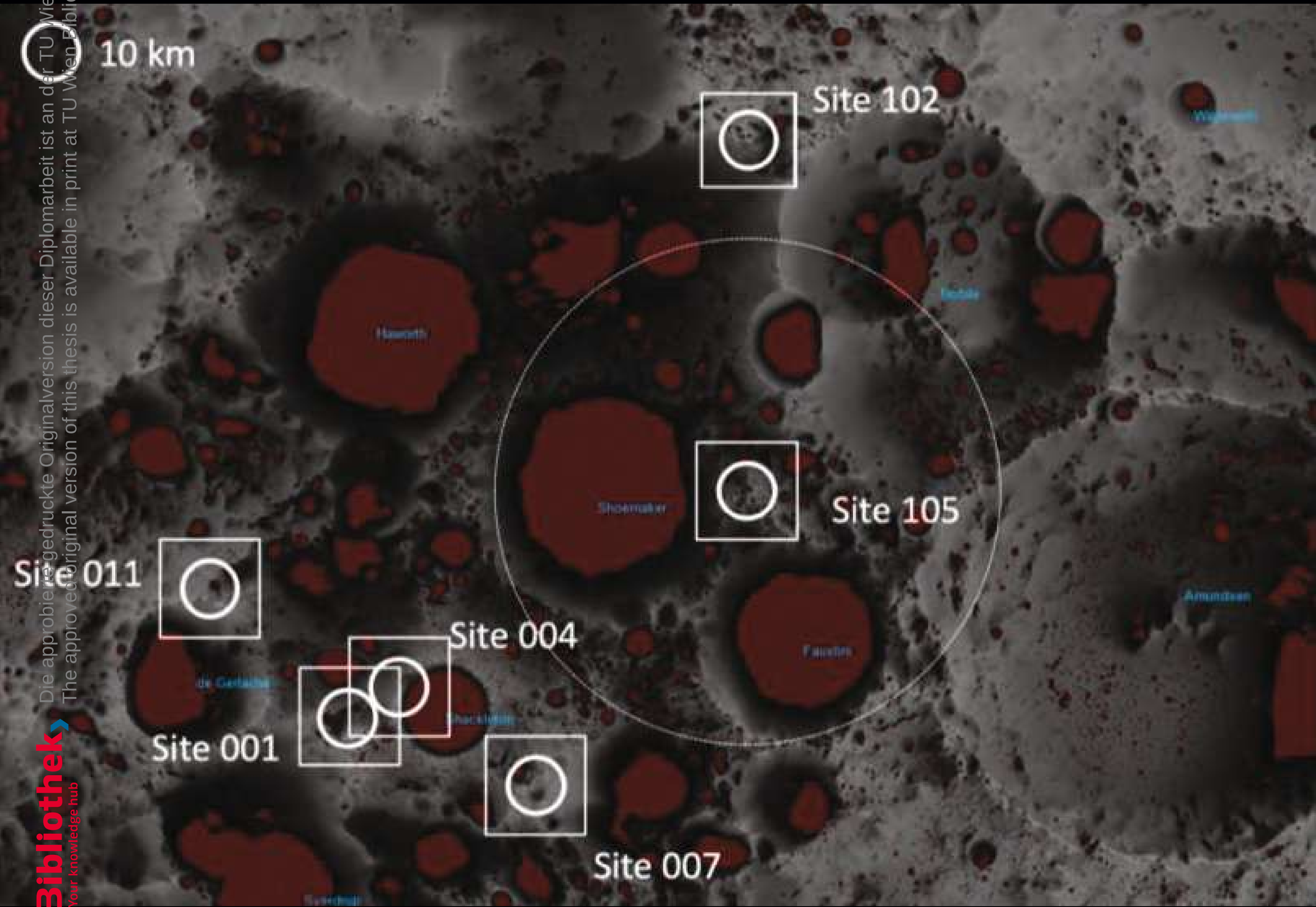


Fig. 1.11 I Lunar South Pole landing sites of interest
Credit: NASA

1.3.3.2 Artemis Timeline

The Artemis program is organized from Artemis I through Artemis V, and beyond (Fig. 1.12) (National Space Council 2018).

Artemis I, an ongoing uncrewed mission, was successfully launched from Kennedy Space Center on November 16, 2022. Its primary goal is to test the Orion spacecraft and its heat shield during a roughly three-week Moon-orbiting mission, in preparation for upcoming Artemis missions. Mission controllers on Earth will gather data to evaluate the performance of both spacecraft.

Artemis II marks the initial crewed flight test of the Space Launch System and Orion. This mission will see astronauts returning to the Moon's vicinity after a gap of over five decades. The fundamental aim is to conduct a lunar flyby lasting up to 21 days using the first crewed Orion MPCV Spacecraft. By the mission's conclusion, NASA aims to have thoroughly tested all hardware, software, and operational elements of Artemis III, barring the final surface landing.

2022 **2023** **2024** **2025**

ARTEMIS **I**
Uncrewed test of the SLS and Orion, marking their inaugural joint test flight. The objective is to deploy Orion into lunar orbit and subsequently bring it back to Earth.

ARTEMIS **II**
Crewed mission for the Orion spacecraft, tasked with executing a lunar flyby trial before returning to Earth.

ARTEMIS **III**
Crewed lunar landing, with two astronauts spending approximately 6.5 days on the Moon's surface. During this time, they will conduct up to four spacewalks, undertake diverse scientific observations, and gather water ice samples.

Artemis III will be the culmination of the rigorous testing that NASA will conduct during Artemis I and II. While four astronauts would leave Earth on board Orion, the surface mission with the Human Landing System (HLS) will consist of two crew members, who will remain on the surface for 6.5 days. The remaining astronauts will stay on board Orion. The two astronauts will conduct up to four spacewalks on the Moon's surface, performing a variety of scientific observations, including sampling water ice. Before the Artemis III landing, some additional equipment will be pre-positioned on the surface, including an unpressurized rover for astronauts to use during their lunar excursions. This rover will have the capability to be controlled remotely.

Artemis IV mission will launch four astronauts on a Space Launch System rocket and an Orion to the Lunar Gateway and the second lunar landing of the Artemis program. The overall plan is to conduct operations on and around the Moon that help prepare us for the mission durations and activities that we will experience during the first human mission to Mars, while also emplacing and building the infrastructure, systems, and robotic missions that can enable a sustained lunar surface presence.

Artemis V through Artemis VIII and beyond are proposed to land astronauts on the lunar surface and seek to reestablish a human presence on the Moon and demonstrate technologies and business approaches needed for future scientific studies, including exploration of Mars (National Space C. 2018).

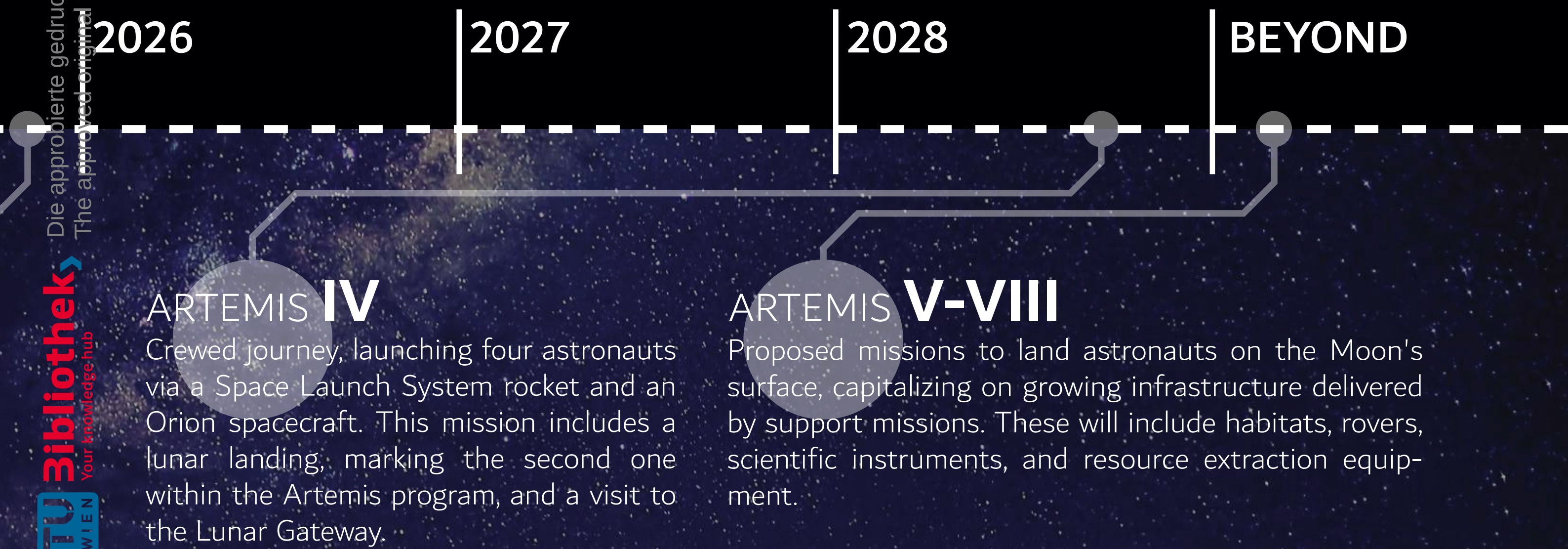


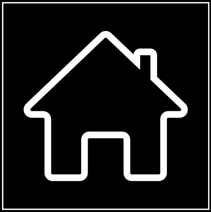
Fig. 1.12 | Artemis Timeline

1.3.3.3 Artemis Base Camp

The Artemis program's goal is to establish a lasting presence on the lunar surface, with the Moon potentially becoming the ultimate destination for exploration. Plans are underway for constructing the Artemis Base Camp, a permanent outpost near the lunar south pole, adjacent to Shackleton Crater. This camp incorporates a **surface lunar habitat**, **a rover**, and **a mobile home**. Initial missions will involve brief surface stays, providing life support systems for short crew visits to the Moon. NASA's vision includes a stable habitat at the Artemis Base Camp, capable of accommodating up to four astronauts for two-month stays in the future (NASA 2022-I).

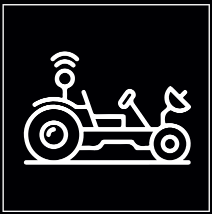
Central to the outpost's triumph and the technology development initiatives will be the capability to transport the essential materials for constructing and assembling the three components of the Artemis Base Camp. Equally essential is the need for sturdy and dependable systems to unload and set up the required supplies, ensuring the facility's prolonged operation. This entails exploring innovative logistics methods that could offer safer, more reliable, and highly efficient approaches for constructing and maintaining a remote Base Camp under the challenges of an extreme and inhospitable environment over several decades (NASA 2020).

Fig. 1.13 I Artemis Base Camp Concept
Credit: NASA



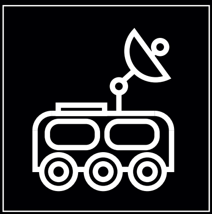
LUNAR HABITAT

The stationary surface habitat, designed for brief visits of a few days (initially), can accommodate up to four astronauts. It's pressurized and equipped with integrated life support systems. To drive forward the essential technologies for Moon habitation and exploration, NASA has initiated the **Lunar Surface Innovation Initiative**. This initiative involves evaluating the capabilities and performance of habitat system prototypes, with human factors teams focusing on layout and ergonomics to enhance efficiency and overall effectiveness (NASA 2021-II).



LUNAR TERRAIN VEHICLE (LTV)

Enhancing mobility on the Moon marks the latest advancement in NASA's Artemis program. The Lunar Terrain Vehicle (LTV) is envisioned as an open-top, unpressurized vehicle capable of carrying astronauts in spacesuits for over 12 miles from their base camp. It's designed as a robotic mobility system for transporting instruments across the lunar surface, enabling vital scientific research over expansive terrains, including areas beyond human exploration. The LTV showcases innovations in electric vehicle energy storage, autonomous driving, and resilience in extreme environments. This vehicle could also follow pre-set routes or be remotely operated from Earth, facilitating additional scientific and exploratory tasks. NASA is in the process of selecting new contractors to design and develop a suitable terrain vehicle (NASA 2020-I).



HABITABLE MOBILITY PLATFORM

Apart from the LTV, a pressurized rover will significantly enhance lunar surface exploration capabilities. With pressurization, astronauts can be inside the vehicle in their regular clothing instead of needing to wear their spacesuits inside as well. This increased comfort allows them to traverse the lunar landscape within their mobile habitat and explore extensive regions. Mobile home, or often referred to as a **habitable mobility platform**, will be a very high tech 'camper van' that will allow astronauts to make long trips for periods as long as a few weeks. NASA is in the early idea stage for a pressurized rover, formulating concepts and evaluating potential science and exploration missions around the South Pole (National Research Council 2007).

02

EXTRATERRESTRIAL ENVIRONMENT AND SPACE ARCHITECTURE

"I am a passenger on the spaceship, Earth."

R. Buckminster Fuller, 1969.

2.1 INTRODUCTION

Designing spacecraft and space and planetary habitats for humans is a complex and fascinating challenge that requres knowledge spanning a range of disciplines: aerospace engineering, architecture and design, human factors design, space sciences, medicine, psychology and art. These disciplines must result in an integrated human-centered system, which should also be reliable, safe and sustainable (Häuplik-Meusburger, Bannova 2016, p. 1). This chapter will explore the unique considerations and challenges of designing buildings in outer space and on planetary bodies, such as environmental factors, human needs, material selection, construction typology, and long-term sustainability:

1 **Environmental Factors:** One of the primary considerations when designing habitats in outer space and on planetary bodies is the unique environmental conditions. Gravity, temperature, radiation levels, and atmospheric pressure can significantly differ from those on Earth. Architects must understand the specific environmental conditions of the location and create structures that can withstand these extremes while providing a comfortable and safe living environment for the inhabitants (Seedhouse 2010, p. 121).

2 **Human Needs and Habitability:** Meeting the physical and psychological needs of the inhabitants is crucial when designing buildings in outer space. Living and working spaces, sleeping arrangements, sanitation facilities, food preparation, and recreational areas must be thoughtfully designed to support the health and well-being of the occupants. Designers should also address the challenges of isolation, confinement, and monotony by creating spaces that foster social interaction and provide opportunities for leisure and relaxation (Häuplik-Meusburger, Bishop 2021, p. 15).

3 **Safety:** Safety is a top priority in designing and building a sustainable space habitat. Emergency protocols, backup systems, and escape routes are critical components that should be incorporated into the design and construction of the habitat to safeguard its inhabitants in case of unexpected events or system failures.

4 **Material Selection:** Selecting appropriate materials for construction is vital for the success of any space architecture project. Materials must be able to withstand the extreme conditions, such as temperature fluctuations, radiation, and micrometeoroid impacts. In addition, architects should consider the possibility of using in-situ resources, such as lunar or Martian regolith, to minimize transportation costs and efforts (Eckart 1999, p. 593).

5 **Construction Typology:** Developing innovative construction methods suitable for the outer space environment is essential. Traditional construction techniques may not be feasible or practical, so alternatives such as 3D printing, robotic assembly, or inflatable habitats should be explored. The use of autonomous or teleoperated robots to perform construction tasks can help reduce the risks and challenges associated with human labor in extreme environments (Kennedy 2000).

6 **Energy Sources and Life Support Systems:** Reliable energy sources and life support systems are critical components of any building in outer space or on planetary bodies. Designers must determine the most suitable energy sources, such as solar panels, nuclear reactors, or radioisotope thermoelectric generators (RTGs), and ensure energy storage and distribution systems are in place. Life support systems, including air filtration, temperature control, water recycling, and waste management, should be designed with redundancy and reliability in mind (Seedhouse 2008, p. 371).

Fig. 2.1 I Moon Village
Credit: SOM & ESA

2.1.1 SPACE ARCHITECTURE DEFINITION

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

This mission statement for space architecture was developed at the World Space Congress in Houston in 2002 by members of the Technical Aerospace Architecture Subcommittee of the American Institute of Aeronautics and Astronautics (AIAA). The manifesto is called "The Millennium Charter" and this document, which was signed by 47 architects, designers, engineers and researchers, declared the fundamental principles of space architecture. It states that space architecture is an interdisciplinary field that organizes and interprets the creation and enrichment of built environments and has complimentary relationships with diverse fields such as aerospace engineering, terrestrial architecture, transportation design, medicine, human factors, space science, law and art.

According to Häuplik-Meusburger and Bannova, space architecture is an interdisciplinary field that encompasses the design of living and working environments in space and on planetary bodies. The precision of technical systems is integrated with human needs for work and living, while also focusing on interface design that fosters harmonious relationships between humans and their built and natural environments (Häuplik-Meusburger, Bannova 2016, p. 2).

Designing environments for space travel poses a unique challenge as it requires consideration of various factors, including radiation, isolation, and microgravity's impact on human physiology and psychology. To ensure and support safety, sustainability, habitability, reliability, and crew efficiency, productivity, and comfort, space architecture requires a fusion of technical, humanistic, and artistic aspects. Designing for humans in extreme environments requires specialized knowledge and a creative approach to create environments that support human life and well-being beyond Earth. The clear and practical focus is to enhance our understanding of creating environments that foster human thriving in space, aligning with humanity's aspiration to explore the universe and turn new spaces into habitable places that support human life and well-being beyond Earth (Häuplik-Meusburger, Bannova 2016, p. 8).

Creating and choosing space architecture concepts requires careful thought. The following diagram (Table 2.1) explores the design considerations for the space environment and their impact on humans, the elements of habitation systems and their connections, the process of analyzing and selecting appropriate habitation systems and their application in different environments (Kennedy 2000).

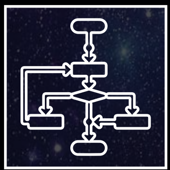
	STEP:	CONSIDERATIONS:
	ASSES ENVIRONMENTAL CONSTRAINTS	• Vacuum • Debris • Gravity • Radiation • Dust
	ASSES HUMAN CONSIDETARIONS	• Psychology • Physiology
	DEFINE HABITATION SYSTEM ELEMENTS	• Internal Subsystems • External Systems and Interfaces
	DETERMINE KEY DESIGN DECISIONS AND TRADES	• Environmental • Human • Subsystem
	ASSES DESIGN APPLICATION	• Orbital • Transfer • Planetary Surface

Table. 2.1 I Space Habitation Design Steps
Credit: Based on Kennedy 2000

2.2 HUMAN FACTORS

Human factors refer to the study of how humans interact with systems, products, and environments. It focuses on understanding human capabilities, limitations, and behaviors in order to design and create systems that are safe, efficient, and user-friendly. This field draws from various areas including psychology, sociology, engineering, biomechanics, industrial design, physiology, anthropometry, interaction design, visual design, user experience, and user interface design, resulting in a varied definition (HFES 2023).

As per NASA's description, human factors covers multiple research domains like human performance, technology design, and human-computer interaction. The study of human factors within NASA's Human Factors Research and Technology Division at NASA Ames Research Center emphasizes the necessity for secure, efficient, and economical operations, maintenance, and training in both flight and ground scenarios (NASA 2010).

The exploration of space is one of the most fascinating domains to study from a human factors perspective. The goal is to optimize the design and functionality of systems and products to enhance user experience and minimize errors or risks associated with human interaction.

The image of the Vitruvian Man depicted on Figure 2.2, created by Leonardo da Vinci, can be analyzed from the perspective of human factors and ergonomics due to its depiction of human proportions and movement. The Vitruvian Man melds humanism, geometry, anatomy, and art. The circle and square, symbolic of the divine and earthly, along with the figure's arrangement, mirror the Renaissance humanist view that the human body mirrors the universe, embracing microcosm within (Encyclopædia Britannica 2023).

From a human factors perspective, the image demonstrates the concept of anthropometry, which involves studying the measurements and physical characteristics of the human body. The Vitruvian Man's arms and legs are extended, illustrating the idea of an outstretched and dynamic posture. This suggests the human body's capability to reach and interact with the environment efficiently. Moreover,

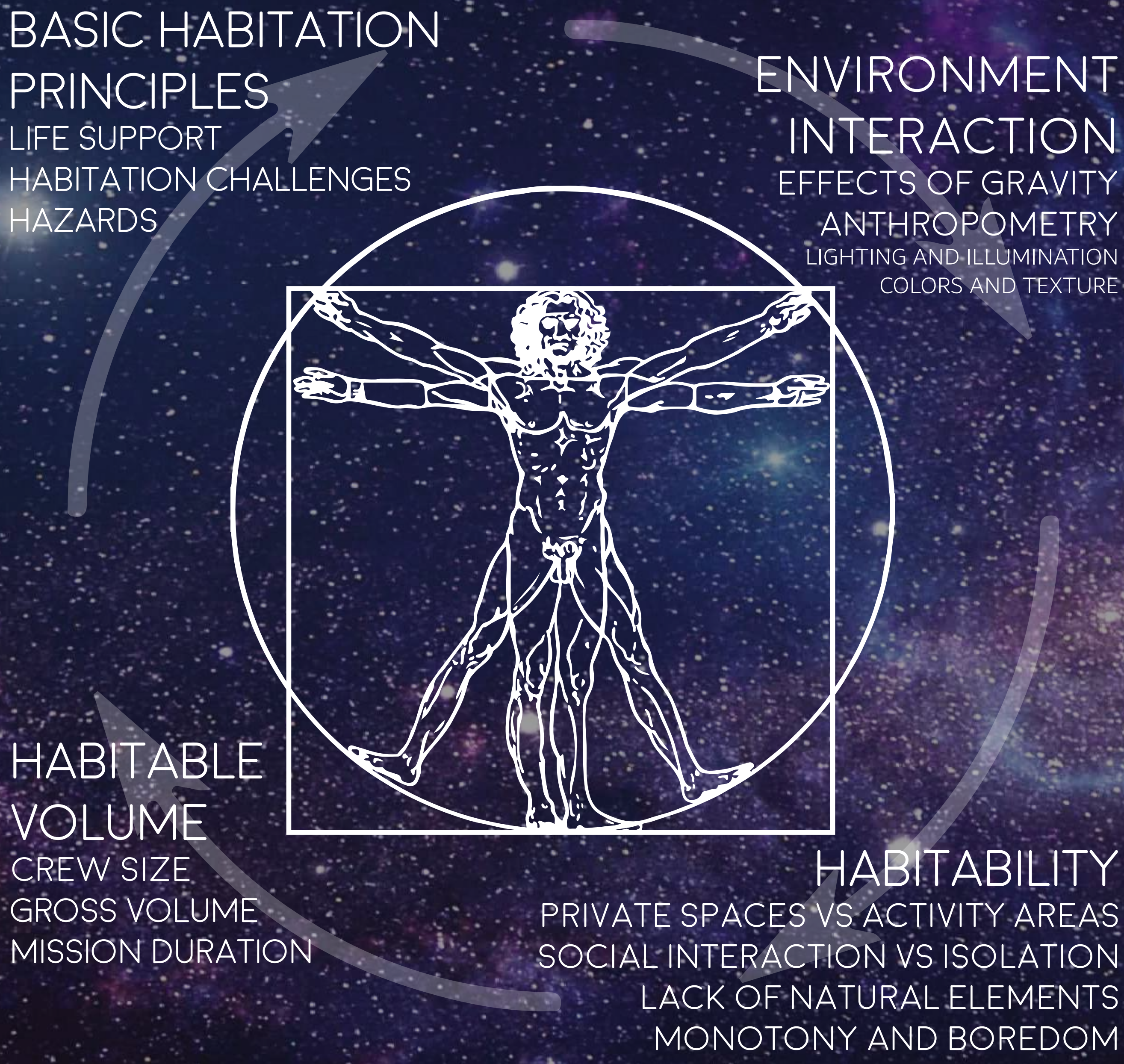


Fig. 2.2 I Vitruvian Man in context Human Factors

it reflects the ergonomic principle of functional fit, which focuses on designing systems and objects that align with human capabilities and limitations. The positioning of the figure within the circle and square implies the ideal proportion and balance for optimal performance and comfort. This concept goes with the ergonomic goal of creating environments, products, and interfaces that promote ease of use, reduce fatigue, and enhance overall well-being.

2.2.1 BASIC HABITATION PRINCIPLES

Space habitats serve as a re-creation of Earth's environment within the inhospitable space environment, enabling the sustenance of human life. Habitats are pressurized crew volumes including areas where astronauts can live, conduct experiments, and perform maintenance tasks. However, space habitation faces challenges due to the lack of air, presence of debris and dust, the absence of gravity (in orbital missions), and exposure to radiation. Their concept development and selection requires careful consideration (Kennedy 2000).

Basic habitation principles encompass essential considerations for designing space habitats and human missions, including understanding space habitat requirements, acknowledging contrasting conditions to Earth, exploring food systems, and comprehending the environmental impact on physiology, anthropometry, and operations. It is crucial to have a solid understanding of these design requirements early in the design process for human missions. Table 2.2, displaying the “Life Support and Habitation Challenges and Hazards”, was sourced from Chapter 4 of the book "Space Architecture Education for Engineers and Architects" by Häuplik-Meusburger and Bannova (2016, p. 103) and provides an introduction to the most significant issues and design drivers, serving as a guideline to support further research in the field of space habitation design. While not exhaustive, it lays the foundation for addressing key considerations and ensuring the success and safety of future space missions.

	CHARACTERISTIC	IMPLICATIONS
LIFE SUPPORT AND HABITATION CHALLENGES	ATMOSPHERE	To ensure human survival, a habitable environment necessitates the provision of a breathable atmosphere. Outer space, with its vacuum conditions, and the Moon's surface, lacking an atmosphere, cannot sustain human life. NASA's standard for long-term habitation aligns with sea-level conditions, primarily composed of Nitrogen (78%), Oxygen (21%), Argon (0.9%), and a small amount of carbon dioxide (0.03%).
	THERMAL ENVIRONMENT AND HUMIDITY	Structures positioned in outer space undergo significant temperature variations ranging from extreme cold to extreme heat. Without adequate protection, these conditions are unsuitable for human survival. It is crucial for habitats to provide a controlled environment resembling Earth's comfortable conditions, enabling the crew to operate instruments and conduct experiments comfortably.
	NUTRITION	Nutrition for astronauts in space involves meticulously planned and specially prepared meals that provide balanced and adequate nutrients to support their health and well-being. These meals are designed to meet the specific dietary requirements of astronauts while considering the challenges of limited food choices, and water availability.
	HYGIENE AND WASTE COLLECTION	Maintaining hygiene and waste collection in space and on the Moon requires careful management systems to ensure cleanliness and proper disposal. Specialized technologies and protocols are implemented to handle waste, including human waste, and to maintain a clean and sanitary environment for the crew's health and well-being.
HAZARDS	MICROMETEOROIDS AND DEBRIS	Micrometeoroids and debris pose significant hazards to humans in space due to their high velocity and potential for collisions. These small but fast-moving objects can cause damage to spacecraft, habitats, and spacesuits, endangering the safety of astronauts and equipment, requiring measures to maintain the well-being of astronauts.
	MICROGRAVITY	Micrgravity poses hazards to astronauts as it can lead to muscle and bone loss, cardiovascular deconditioning, and changes in fluid distribution within the body. These effects can impact astronaut health and require countermeasures such as exercise, specialized equipment, and medical interventions to mitigate the risks associated with prolonged exposure to micrograivty.
	RADIATION	Radiation in space, including Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPE), poses a substantial hazard to humans during space missions. Exposure to these types of radiation can increase the risk of cancer, damage DNA, and lead to acute radiation sickness, emphasizing the need for effective shielding and mitigation strategies to protect astronauts and ensure their long-term health and safety.
	OTHER	Potential hazards in space may encompass biological threats of unknown nature, including uncertainties surrounding the chemical composition of soil or dust, as well as physical qualities like the electrostatic properties, particle sharpness, and cohesiveness.

Table 2.2. I Basic Habitaiton Principles
Credit: Häuplik-Meusburger and Bannova

2.2.2 HUMANS AND ENVIRONMENT INTERACTION

Humans and environment interaction in the context of space exploration involves understanding the influence of gravity on the human body and its implications for designing habitats and equipment. Gravity plays a crucial role in human physiology, affecting bone density, muscle strength, cardiovascular function, and more. Design solutions for habitats and equipment need to consider these effects to counteract the negative consequences of microgravity or partial gravity conditions. Anthropometry, the measurement of human body dimensions, plays a critical role in space design and equipment development. Designing spacesuits, workstations, and living quarters that accommodate the unique anthropometric requirements of astronauts ensures comfort, functionality, and efficiency and optimizes human performance, safety, and well-being during space exploration missions (Häuplik-Meusburger, Bannova 2016, p. 111).

2.2.2.1 Effects of Gravity

Gravity levels significantly impact the design of space facilities, posing complex physical and psychological challenges for astronauts accustomed to Earth's conditions. Designers bear the responsibility of creating safe and comfortable facilities that promote health, safety, performance, and comfort. Spacecraft designers encounter varying gravity conditions, necessitating substantial design differences. This subchapter provides an overview of spacecraft architecture and human factors considerations for different gravity conditions, including partial gravity (Moon and Mars) and microgravity (low Earth orbit). When gravity conditions differ from those on Earth, notable effects on human activities can be observed. Insights from missions in Earth orbit and on the lunar surface have provided valuable lessons regarding the effects of altered gravity on design (Häuplik-Meusburger, Bannova 2016, p. 111).

Effects of microgravity environment:

- Weightlessness does permit astronauts to use space three-dimensionally and in all directions
- It is much easier to pull the feet to the chest then to bend over
- A person may be stranded in the middle of a large space module if there are no means provided to pull to or push from for propulsion

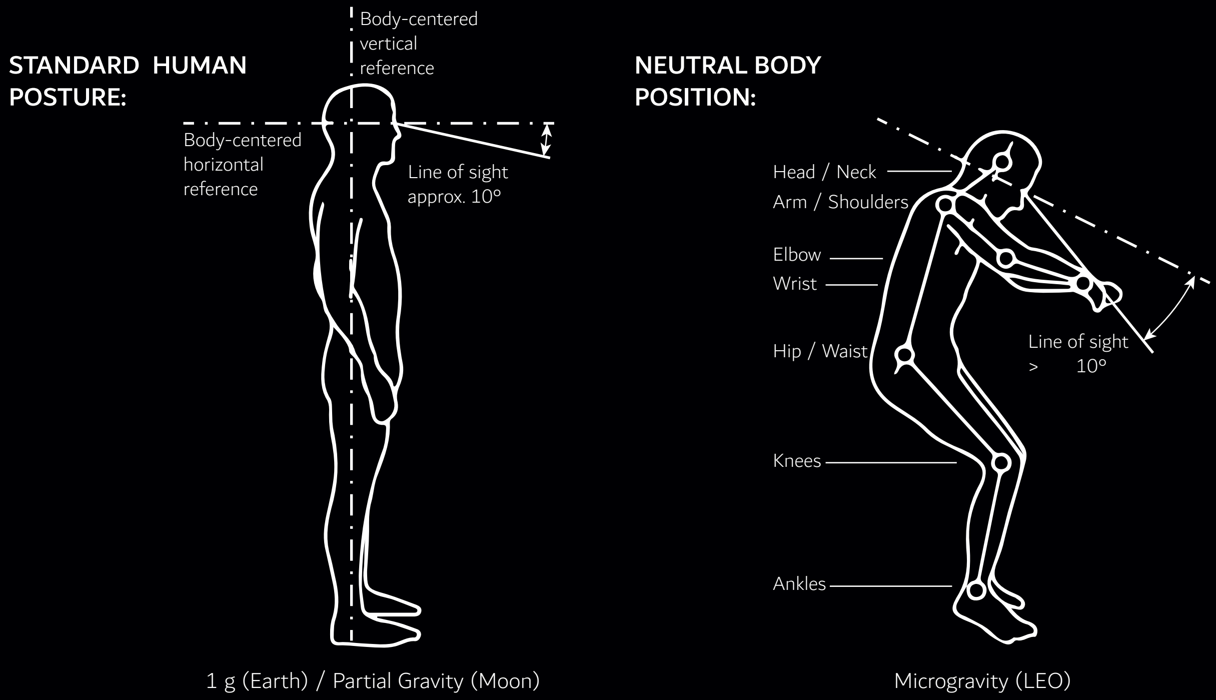
Effects of partial gravity (Moon):

- Human walking and running speed is reduced by 40% compared to Earth
- The stepping rate is lower than on Earth
- Humans experience a decreased ability to change direction quickly
- Stopping and turning become challenging
- The lack of traction poses mobility challenges for surface vehicles

Variable gravity conditions impact individual performance, human-equipment interaction, and engineering design. Even short-term space missions have shown changes in bone, muscle, and brain neurophysiology, as exemplified by long-term Russian Mir and US Skylab missions. These missions uncovered psychological changes, including bone deterioration, fluid shifts, and muscle atrophy, underscoring the importance of exercise accommodations to mitigate adverse health effects in microgravity environments.

2.2.2.2 Anthropometric Design

Establishing an appropriate gravity regime and integrating ergonomic design is crucial for creating functional living and working spaces, especially in the unique microgravity environment that deviates from Earth's familiar conditions. Different gravity conditions not only affect the human body but also impact design and engineering considerations. Figure 2.3 illustrates the neutral body position observed in microgravity, offering a comparison to the standard human posture observed in Earth’s gravity or partial gravity conditions (Moon). The neutral body position is defined by a relaxed and elongated posture with joints naturally aligned. In a partial gravity environment, spatial orientation resembles that of Earth, where the downward and upward directions are influenced by gravity, resulting in individuals often working in a standing position with their heads held upright (Häuplik-Meusburger, Bannova 2016, p. 114).



Key design interventions for reduced gravity can be summarized as following (Häuplik-Meusburger, Bannova 2016, p. 115)**:**

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

Fig. 2.3. I Standard Human Posture and Neutral Body Position
Credit: Häuplik-Meusburger 2011

2.2.2.3 Other Environmental Factors

1 LIGHTING AND ILLUMINATION

Lighting and illumination are crucial environmental factors in space exploration, particularly concerning the regulation of the circadian rhythm. They help synchronize the sleep-wake cycle and other physiological functions, promoting healthy sleep patterns and overall well-being. Proper lighting design and illumination levels optimize performance, ensuring quality sleep and enhancing cognitive function. Additionally, lighting conditions have psychological effects, influencing mood and creating a positive and stimulating environment. Effective lighting is vital for task performance, providing adequate visibility for critical operations and ensuring crew safety (Häuplik-Meusburger, Bannova 2016, p. 118).

2 COLORS AND TEXTURE

It is crucial to acknowledge that individuals can be either visual or vestibular dominant, and for visual dominant individuals, colors play a significant role in spatial orientation. Considering the impact of colors and textures on psychological well-being, visual stimulation, wayfinding, and design differentiation, integrating these factors into space exploration design becomes essential for creating an aesthetically pleasing, functional, and supportive environment for astronauts during their missions. Colors can be employed in diverse ways, including (Häuplik-Meusburger, Bannova 2016, p. 118):

- **Spatial Orientation:** to improve coordination, orientation, and guidance
- **Color-Coding:** to enhance the visibility of specific items in contrast to the background
- **Comfort and Spaciousness:** to enhance the feeling of comfort and the feeling of spaciousness

2.2.3 HABITABILITY

Habitability is a term that describes the suitability and value of a built habitat for its inhabitants in a specific environment (Häuplik-Meusburger 2011). It is a complex system related to the individual as well as society in relation to the (built) environment. Figure 2.4 illustrates the interconnectedness between inhabitants and their lived-in environment, capturing the interrelation between individuals or groups and the built and natural surroundings. (Häuplik-Meusburger, Bishop 2021, p. 4)

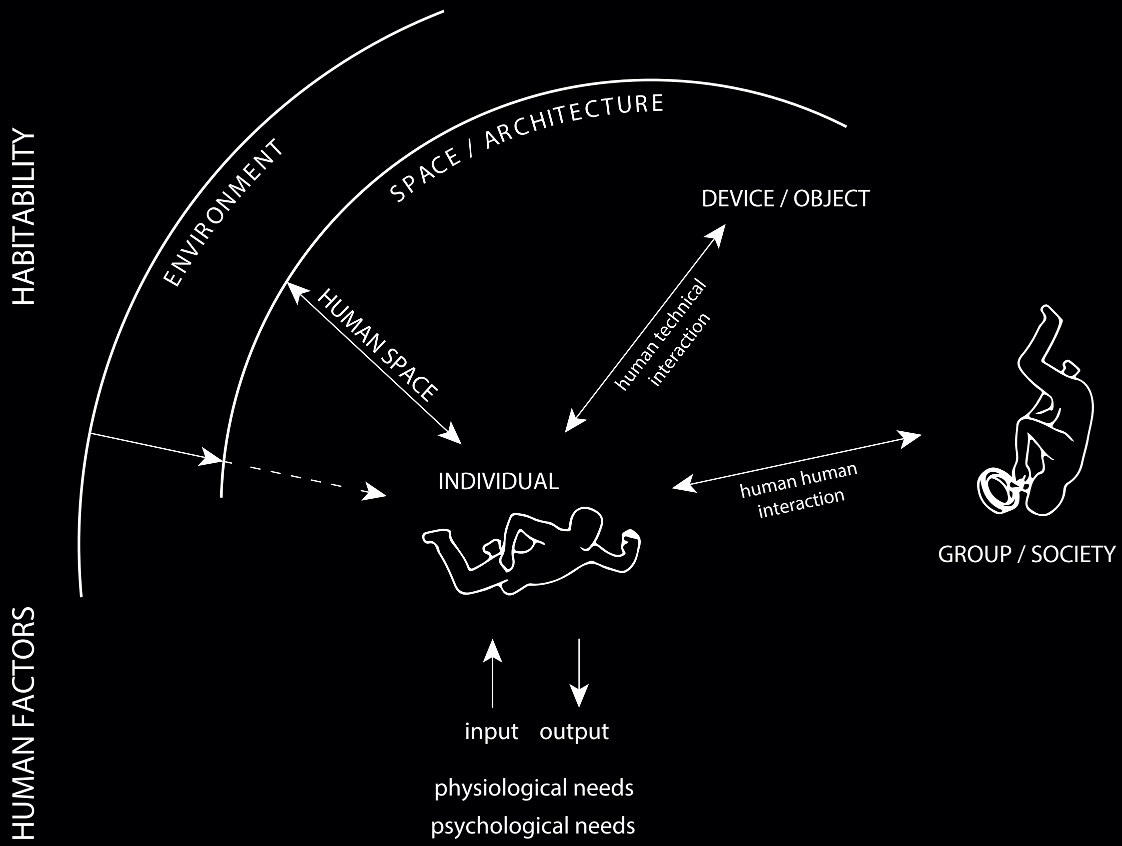


Fig. 2.4 I The Habitability system
Credit: Häuplik-Meusburger, Bishop 2021

Habitability encompasses the conditions, factors, and features that contribute to the well-being, comfort, and functionality of individuals or groups living and working in a given space or place. Creating habitable environments is crucial for supporting human health, performance, and overall well-being in different settings, including space exploration, underwater habitats, extreme climates, and more.

Components of the Habitability system (Fig. 2.4) include (Häuplik-Meusburger, Bishop 2021, p. 4):

- **The Setting:** The environment in which human-operated missions occur poses life-threatening challenges and demands that impact individuals physically, psychologically, and socially. As mission durations lengthen, the psychological strain on both individual crew members and the entire crew intensifies. Furthermore, longer missions necessitate more advanced technological requirements for the habitat and associated systems. Subcomponents encompass factors such as the actual environmental conditions, mission duration, tasks, habitat type, and other relevant aspects.

- **The Individual:** Individuals chosen for space missions represent a limited range of our society. They undergo a meticulous selection process based on specific criteria, which involves both excluding individuals with physical and/or psychological disabilities and including those with desirable attributes such as knowledge, experience, and compatible personalities. Subcomponents encompass factors such as the physical and psychological well-being of individuals, their behavioral health, previous experience, and other relevant considerations.

- **The Group or (Micro)society:** In extraterrestrial habitats, a compact group of individuals resides together within a relatively confined space, forming what is commonly known as a microsociety. Cut off from the usual social fabric of Earth, social relationships in such environments often intensify, giving rise to interpersonal challenges for the entire group. Subcomponents encompass various factors, including crew composition, selection processes, gender dynamics, cultural influences, and more.

- **The Time:** Mission duration impacts every aspect of the system, including the individual, the entire group, as well as the habitat and technical infrastructure. Subcomponents encompass factors such as the length of the mission, alterations that occur throughout the mission, and the scheduling considerations involved.

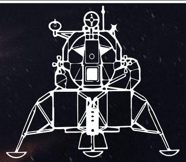
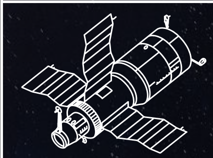
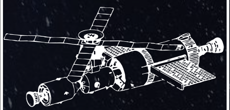
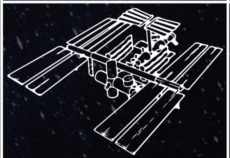
STATION	DESCRIPTION	SLEEP	HYGIENE	FOOD	WORK	LEISURE
 APOLLO LM	Lunar Module (LM) was the lunar lander spacecraft during the Apollo program; crew: 2	In main module	In main module	In main module	In main module. Outside on the lunar surface (EVAs)	In main module. Outside on the lunar surface
 SALYUT	The first space station programme, by the Soviet Union; crew: 4	In main module	Deployable shower and personal hygiene in work area. Toilet close to work area	Wardroom with table in work area	Instrument area could be partitioned from living area. EVAs	Exercize and recreation in main module
 SKYLAB	Frst USA space station, launched by NASA, from 1973 to 1974; crew: 3	Spatially separated in private crew quarters	Collapsible shower in work area. Spatially separated hygiene area	Spatially separated wardroom for food prepara-tion and dining	Experiment area and Dome in the OWS. EVAs	Dedicatd area for exercize in work area. Private Crew quarters
 SHUTTLE	Retired, partially reusable LEO spacecraft system operated from 1981 to 2011 by NASA; crew: 2-7	Mission depen-dant: In main module (sleeping bags) or spatially separated area (sleep boxes)	No dedicated area for advanced per-sonal hygiene. Separate toilet area	No dedicated area for dining; galley rack for food preparation	In main volume. EVAs	Exercize and recreation in work area (Middeck, Flight Deck)
 MIR	First modular space station from 1986 to 1996. Operated by the Soviet Union; crew: 2-3	Spatially separated in individual cabins	Permanent shower in Kosmos. Toilet with curtain in core module	Food cabinet with table in work area	In core module and dedicated science modules. EVAs	In core module and dedicated science modules. EVAs
 ISS	The largest modular space station in LEO, occupied since November 2000; crew: 7	Spatially separated in individual crew quarters	No shower. Two toilet compartments	Food cabinet with table for all astronauts	Dedicated modules and rack system. EVAs	Exercize in work area, but in different modules. Recreation in crew quarters

Table 2.3 I Allocation of activities in space habitats
Credit: Based on Häuplik-Meusburger, Bannova 2016

2.2.3.1 Private Spaces Versus Activity Areas

Psychologist Robert Sommer introduced the concept of "personal space" in the 1960s, defining it as an intangible boundary surrounding a person's body that others should not intrude upon. The perception of privacy can vary based on an individual's social and cultural background. In the confined setting of a space module, ensuring an adequate level of privacy can be challenging and necessitates appropriate design considerations (Häuplik-Meusburger, Bannova 2016, p. 109).

Designing space habitats that strike a balance between private spaces and activity areas is essential for creating functional and comfortable environments for astronauts during long-duration space missions. One key aspect to consider is the balance between private spaces and activity areas within the overall spatial arrangement. Exploring the importance of functional activity areas zoning and layout in relation to private spaces, this discussion focuses on the challenges and considerations of achieving an optimal design that enhances the well-being and productivity of astronauts. Function allocation, as shown in Table 2.3 outlines the allocation of basic function activities in past and present space habitats. The interior layout of a habitat is organized based on the functional needs of the crew, including working, hygiene, food preparation, and leisure/exercize. For instance, crew quarters are considered private domains and are typically situated in quiet areas within the habitat. The specific arrangement of diagrams depends on the mission's requirements and can vary accordingly.

2.2.3.2 Social Interaction Versus Isolation

During long space missions, humans are isolated from their normal social environment and placed in a microsociety that becomes their entire world. This is unlike their usual life on Earth, where they are connected to family, friends, organizations, and society at large. They experience a complete separation from their usual social environment, necessitating specific privacy considerations within habitats. The profound psychological and social effects of isolation and confinement are significant. To support the crew's psychological well-being, social interaction plays a crucial role, and this can be facilitated through design interventions and architectural solutions (Häuplik-Meusburger, Bannova 2016). The design process involves understanding user needs, the design environment, and mission objectives, and translating them into functional relationships that generate multiple design solutions. By defining design requirements and estimating parameters, the design options can be narrowed down quickly, allowing for focused design development and analysis of a reduced number of alternatives (Kennedy 2000).

2.2.3.3 Monotony and Boredom

Monotony is another significant element that contributes to the sense of confinement. The most pronounced sources of stress in isolation and confinement stem from the monotonous and tedious nature of low workloads, limited stimulation, restricted social interactions with loved ones, and an unchanging environment. In space, where seasons, varying weather conditions, and dynamic lighting are absent, as well as in polar regions where such changes are minimal, the experience of monotony and boredom becomes particularly profound.

According to psychologist Vladimir Gushin from Russia's Institute for Biomedical Problems, the issue in confinement on the space station is not the confinement itself, but rather the lack of stimuli (Häuplik-Meusburger, Bishop 2021). Regardless of how initially exciting and novel an environment may be, familiarity breeds a loss of stimulation and an increase in the perception of monotony. When experiences become repetitive and devoid of variation, they are perceived as dull, tedious, and uninteresting. Such unstimulating environments lead to disassociation, reduced monitoring, and diminished situational awareness, focus, and attention. In closed-loop technological environments, boredom can result in decreased vigilance, potentially leading to the oversight of critical indicators and warnings. Interestingly, even a change in the environment, even if it initially worsens, is viewed as a positive stimulus based on Soviet ground-based experiments (Häuplik-Meusburger, Bishop 2021, p. 214).

2.2.3.4 Lack of Natural Elements

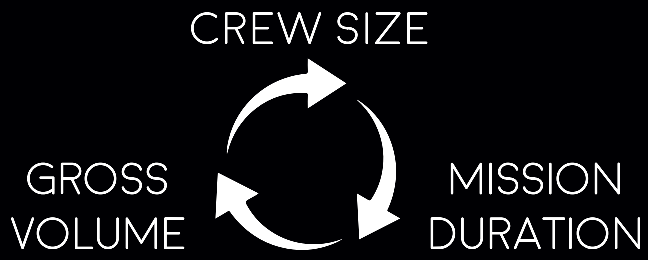
An extraterrestrial habitat, being artificial, differs significantly from the natural world on Earth. Notably, it lacks the green richness of plant life, which includes vivid colors, diverse textures, enchanting aromas, growth, and food production. While the discovery of even basic extraterrestrial lifeforms is meaningful, the absence of the nature found on our home planet has profound implications for extraterrestrial habitation in our solar system. These implications deserve further investigation and consideration.

Integrating plants into the design of extraterrestrial habitats (Fig. 2.5) can offer valuable noninvasive and passive countermeasures against the negative impacts of confinement and monotony. Through sensory and spatial enhancement, plants have the potential to transform the otherwise technical and monotonous space environment, mitigating the detrimental effects and creating a more stimulating and enriching atmosphere. Greenery is not only restorative but also aligns with our evolutionary predisposition for optimal cognitive functioning in environments rich in botanical complexity. To create surprise, harmony, and complexity within interior habitat environments, integrating natural design elements based on bionomic principles can be a key approach. The inclusion of natural properties in building and interior design is widely acknowledged for its psychological and sensory integration benefits. Nature's intricate and varied characteristics have been consistently found to have positive effects on human functioning, offering desirable visual complexity and promoting relaxation and stress reduction. This connection with nature, known as 'Biophilia,' stems from our ancestral relationship with the natural environment that nurtured our evolution (Häuplik-Meusburger, Bishop 2021, p. 220).

Fig. 2.5 I ATRIO Library
Credit: ATRIO Authors

2.2.4 HABITABLE VOLUME

Psychological considerations in habitat design are influenced by the duration of the mission and the number of crew members. Longer missions necessitate greater provisions for crew privacy and recreational activities. Additionally, larger crew sizes introduce challenges related to human solitude, increased complexity of interpersonal interactions, and social dynamics. This section explores the impact of mission duration and crew size on habitability and the corresponding requirements for privacy.



1 MISSION DURATION

Space habitats can be divided into three categories based on duration; short (days to weeks), medium (weeks to months), and long (months to years), with requirements visible in Table 2.4 For missions lasting from a few days to a couple of weeks, crew members can share living quarters through rotating shifts, and the need for recreational, exercise, and dining spaces is reduced due to the limited duration and shift rotation (Kennedy 2007).

For missions lasting up to six months, crew members require their own private sleeping quarters and dedicated spaces for personal recreation and communication with loved ones. Adequate volume is needed for grooming and personal hygiene, and there is a greater demand for dining, recreation, exercise, and meeting areas as crew members work standard shifts.

During missions lasting six months or longer, providing crews with the essential "comforts of home" becomes crucial. Individual crew members necessitate private sleeping quarters equipped with personal storage, dressing areas, and sitting areas. Moreover, the need for ample recreational and exercise facilities increases, and a comprehensive health maintenance facility becomes essential. Aditionally, long-duration space habitats impose demanding requirements on space stations, transfer vehicle systems, and planetary surface systems to ensure the well-being and functionality of the crew (Kennedy 2007).

MISSION DURATION		TOTAL PRESSURIZED VOLUME	RECOM. VOLUME FOR CREW: 4
SHORT:	3-14 days	5 - 15 m³ / crew	20 - 60 m³
MEDIUM:	2 weeks - 4 months	30-50 m³ / crew	120 - 150 m³
LONG:	over 6 months	60 - 80 m³ / crew	240 - 320 m³

2 GROSS VOLUME

By analyzing historical data and combining it with International Space Station (ISS) data, habitation volumes can be categorized into **minimum tolerable limits**, **minimum performance limits**, and **preferred limits** (Fig. 2.6). These rules-of-thumb serve as a starting point for medium-duration missions. For short-duration missions, the estimations can be roughly analogous to the Space Shuttle, while limited data is available for determining volumes in long-duration missions. When determining the initial volume requirements, it is advisable to consider a parametric range of volumes based on the mission objectives and requirements.

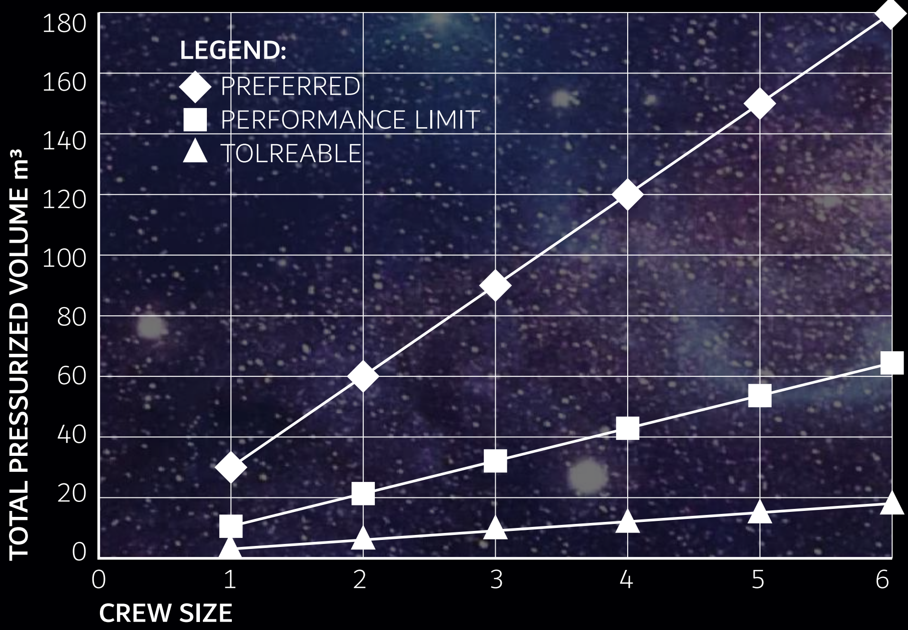


Table 2.4 I Space Habitat Recommended Crew Size
Credit: Kennedy 2007

Fig. 2.6 I Habitable Volume for Increasing Crew Size
Credit: Kennedy 2007

2.3 HABITAT STRUCTURAL SYSTEMS

Space habitats are sophisticated pressurized structures designed to protect and accommodate human occupants, making them invaluable cargo. These habitats, serving as the fundamental elements for support systems in transportation and permanent installations such as space stations and future planetary bases, are complex, substantial, and costly. Given their critical role, the development and selection of space habitats require careful consideration and assessment.

According to Kennedy (2007), habitats are divided into three distinct classifications: **Class I**, **Class II** and **Class III**.

1 CLASS I

Class I habitats are pre-integrated structures that are manufactured on Earth. They are constructed, fully outfitted, and thoroughly tested prior to launch. Once in space, they are capable of immediate operation. However, these habitats have limited volume and mass, as they must adhere to the payload size and mass capacity of the launch vehicle.

2 CLASS II

Class II encompasses pre-fabricated structures that are manufactured on Earth. They require assembly or deployment in space or on the surface. The assembly process involves both robotic and human involvement, requiring time and coordination. These habitats have the capability for partial integration of subsystems, and some or all of the internal outfitting is done during assembly. Critical subsystems are tested on Earth before launch, and the habitat needs to be assembled before it becomes operational. Unlike Class I habitats, Class II are not restricted to the size or mass limitations of the launch vehicle.

3 CLASS III

Class III habitats are derived and constructed using resources available in the target location, such as the Moon or Mars. They are manufactured in-situ, utilizing space resources. The construction process requires manufacturing capabilities and infrastructure on-site. Both robotic and human involvement is necessary during the construction phase. Subsystems need to be integrated, and all internal outfitting is done on-site. Critical subsystems are tested on Earth before launch, and the habitat requires assembly to become operational. Class III habitats have the potential for larger volumes and are not restricted by the size or mass limitations of the launch vehicle.

2.3.1 HARD-SHELL STRUCTURES

A commonly used approach in space habitats is the fabrication of a free-standing hard shell or a conventional pressurized module, which consists of a primary and secondary structure. This module type is prevalent in the International Space Station (ISS module, Fig. 2.7). The primary structure of the module ensures the structural integrity of the pressurized envelope, incorporating components such as ring frames, longerons, pressure shells, windows, and other integrated elements. On the other hand, the secondary structure of the module transfers structural loads to the primary structure and can be present internally or externally. For instance, the racks inside the ISS module serve as an example of asecondary internal structure, while the handrails used for extravehicular activities (EVA) assistance represent a secondary external structure.

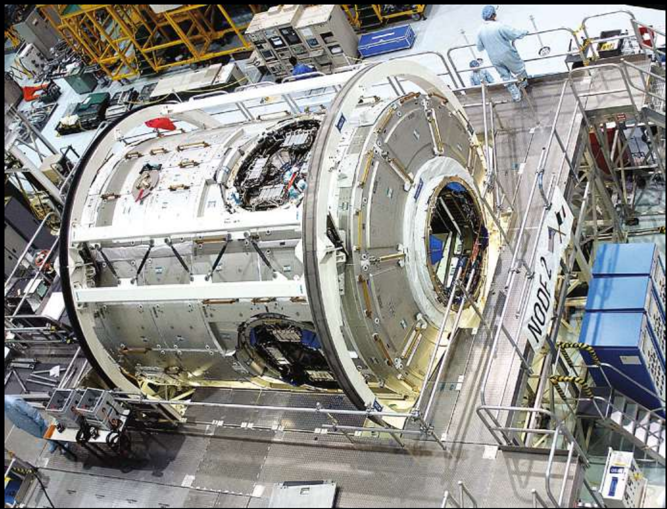


Fig. 2.7 I ISS Node 2 (Harmony) under construction
Credit: NASA

Conventional modules employ well-established pressure vessel construction techniques and can easily incorporate penetrations and attachments like viewports, suit ports, and hatches. In certain cases, modules may be pressurized before landing to enhance their rigidity, especially for large cylindrical elements susceptible to impacts in their horizontal position (Häuplik-Meusburger, Bannova 2016, p. 178).

2.3.2 INFLATABLE STRUCTURES

Expendable in nature, inflatable modules (Fig. 2.8) provide the significant advantage of offering additional volume and space once deployed. The launch of these modules in a compact configuration allows for a notable increase in payload volume. Furthermore, inflatable structures enable the launch and deployment of habitats that surpass the internal volume provided by hard shell modules. Some of these systems have already been successfully demonstrated in space, while others are currently undergoing various stages of design and testing. The pressure walls of inflatable modules consist of specialized pliable layers, each contributing to the essential features required for a pressurized environment. These modules can be expanded in various configurations of pressurized envelopes, including cylinder, capsule, torus, sphere, and combinations thereof. They find utility as both orbital and planetary modules. (Häuplik-Meusburger, Bannova 2016, p. 179). The number of layers in the inflatable structure, typically exceeding 60, is determined by the thermal conditions of the mission. Once fully deployed, the shell can

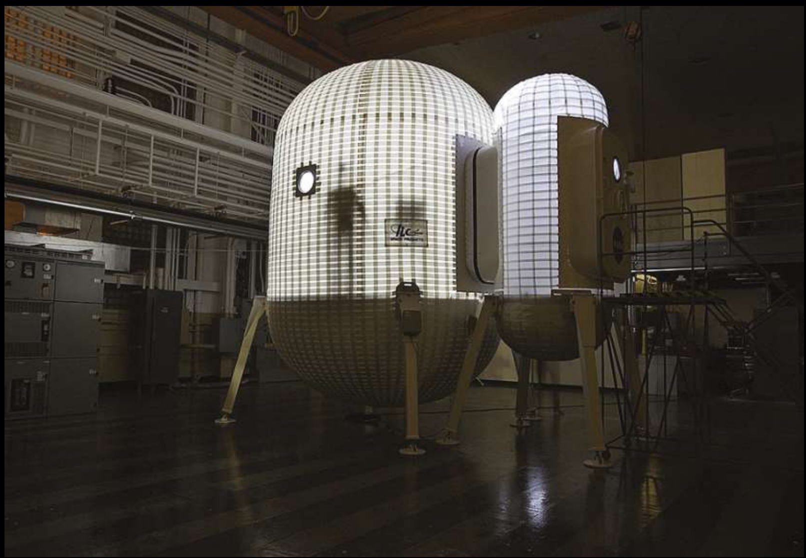


Fig. 2.8 I Inflatable Habitat, Langley Research Center
Credit: NASA

reach thickness of 30-50 cm. Layers, combined in sub-assembly, offer the necessary structural strength and environmental shielding for a space habitat. The shell assembly consists of five primary layers:

1. **The inner layer:** The innermost layer, provides protection to the bladder and offers a durable and easy-to-clean surface for human contact. It is flame and puncture resistant, made of materials like Nomex and Kevlar, and also provides acoustic dampening.
2. **The bladder layer:** The bladder, which serves as the gas barrier, is the second layer and is responsible for containing the internal atmosphere. It needs to be flexible, durable, and have low permeability in both high and low temperature ranges. The bladder is stacked as three layers for redundancy, with each layer sandwiched between Kevlar.
3. **The restraint layer:** Acting as the primary structural layer, carries hoop and axial loads. It requires high tensile strength, flexibility, and foldability for packaging and deployment. Materials like Kevlar and Vectran webbing are woven together to create this layer.
4. **The MMOD protection layer:** Micrometeoroid/orbital debris layer is designed to protect the restraint and bladder layers from potential damage caused by high-speed impacts. It consists of ceramic fabric bumper layers separated by low-density foam and a high-strength fabric rear wall.
5. **The thermal protection layer:** The outermost layer is responsible for passively regulating the habitat's temperature. Similar to the fabric layup of an extra-vehicular activity (EVA) space suit, it utilizes multi-layer insulation to provide thermal insulation (Valle et al 2019).

2.3.3 HYBRID STRUCTURES

Combining hard shell structures with inflatable elements provides the advantages of both types, though there are concerns regarding pressure seal safety. The advantages of this combination include:

- Inflatable sections offer spacious internal volumes for enhanced habitability features.
- Hard sections allow for pre-integrated utility and equipment systems, as well as accommodating viewports, docking interfaces, and other structures.
- Conventional hard modules provide operational capability with pre-integrated utilities/equipment.
- Inflatable laboratories and habitats can be added during growth stages. (Häuplik-Meusburger, Bannova 2016, p. 182)

2.4 MOBILE LUNAR HABITATION CONCEPTS

The realm of lunar rover development has witnessed remarkable progress, driven by the imperative for enhanced mobility and habitability in Moon exploration. Enhanced mobility in lunar rover design is driven by the need for effective exploration, improved safety, expanded range, and efficient resource utilization during lunar missions. The inclusion of early lunar rover concepts provides valuable insights that shape the design and development of modern rovers for both exploration and habitation. This chapter delves into the significance of studying early lunar rover concepts and their profound relevance in shaping the future of lunar exploration. Both pressurized and unpressurized rovers have been extensively studied to gain valuable insights into mobility for lunar exploration to enhance the understanding of the challenges and opportunities related to lunar mobility.

2.4.1 EARLY LUNAR ROVER CONCEPTS

The early concepts of lunar rovers played a crucial role in shaping our understanding of lunar exploration. This list explores the pioneering efforts and breakthrough ideas that emerged during the early stages of lunar rover development. By examining the challenges faced and innovative solutions devised by early engineers and scientists, we gain valuable insights into the fundamental principles of lunar rover design. The lessons learned from these early concepts continue to inform and guide the development of modern lunar vehicles. The following titles encompass not only **pressurized rover concepts** but also unpressurized counterparts, like the **Lunar Roving Vehicle**, expanding the scope of exploration and opening up possibilities for a wider range of lunar rover concepts.

2.4.1.1 Lunar Roving Vehicle (LRV)

The Lunar Roving Vehicle (LRV) was specifically designed as an electric vehicle to navigate the lunar surface in the vacuum of the Moon, extending the range of surface extravehicular activities for Apollo astronauts. The requirement stated that the vehicle should carry two suited astronauts, fit between the lunar module's legs, and weigh no more than 181.4 kilograms (kg) when empty. The solution was the Lunar Roving Vehicle (LRV). The LRV measured 310 cm in length with a 183 cm tread width; a wheel base of 229 cm and a height of 114 cm, visible on figures 2.9 and 2.10 (Boeing LRV 1971).

Throughout the Apollo missions, three LRVs were utilized in 1971. and 1972. (on Apollo 15, 16 and 17) with performances visible in Table 2.5. Each rover completed three traverses, one per day during the respective mission's three-day duration. To generate the vehicle's power, two 36-volt batteries were utilized. The wheels were individually driven by quarter-horsepower electric motors, granting the LRV a maximum speed of 13 kilometers per hour (kph). Despite being 27.2 kg heavier than initially intended

Fig. 2.9 I Lunar Roving Vehicle
Credit: NASA

(total weight of the LRV was 209 kg), the vehicle could carry a total payload of 490 kg. The LRV's design aimed for an operation of 78 hours during the lunar day, covering a range of 65 kilometers. However, the astronauts' portable life support system (PLSS) limitations led to the vehicle's range being constrained to 9.5 km (Howard and Litaker 2020).

PARAMETERS	APOLLO 15	APOLLO 16	APOLLO 17
Total Driving Time [hr:mm]	3:00	3:19	4:29
Total Distance [km]	27.8	26.5	34.7
Average Speed [km/h]	9.3	8.0	7.7
Longest Traverse [km]	12.5	11.2	20.1
Rock Samples [kg]	77.1	96.6	112.9

The Lunar Roving Vehicle (LRV) was deployed from the lunar lander using a system of pulleys and braked reels, allowing for a controlled release. One astronaut would release the folded rover from the egress ladder of the lander, while another astronaut on the ground would guide its descent. As the rover touched the ground, the rear wheels would automatically fold out and lock into place, enabling the unfolding of the front section and deployment of the wheels. The rover's components would securely lock upon opening, and cabling, pins, and tripods would be removed. Finally, the seats and footrests would be raised, electronics switched on, and the vehicle ready to move away from the lander (NASA 2016).

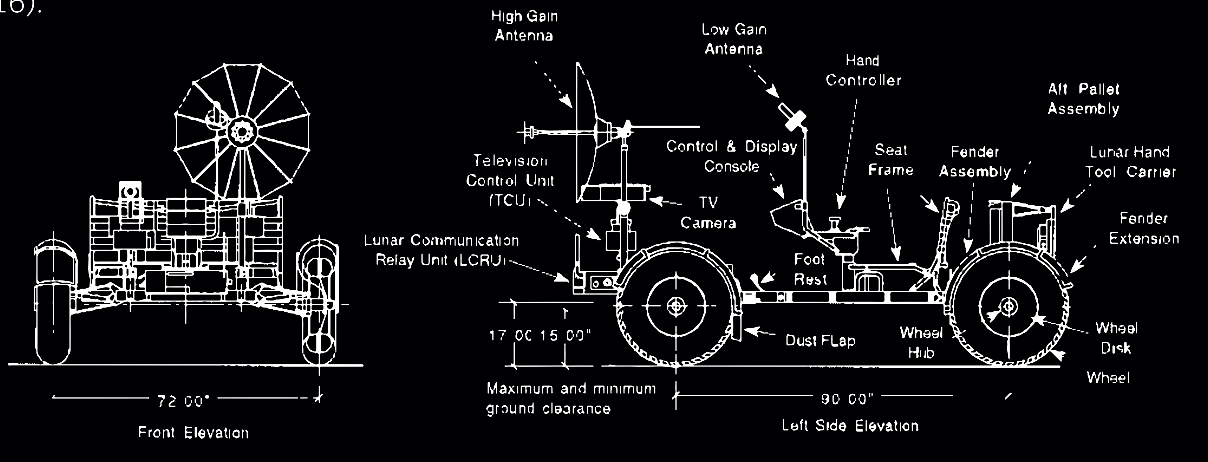


Table 2.5 I Lunar Roving Vehicle (LRV) Performance
Credit: Howard and Litaker 2020

Fig. 2.10 I Lunar Roving Vehicle: Front and Side View
Credit: Boeing LRV 1971

2.4.1.2 Pressurized Rover Concepts

Since the initial development of the of the Apollo-era lunar rover, numerous proposals have emerged for surface exploration vehicles, encompassing a wide range of sizes and capabilities. These concepts range from pressurized crewed rovers to mobile bases, designed to accommodate multiple astronauts for extended missions spanning hundreds of kilometers and weeks. Below is a brief summary of these rover concepts, emphasizing their individual strengths and limitations, along with a table that summarizes and compares all the concepts investigated.

1 DAYLIGHT ROVER

The "Daylight Rover" is a lunar rover concept developed by Boeing in 1990 for manned missions. The concept has two separate pressure vessels, as shown in figure 2.11 (Griffin, Brand N. 1991). The forward serves as the driving station, and the rear serves as a storm shelter, and EVA airlock. The two manipulating arms at the front of the rover performs most of the geological sampling and collecting, this minimizing actual EVA required. A small airlock is incorporated in the front to allow samples to be transferred to the module. Additional characteristics are as follows (Zakrajsek et al 2005):

- **Size:** 23 to 25 mt.
- **Structural Characteristics:** Two cylindrical pressure vessels, the rear of which serves as the airlock
- **Power System:** 10kW continuous electrical power from regenerative fuel cells.

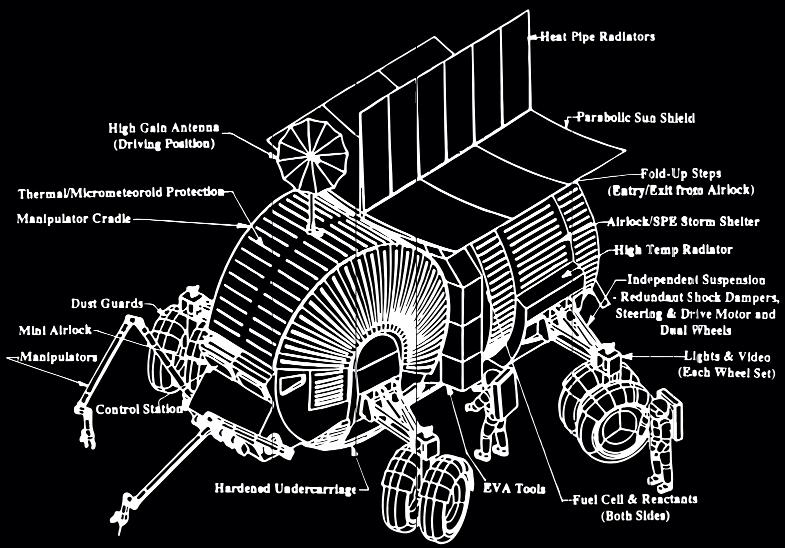


Fig. 2.11 I Daylight Rover
Credit: Boeing and Griffin, Brand N. 1991.

- **Mobility System:** Four sets of dual wheels, two on each vessel. The wheels have integrated steering and electric drive mechanisms.
- **Unique Characteristics:** Two manipulating arms for a majority of geological sampling and collecting.
- **Capabilities:** Crew of 2 for up to an 80 day mission, at a maximum range of 1000km. Can accommodate 4 people in an emergency. Average speed is 4 km/hr in daylight, and 2km/hr in dark.

2 NOMAD EXPLORER VLTV

In 1992. Thangavelu proposes the Nomad Explorer VLTV (Very Long Traverse Vehicle), visible on Figure 2.12 as a solution to two key challenges in establishing a lunar base: dust management and spacesuit protection, specifically the need for effective dust barriers. By merging the wheel and diving bell technologies, an approach is proposed to successfully address these challenges. The crewmembers would primarily operate inside a mega-rover, supporting a team of six during extensive exploration spanning thousands of kilometers (Cohen 2003).

- **Size:** 35-ton VLTV measures 16 meters long, 4.5 meters wide, and 10 meters high.
- **Structural Characteristics:** The mobile base would actually comprise two vehicles; VLTV with complex wheels that change shape automatically to accommodate obstacles and ensures a smooth ride and an automated "power cart" bearing a nuclear reactor would follow about a kilometer behind the VLTV.
- **Power System:** The power cart provides 50 kW of electricity to the piloted rover through a durable cable or intermittent microwave beaming.
- **Mobility System:** The vehicle has four large wheels, each independently powered by a 120-horsepower electric motor.
- **Unique Characteristics:** The EVA Bell concept aims to overcome the drawbacks of bulky spacesuits during

Fig. 2.12 I Nomad Explorer VLTV
Credit: M. Thangavelu

moonwalks. It eliminates EVA mobility restrictions, fatigue, and time-consuming donning while also protecting astronauts from abrasive lunar dust.

- **Capabilities:** 600 cubic meters of pressurized volume for its six-person crew, including a control cockpit, individual crew cabins, a meeting room/galley, an airlock, and a hygiene facility (Wired 2013).

3 MOBITAT

The Mobitat is a combination lander/hopper and mobile rover consisting of two major subsystems: mobile platform/lander and modular pressure vessel (Fig. 2.13). The mobile platform portion can be detached from the pressure vessel for use as a separate crane or mount for drilling and construction implements. The pressure vessel can be docked with others of its kind to create larger outposts and bases (Howe 2004).

- **Size:** 7.2 m in length and 4.2 m in diameter when folded.
- **Structural Characteristics:** The system consists of a mobile platform that can function independently or in conjunction with a modular pressure vessel. In addition, it supports surface operations such as excavation, drilling and construction implements. Its height can be adjusted between 1.9 m and 5 m from the surface. The modular pressure vessel can also be assembled into larger bases or used with a rover (Haeuplik-Meusburger and Ozdemir 2012).
- **Mobility System:** Mobile platform that has 8-wheel carriage assembly.
- **Unique Characteristics:** It can be used as a modular surface exploration vehicle and habitat. The vehicle can function as both a rover and a fixed modular base with an uncrewed, remotely controlled work platform, due to the separability of its pressure vessel and mobile platform.

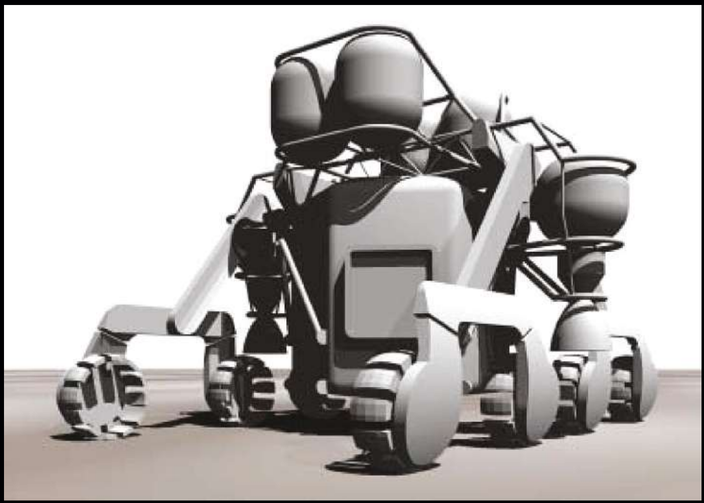


Fig. 2.13 I Mobitat
Credit: A. Scott Howe

4 MOONWALKER

The Moonwalker (Fig. 2.14) project is grounded on the principle that human behavior is closely intertwined with space and its spatial elements. By incorporating findings from psychological and sociological studies, as well as aspects of spatial perception and creation, a sustainable concept for a mobile lunar base has been developed. The emphasis is placed on the interdependent relationship between technical and functional design components. Various forms of adaptability and their corresponding architectural implementation have been carefully considered in this project (Haeuplik-Meusburger 2005).

- **Size:** When packed, the dimensions of the structure are 5.5 meters in diameter and 6 meters in length, while when deployed, it expands to a diameter of 11 meters and a height of 10 meters.
- **Structural Characteristics:** The habitat incorporates inflatable and rigid modules, as well as inflatable 'airbags' for enhanced meteorite protection. The multi-layer membranes, composed of inflated materials, are reinforced by a tensile net.
- **Mobility System:** In order to move safely across unknown terrains, Moonwalker possesses six legs that function as landing, standing and locomotion tools – and occasionally as bionic arms.
- **Unique Characteristics:** The inflatable rigidized structure offers twelve docking possibilities for plug-ins and expansions thus enabling efficient adaptation to any given future mission.
- **Capabilities:** The interior of Moonwalker can be adapted to the changing user-preferences of the crew. The crew quarters are divided into two parts: one that directly interacts with the lunar environment and can be expanded externally, and another that reflects and facilitates social dynamics (Haeuplik-Meusburger and Ozdemir 2012).

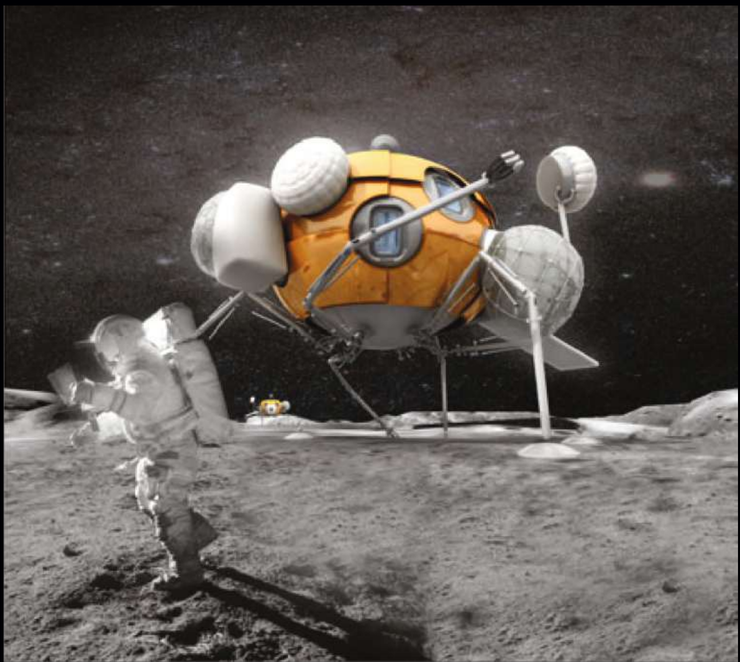


Fig. 2.14 I Moonwalker
Credit: S. Haeuplik-Meusburger

2.4.2 CONTEMPORARY LUNAR ROVER CONCEPTS

Advancements in technology and scientific knowledge have led to the emergence of sophisticated modern lunar rover concepts. With the Artemis program gaining momentum, there is a pressing need to explore innovative approaches that can fulfill the specific requirements of this ambitious lunar exploration initiative. This chapter focuses on the state-of-the-art technologies, design principles, and operational capabilities of modern lunar exploration rovers, namely the **Lunar Terrain Vehicle (LTV)** and the **Habitable Mobility Platform**, with a focus on requirements of the NASA's Artemis program.

2.4.2.1 Lunar Terrain Vehicle (LTV)

In August 2021, NASA unveiled its preliminary plans to procure a commercial rover for the Artemis program, designed to be operated by astronauts on the lunar surface. The agency outlined the desired capabilities of the Lunar Terrain Vehicle (LTV), emphasizing that it must surpass the capabilities of the Apollo-era Lunar Roving Vehicle (LRV) and surpass the sophistication of current Mars rovers. NASA has set a stringent set of requirements that must be met to ensure the sustainability of its return to the Moon, as outlined in Table 2.6 (SAM 2022) NASA intends for the LTV to be delivered to the Moon's south pole no earlier than August 2028, with first use starting with the Artemis V crewed mission the same year (NASA 20222-II).

The Lunar Terrain Vehicle (LTV) is designed as an open-roof, fully electric rover capable of accommodating two astronauts on the Moon. It boasts an impressive range of up to 20 kilometers, allowing for an eight-hour roundtrip without requiring recharging. This range surpasses that of the Apollo Lunar Roving Vehicle (LRV) by threefold and provides double the driving time.

One significant challenge for the LTV is surviving the frigid temperatures experienced during lunar night-time at the Moon's south pole. Despite careful selection of high-altitude hibernation locations, these nights can last from a few hours to 150 hours. Additionally, the LTV must be capable of traversing slopes of up to 20 degrees and effectively navigating the demanding and rugged terrain found at the Moon's south pole, which serves as the primary location for planned Artemis surface missions. Furthermore, the LTV should have the capability to spend up to two hours in permanently shadowed regions where temperatures plummet well below -180 degrees Celsius (NASA 2021-II).

1 LOCKHEED MARTIN LTV

One of the proposed concepts, Lockheed Martin's LTV (Fig. 2.15), not only boasts capabilities for extended missions but also provides the option for autonomous operation. The inclusion of autonomous, self-driving systems allows the vehicle to function with or without human occupants, paving the way for future human missions, commercial payload services, and increased scientific capabilities. It can autonomously position itself near a landing site prior to the arrival of astronauts. These astronauts can then assign tasks to the rover from either the Human Landing System or the orbiting lunar Gateway for conducting scientific operations without the need for a driver. This capability enables NASA to maximize scientific productivity within a limited timeframe and provides an opportunity to uncover crucial information hidden across the remaining 95% of the lunar surface (Lockheed Martin 2021).

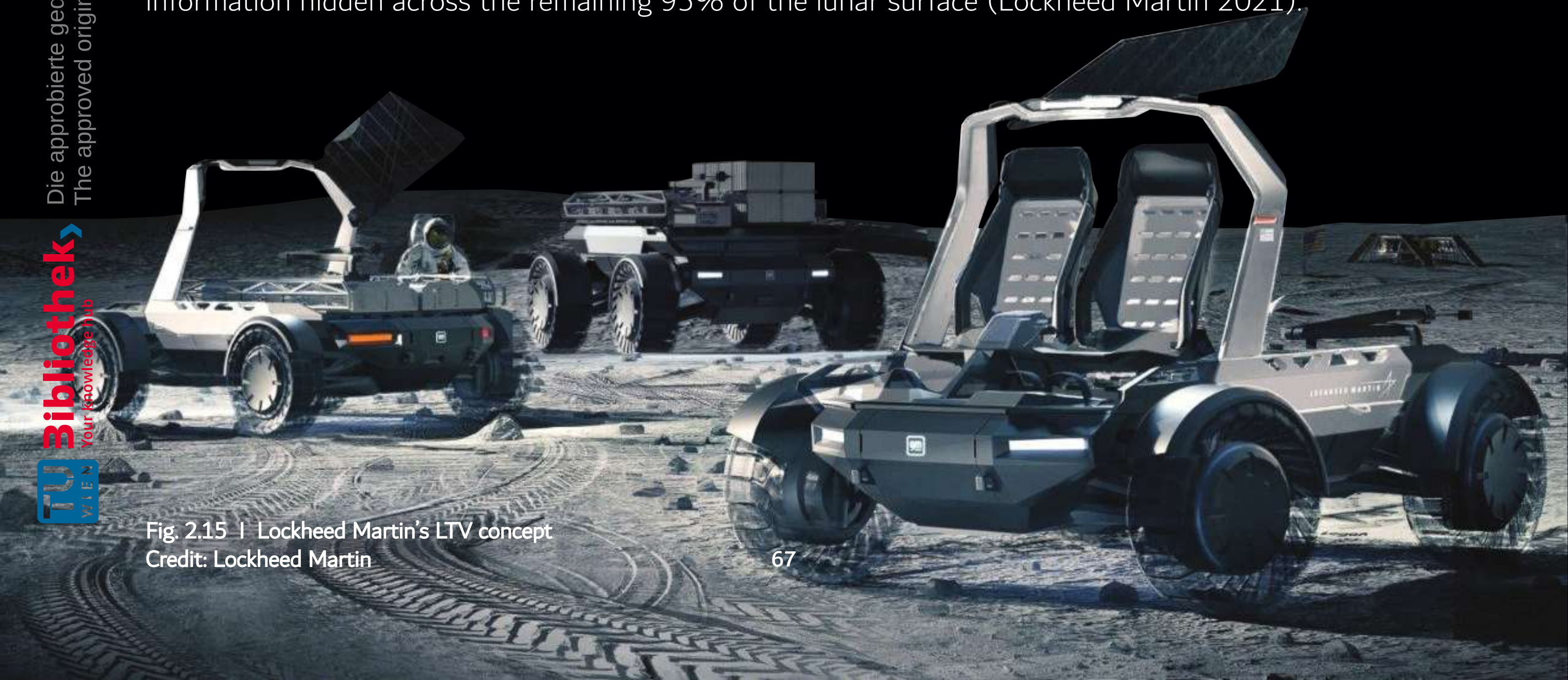


Fig. 2.15 I Lockheed Martin's LTV concept
Credit: Lockheed Martin

CREW CAPACITY • Carry two suited crew members	**LUNAR ENVIRONMENT SURVIVABILITY** • Survive extreme temperatures of the Lunar South Pole • Operate for at least 2 hours in a Permanently Shadowed Region • Survive extended lunar nights of at least 150 hours
PERFORMANCE CHARACTERISTICS • Traverse 20 km on single charge • Reach a top speed of 15 km/h • Operable over a max slope of ± 20° • Nominal transport of 800 kg, consisting of crew (550 kg) anf payload (250 kg) • Logistic transport of 1600 kg • Capable of traversing cratered highlind terrain • Support 8 hours of EVA	**MISSION DURATION** • Support at least 10 years of the Artemis Program
ROBOTIC MANIPULATION • Robotics manipulator to support science exploration • Robotically exchangeable end-effectors	**REMOTE OPERATIONS** • Operable by on-board and remote crew on lunar surface, cislunar space, or Earth • Supervised autonomous operations required, development path to increase levels of autonomy desired
RECHARGE CAPABILITY • Capable of recharging itself and external power exchange	**FAILURE TOLERANCE** • Single fault tolerant against catastrophic hazards and to prevent loss of mobility

Table 2.6 I List of Capabilities for an LTV
Credit: NASA

2 NASA LTV

Due to its crucial role in ensuring the safe return of astronauts to the lander or Artemis Base Camp, NASA mandates that the mobility of the LTV exhibits a minimum level of single-fault tolerance. Additionally, the rover must possess the capability to establish direct communication with Earth, as well as communicate through lunar satellites or other relay systems. NASA aims for the LTV to be remotely operated from anywhere between the Moon's surface and Earth, with a strong emphasis on high autonomy. These specifications are set by NASA's Science Mission Directorate to maximize the rover's scientific utility during periods when crewed missions are not active, which will be the case for at least 11 months annually in all foreseeable Artemis missions.

NASA's plan for the LTV (Figure 2.16) includes its role as a lunar cargo carrier. Alongside its primary task of accommodating a suited crew of two individuals weighing approximately 550 kilograms, the LTV is required to transport up to 250 kilograms of cargo, scientific instruments, lunar samples, tools, and technology demonstration payloads to specified locations on the Moon. During non-crew missions, the LTV can carry up to 1,600 kilograms at reduced speeds. To fulfill this objective, NASA also envisions equipping the LTV with a robotic manipulator arm for deploying scientific instruments and other equipment. Furthermore, before a crew from the Artemis mission lands, the LTV will autonomously navigate to a location near the landing site to capture the crew's descent and touchdown, repeating the same process during ascent (NASA 2022-II).

Fig. 2.16 I NASA's LTV concept
Credit: NASA

2.4.2.2 Habitable Mobility Platform

The LTV is just one of the two rover types within NASA's Artemis Base Camp project, which is focused on establishing the necessary infrastructure for four astronauts to sustain themselves on the Moon for at least 33-day periods. The second rover is designed to be pressurized and habitable, allowing astronauts to explore the Moon's south pole for a few weeks at a time (NASA 2022-I). NASA is continually building upon the knowledge gained from the Apollo missions and drawing from the operational experiences of unmanned rovers on Mars. Some of the planned concepts include **The Lunar Cruiser**, **Lunar Electric Rover (LER)**, and **ATHLETE**, with a detailed comparison available in Table 2.7.

1 THE LUNAR CRUISER

The Lunar Cruiser, an autonomous and crewed pressurized rover developed by JAXA and Toyota for NASA's Artemis Program (Fig. 2.17), prioritizes mobility, reliability, durability, and driving performance to ensure safe and comfortable astronaut exploration. Similar to the LTV, this rover is designed for a

Fig. 2.17 I JAXA-Toyota concept
Credit: JAXA

minimum of 10 years of operation and has the capability to traverse permanently shadowed regions with slopes less than 20 degrees. Currently in production, the Lunar Cruiser is scheduled for launch in the latter half of the 2020s (Toyota 2020). To make the lunar rover, JAXA and Toyota have been asked to consider the following parameters (Toyota 2019):

- The vehicle must be able to travel on the moon's surface for up to 6 weeks
- The interior must be designed to allow the astronauts to remove their space suits and live
- The space inside needs to be able to provide just under about 13 m3 of living space
- The exterior should be slightly larger than "the size of two microbuses"

The LUNAR CRUISER, chosen as the nickname for the vehicle prototype, provides a sense of familiarity for those involved in its development and the general public. It has approximate dimensions of 6.0m length, 5.2m width, and 3.8m height, equivalent to two minibuses. With $13m^3$ of living space, it offers comfortable accommodation for two individuals or emergency accommodation for four (Toyota 2020-I). The vehicle's primary purpose is to undertake missions in the moon's polar regions, exploring the potential utilization of lunar resources, such as frozen water, and developing technologies for surface exploration of large celestial bodies (Toyota 2019-I). It features a versatile robotic arm capable of performing various inspection, maintenance, scooping, lifting, and sweeping tasks.

Despite the energy constraints on the moon, the Lunar Cruiser is designed to achieve an impressive cruising range of 10,000km over 42 days on the lunar surface. To ensure an adequate energy supply for travel, Toyota intends to incorporate its advanced fuel cell electric vehicle (FCEV) technologies into the vehicle. The Lunar Cruiser will generate electricity using solar photovoltaic panels, while also storing electricity for powering other electronic devices apart from vehicle movement (Toyota 2019).

2 LUNAR ELECTRIC ROVER (LER)

The Lunar Electric Rover (LER) is a modular vehicle concept created by NASA (Figure 2.18). It comprises a pressurized cabin that can be attached to a wheeled chassis, forming a rover suitable for planetary surface exploration. This concept offers a mobile means of exploration, serving as the primary mode of transportation for astronauts. Importantly, unlike the unpressurized Apollo lunar rover, it enables astronauts to undertake extended excursions without the constraints of spacesuits (NASA 2015).

The mobility chassis and pressurized cabin module can be transported to the lunar surface either as an

Fig. 1.1 I Moon, photograph
Credit: Britannica

integrated unit or as separate components. Astronauts have the option to operate the mobility chassis independently, using rotating turrets while wearing spacesuits, and the chassis can also serve for cargo transport. This modular design permits the attachment of various tools such as winches, cable reels, backhoes, cranes, and bulldozer blades for specific missions. Additionally, the chassis has the capability to retrieve and relocate solar-powered charging stations, communication relays, and scientific equipment packages.

This vehicle, about the size of a compact pickup truck and equipped with 12 wheels, can accommodate two astronauts for extended stays of up to two weeks, with emergency capacity for up to four individuals. The pressurized interior boasts a bathroom with privacy curtains and a shower head for water mist sponge baths, alongside tool cabinets, workbench areas, and two convertible crew seats that convert into beds. The vehicle features a Suitport, enabling multiple shorter moonwalks. Its adaptable design incorporates pivoting wheels for "crab style" sideways movement to navigate challenging terrain, while the tiltable cockpit provides drivers with an optimal view of the terrain ahead. These concept vehicles underwent testing during the "Desert Research and Technology Studies" from 2008 to 2011. One of the primary objectives of testing prototypes on Earth is to identify features that will be most beneficial for lunar missions (NASA 2015).

Fig. 2.18 I Lunar Electric Rover during desert research
Credit: NASA

3 ATHLETE

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility platform is a multi-use platform designed for maximum efficiency that is able to both roll and walk over a wide range of terrains. It is a multi-use platform designed to use swap-out tools and implements that can be applied to any number of tasks that need precision limb manipulation or mobility. Major capabilities include off-loading habitats, transporting surface assets, robotically assembling outposts from multiple mission manifests, and supporting science and technology objectives. The system is in development along with NASA's Johnson and Ames Centers, Stanford University and Boeing (Howe et al 2016).

Even though it is planned mostly as a cargo handling platform, exploration work platform, and assembler of planetary outposts, lunar pressurized habitation modules can be mounted and transported on desired locations. Mobile habitats can enhance lunar exploration by serving as local bases for smaller crewed rovers. These mobile bases would strategically position themselves in lunar polar regions to maximize solar energy collection, which serves their own needs and recharges smaller rovers. They also act as communication relays when the smaller pressurized rovers venture into areas with limited visibility and offer more spacious living quarters compared to the smaller rovers (Wilcox 2009).

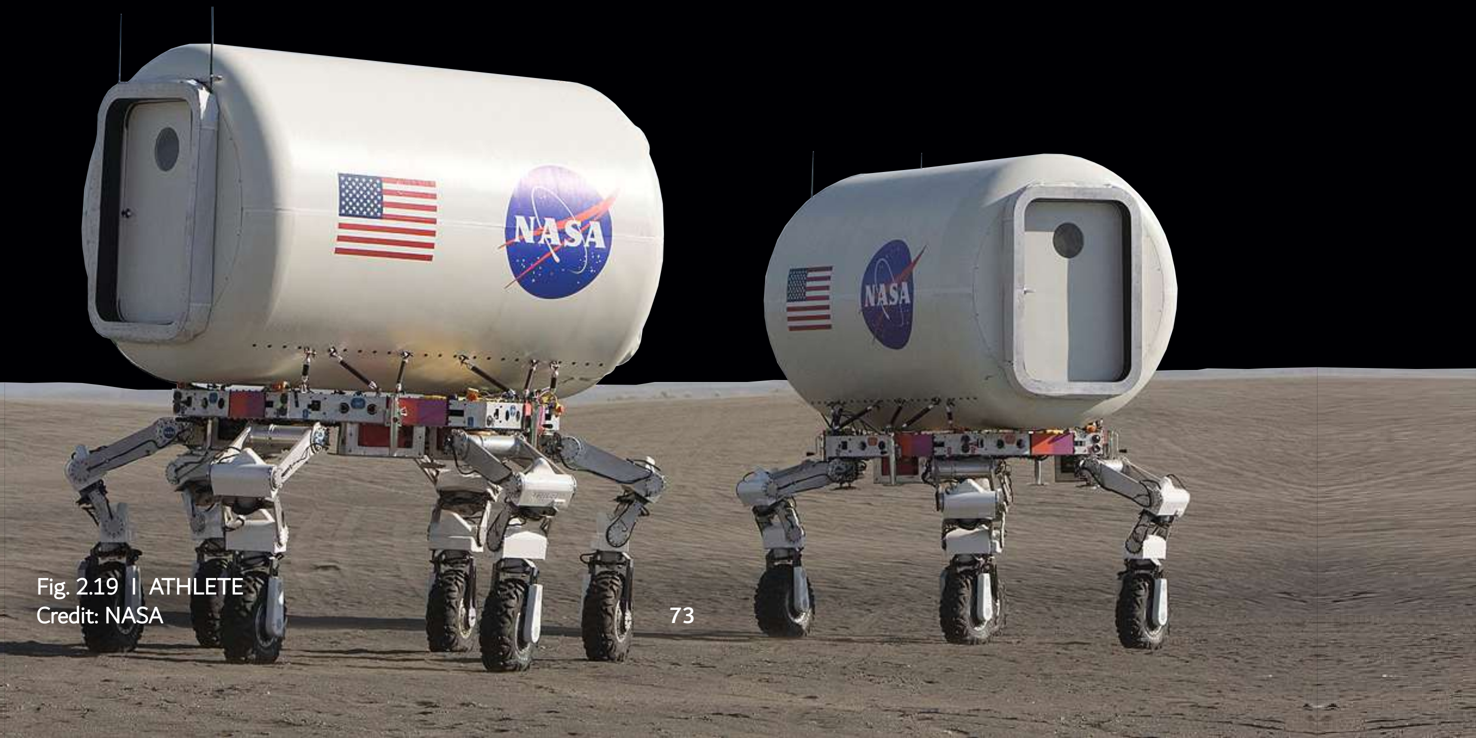


Fig. 2.19 I ATHLETE
Credit: NASA

The vehicle concept relies on six Degrees-of-Freedom (DoF) limbs for efficient travel over stable, gently rolling terrain. However, each limb can also serve as a versatile leg when needed. In this mode, the wheels can be immobilized and used as feet to navigate through exceptionally soft, obstacle-filled, steep, or otherwise challenging terrain.

Each ATHLETE unit is designed to carry up to 450 kilograms of payload and can connect with multiple other ATHLETE vehicles to handle larger loads. A single ATHLETE has a diameter of approximately 4 meters and a reach of about 6 meters. Future plans include enhancing the system's ability to navigate rough terrain and increasing the ATHLETE's speed to 10 kilometers per hour while extending its operational lifespan to 10 years (JPL Robotics 2018).

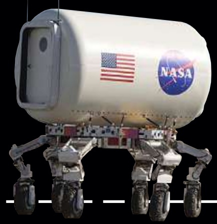
2.4.2.3 Comparative Analysis

This section seeks to offer a thorough analysis and comparison of three lunar rovers: the Lunar Cruiser, Lunar Terrain Vehicle (LTV), and ATHLETE, as listed in Table 2.7. The comparative analysis presented here is based on the same source that has been previously listed in the preceding chapter. Through the evaluation of parameters such as dimensions, habitable volume, weight, range, mission length, autonomy and power supply, we can gain valuable insights into their respective capabilities and potential applications.

In terms of Dimensions and Habitable Volume, the Lunar Cruiser is larger, measuring 6.0 m (L) x 5.2 m (W) x 3.8 m (H), providing a habitation volume of approximately 13 m^3 for two individuals, with emergency capacity for two more. The Lunar Terrain Vehicle is smaller, with dimensions of 4.5 m (L) x 3.0 m (W) x 3.0 m (H), accommodating two individuals with an estimated habitation volume of around 10 m^3. ATHLETE falls in between, measuring 3.66 m (L) x 2.34 m (W) x 2.34 m (H), with an approximate habitation volume of 14 m^3. Regarding Weight and Pressurization, the Lunar Cruiser's weight remains undisclosed, while the Lunar Terrain Vehicle weighs 4000 kg, lighter than the other rovers. Both rovers are pressurized for human habitation. ATHLETE weighs 850 kg with an additional 450 kg cargo capacity, and also has pressurized compartments.

PARAMETERS	THE LUNAR CRUISER	LUNAR TERRAIN VEHICLE	ATHLETE
DIMENSIONS [m]	vehicle: 6.0 m L x 5.2 W x 3. 8 m H	habitat: 4.5 m L x 3.0 m W x 3.0 m H	habitat: 3.66 m L x 2.34 m Wx 2.34 m H
HAB. VOLUME [m³]	13 m³	approx 10 m³	approx 14 m³
WEIGH T [kg]	UNKNOWN	4000 kg	850 kg + 450 kg cargo
PRESSURIZED	YES	YES	YES
NUMBER OF PEOPLE	2 (+2 in emergency)	2 (+2 in emergency)	UNKNOWN
SPEED [km/h]	UNKNOWN	10 [km/h]	10 [km/h]
RANGE [km]	10 000 km	125 km	UNKNOWN
RANGE [weeks]	6 weeks	2 weeks	UNKNOWN
MISSION LENGHT	10 years	UNKNOWN	10 years
MODULAR	NO	YES	YES
AUTONOMOUS	YES	NO	NO
SUITPORT	YES	YES	UNKNOWN
POWER SUPPLY	FCEV (hydrogen fuel cells)	FCEV (hydrogen fuel cells)	Solar
WHEELS	6 wheels	12 wheels, can pivot 360°	6 DoF limbs
ROBOTIC ARM	UNKNOWN	YES	YES, robotic limbs





In terms of Capacity and Emergency Situations, the Lunar Cruiser and the Lunar Terrain Vehicle are designed to accommodate two people, with the ability to support an additional two individuals in emergency scenarios. The exact capacity of the ATHLETE for accommodating people is not specified.

In terms of Speed and Range, the Lunar Cruiser's specifications remain undisclosed, making it difficult to assess its capabilities. The Lunar Terrain Vehicle can reach a speed of 10 km/h and has a range of 125 km, offering reasonable coverage for lunar exploration. ATHLETE matches the Lunar Terrain Vehicle's speed, but information about its range is unavailable.

Table 2.7 I Comparison List

Regarding Mission Length and Modularity, the Lunar Cruiser is designed for a 10-year mission, highlighting its durability and long-term viability. The mission length of the Lunar Terrain Vehicle is unspecified. While the Lunar Cruiser is non-modular, indicating potential challenges for upgrades or alterations, the Lunar Terrain Vehicle and ATHLETE are modular, allowing for enhancements and customization during extended missions.

In terms of Autonomy and Suitport, the Lunar Cruiser is autonomous and capable of operating independently without constant human control. On the other hand, the Lunar Terrain Vehicle and ATHLETE require human guidance. All three rovers feature a suitport, facilitating astronauts' access to their space suits from within the pressurized environment of the rover.

In terms of Power Supply and Wheels, both the Lunar Cruiser and Lunar Terrain Vehicle utilize hydrogen fuel cells (FCEV) for sustainable and efficient energy. ATHLETE, on the other hand, relies on solar power. The Lunar Cruiser has six wheels, while the Lunar Terrain Vehicle has 12 wheels that can pivot 360 degrees for enhanced mobility. ATHLETE features six degrees of freedom (DoF) limbs, providing versatile maneuverability across lunar terrain.

Regarding Robotic Arm and Additional Features, information about the presence or absence of a robotic arm is not available for the Lunar Cruiser and Lunar Terrain Vehicle. In contrast, ATHLETE is equipped with robotic limbs, enhancing its capabilities for complex tasks and object manipulation.

All three habitable mobility platform concepts possess unique characteristics and capabilities that cater to different lunar mission requirements. The Lunar Cruiser offers a larger habitation volume and longer mission duration, while the Lunar Terrain Vehicle excels in its range and modularity. ATHLETE stands out with its solar power supply and robotic limbs.

MISSION SCENARIO 03

“To confine our attention to terrestrial matters would be to limit the human spirit.”

Stephen Hawking

3.1 INTRODUCTION

Each exploration strategy commences by establishing the objectives to accomplish and sketching out the necessary missions required to reach the specified goals. Thorough planning plays a crucial role in ensuring the success of space exploration endeavors. Planning involves the integration of multiple factors, such as goals, requirements, and potential outposts, into a complete process that ensures that all aspects of the mission are properly considered and that potential challenges and risks are identified and addressed (Häuplik-Meusburger, Bannova 2016, p. 53).

The first step in this process is to determine the goals of the mission and the specific targets that need to be achieved in order to accomplish those goals. This typically involves identifying scientific objectives, exploring potential landing sites, and assessing the feasibility of different mission scenarios.

Once the goals have been established, the next step is to outline the missions that need to be performed to achieve those goals. This might involve developing spacecraft designs, selecting launch vehicles, determining mission trajectories, and defining the specific operations that will be required during the mission.

Comprehensive planning is essential to ensure that all aspects of the mission are properly considered and that potential challenges and risks are identified and addressed. This might involve conducting feasibility studies, analyzing data from previous missions, and consulting with experts in various fields, such as spacecraft engineering, astrophysics, and planetary science.

In essence, mission goals and objectives extend well beyond the destination of a space voyage. They originate on Earth and have far-reaching implications, including preparations for upcoming missions, advancements on our home planet, and potential benefits that may not be immediately apparent. The planning and execution of future long-term space missions present significant challenges due to the intricate nature of human factors and the need to address both technological and human endurance considerations (Häuplik-Meusburger, Bannova 2016, p. 56).

For the purposes of this thesis, the ATRIO lunar habitat[1] has been chosen as the lunar habitat for the Artemis Base Camp. The selection of ATRIO was based on a thorough analysis of various factors, including the size, capacity, and technological capabilities required to support long-duration human spaceflight missions.

ATRIO was designed as a research facility that explores the relationship between humans and plants, with an emphasis on discovering the full potential of plant development in a micro-gravity environment. The lunar facility can accommodate six crew members and is located on Shackleton crater ridge on Lunar South Pole (Kugic A., Radic V., Alkaabi A., Ayman M., Saeed F., Zrik K. 2021).

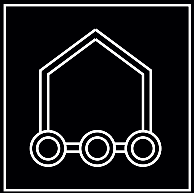
ATRIO was chosen for its innovative design, which incorporates a range of features to enable sustainable and efficient operations on the lunar surface. These features include a flexible and inflatable architecture, radiation shielding, life support systems, and in-situ resource utilization technologies. Additionally, it was selected for its ability to withstand the harsh lunar environment, including extreme temperatures, radiation exposure, and micrometeoroid impacts. The habitat is designed to provide a comfortable and safe living environment for the crew, with emphasis on habitability and maintenance of mental and physical health of the crew

[1] ATRIO lunar habitat is a project made at Lunar Oasis Design studio WS 2021/2022 as TU Vienna and Abu Dhabi University collaboration, under mentorship of dr. Sandra Haeuplik-Meusburger and dr. Paolo Caratelli.

Fig. 3.1 I ATRIO lunar habitat
Credit: ATRIO authors

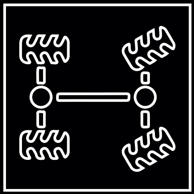
3.2 MISSION OBJECTIVES

X-plor is a self-deployable exploration and habitation vehicle designed as a proposal for Artemis Base Camp. It is adapted to optimize astronaut safety and performance during lunar exploration and can support crew operations of 2+2 members for multiple short term missions on extreme and complex surfaces. It's primary mission objective is providing a mobile habitat for astronauts to explore the lunar surface for an extended period of two weeks. Secondary mission objectives include: conducting scientific experiments, cargo transport, communication, mobility and testing technologies.



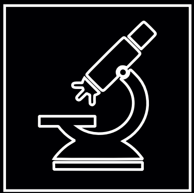
Providing a mobile habitat for astronauts to explore the lunar surface: Creating a mobile habitat means designing a comfortable and safe living environment for the crew during their extended stay on the Moon with some important considerations:

- The vehicle will need to be equipped with life support systems that provide the crew with the necessary resources to sustain life on the Moon. These include systems for air and water purification, waste management and food production.
- The living quarters on the vehicle will need to be designed to provide a comfortable and safe environment for the crew. This includes provisions for sleeping, hygiene, exercise and recreation.
- The lunar environment presents unique challenges for humans, including extreme temperatures, radiation, and dust. The design of the vehicle may involve the use of shielding materials and careful placement of living areas within the rover, as well as maintaining a comfortable temperature for the crew, which may involve the use of insulation and heating/cooling systems.
- The vehicle will need to be equipped with a reliable power source to support the living environment and other systems on board. This may involve the use of solar panels, as well as batteries or other energy storage systems.
- The crew will need to stay in communication with Earth and with each other, and the vehicle will need to be equipped with reliable communication systems to support this.



Mobility: A habitable lunar vehicle could provides means for the crew to explore the lunar surface and access resources, while also ensuring the safety and reliability of the rover. Some of important objectives include:

- The vehicle will need to be designed to navigate a variety of terrains on the lunar surface, including rough terrain, steep inclines, and loose or rocky surfaces. This may involve the use of specialized wheels, treads, or other mobility systems.
- The vehicle will need to have a sufficient range and endurance to support the crew's exploration missions. This may involve the use of advanced power systems, as well as careful planning of mission routes and schedules.
- The vehicle will need to be designed for reliability and safety, with redundant systems and fail-safe mechanisms to ensure that the crew can operate and navigate the vehicle safely on the lunar surface

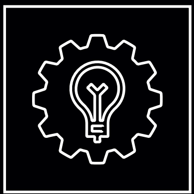


Scientific exploration: X-plor carries various scientific instruments to perform experiments that require mobility, such as studying the lunar geology, conducting biological experiments and analyzing the lunar atmosphere. Important considerations:

- A variety of instruments can be used on a lunar vehicle, including robotic arm, cameras, spectrometers, seismometers, and soil analyzers. Each instrument will need to be carefully selected to meet the scientific objectives of the experiment, as well as the specific challenges of the lunar environment.

Cargo transport: Cargo transport on X-plor involves designing and equipping the vehicle to carry payloads or cargo from one location to another on the Moon's surface. There are several factors to consider when designing a lunar rover for cargo transport:

- The vehicle must be able to carry the weight of the cargo without compromising its stability or mobility. This requires designing a larger and more robust rover than one designed solely for human transportation.
- The vehicle must be equipped with sufficient power and energy storage to support the additional weight of the cargo, as well as any additional systems or equipment needed for cargo transport



Testing technologies: X-plor can be used as a test bed for new technologies, such as new types of modular design and autonomous navigation systems, that could be used in future martian missions.

3.3 WHY THE LUNAR SOUTH?

As previously noted, NASA has chosen the lunar south pole as a site for human landing under the Artemis program. However, what sets the lunar south pole apart from the rest of the Moon and makes it a desirable location for exploration and research? The selection of a suitable lunar site is dependent on various location implications, such as proximity to the poles or equator, or the near or far side of the Moon, as variations in factors such as sunlight, temperature, energy, and communication capabilities can differ significantly, as shown in Table 3.1 (Griffin 2021).

At an equatorial site, there are 14 days of sunlight and 14 days of darkness, resulting in extreme temperature fluctuations. To mitigate this, energy storage is required for the night, and solar arrays must be designed to rotate east/west to track the overhead sun, which moves about 12 degrees every day. Radiators should be positioned to avoid solar pointing. In contrast, a polar site benefits from near-continuous sunlight, resulting in more stable thermal conditions. Solar arrays can continuously track 360 degrees, pointing at the sun on the lunar horizon. Radiators should be oriented upward to look at "cold" space (Griffin 2021). Another significant difference between the poles and equator is the presence of water ice. The polar regions of the Moon are of particular interest to scientists and space agencies because they are believed to contain water ice in permanently shadowed areas. In contrast, the equatorial regions are much drier and lack significant deposits of water ice (NASA 2019).

Another consideration is communication. A near side site is always Earth-facing, allowing for direct communication. However, a far side site never sees the Earth, requiring a communication relay system. This side of the Moon also provides a unique advantage for radio astronomy, as the Moon blocks Earth-generated electromagnetic interference. It's important to note that there is no actual "dark side" of the Moon, as both sides receive an equal amount of sunlight, but the term refers to the side that is not visible from Earth (Adam 2018).

When selecting a local lunar site for human habitation, there are several important factors to consider. The topography of the site must be taken into account, as it can present challenges such as craters, slopes, rocks, uneven terrain, and other obstacles that need to be accommodated. Methods of leveling and site improvement may be necessary to make the site safe and suitable for human habitation. Zoning is also critical, since it designates different areas for different activities, such as liftoff/landing zones, science zones for conducting experiments and research, power zones for generating energy, and ISRU (In-Situ Resource Utilization) for extracting resources from the Moon. Finally, growth potential must be considered to ensure that the base can adapt to changing needs over time. Element size and functionality are important considerations when planning for growth, as they can impact the base's capacity to expand or adapt to changing needs (Griffin 2021).

PLANETARY SITING	**Equatorial Site**	14 days of sun means it gets hot and 14 days of dark means cold temperatures and energy storage is required for the night. Solar arrays rotate east/west to track overhead sun which moves about 12 degrees every day. Radiators should avoid solar pointing.
	Polar Site	Near continuous sunlight means more stable thermal conditions. Solar arrays coninuously track 360 degrees pointing at the Sun on the lunar horizon. Radiators oriented upward to look at "cold" space
	Near Side	Always Earth facing allows direct communication
	Far Side	This side never sees the Earth which means a comm relay system. Moon blocks Earth-generated elecrtomagnetic interference therefore it is a good site for radio astronomy. There is no "dark side".
LOCAL SITING	**Topography**	Site improvement and methods of leveling are necessary to accomodate craters, slope, rocks, uneven terrain, etc.
	Zoning	Liftoff/Landing, Science, Power, ISRU
	Growth	Element size, functionality

Table 3.1 I Siting Implications
Credit: Brand Griffin

NASA has been using the Lunar Reconnaissance Orbiter satellite to create highly detailed 3-D maps of the lunar surface. One such image is the result of over 6.5 billion measurements taken by the Lunar Orbiter Laser Altimeter, a technology that uses precise laser measurements to calculate the changes in height of the Moon's surface features. Dark blue areas on the map indicate deeper craters at the south pole of the Moon, which exhibit greater variation in elevation compared to the north pole (Trent M. Hare et al 2015).

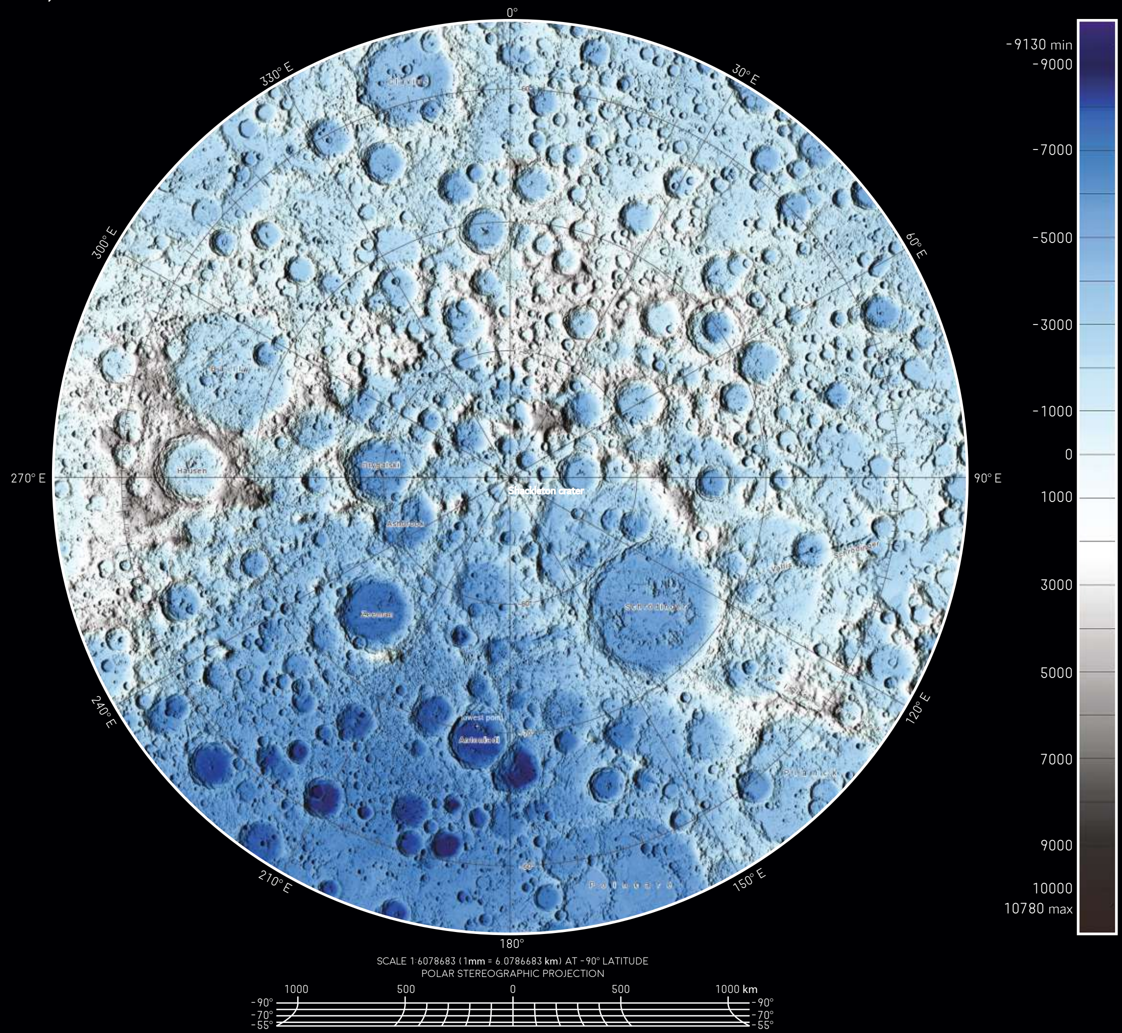


Fig. 3.2 I Topographic Map of the Moon
Credit: NASA

3.3.1 SHACKLETON CRATER RIDGE

Shackleton crater is an impact crater located on the south pole of the Moon, and it has been identified as a potential site for future Artemis missions (NASA 2019). Given that Shackleton Crater meets all the siting implications for a lunar base location, it has been selected as a suitable site for future human exploration under the ATRIO lunar habitat and as X-plor landing site. The chosen location has coordinates of 89.68°S 166.0°W and was selected due to favorable illumination conditions, visible in the Table 3.2. According to data from 2020, this site is illuminated about 81% of the time over the course of a lunar year, with the longest period of darkness lasting approximately 7 Earth days during the worst lunar day. The shortest periods of light between darkness are about 3 Earth days (Bussey et al 2010).

Shackleton is situated within the topographical rim of the South Pole-Aitken basin, which is the Moon's largest and oldest impact crater. It rests on the edge of an interior basin massif and is notable for its depth, extending 4 km down and 21 km across. This crater takes on a cone-shaped form with walls sloping at around 30° (Fig. 3.3-c), and it features a level floor at the bottom. Its central peak reaches a height of approximately 200 meters. Shackleton has been extensively studied, primarily due to its proximity to the south pole. In essence, it is a rather ordinary crater, with most of its interior permanently in shadow (Hawke and Kring 2008).

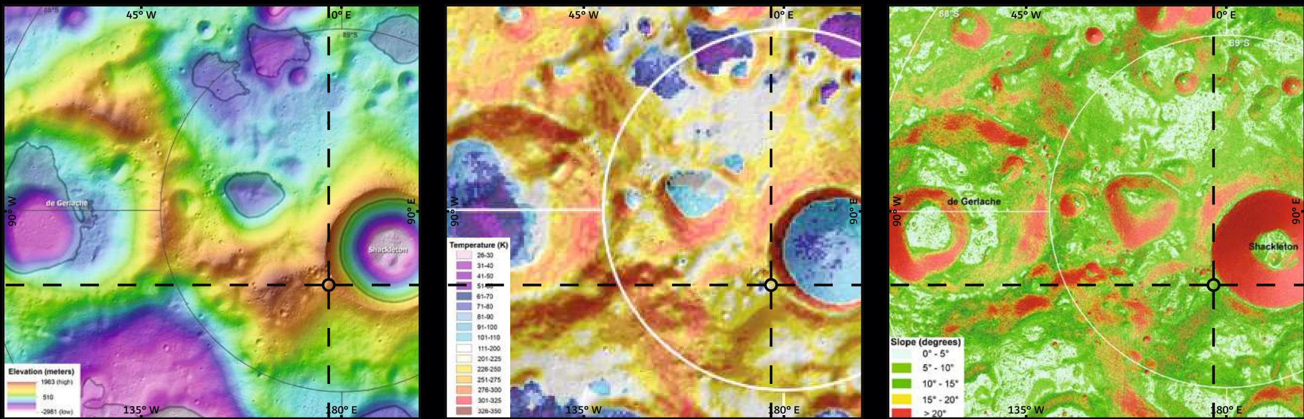
SHACKLETON CRATER RIDGE ATRIO AND X-PLOR SITE		Lunar Coordinates	89.68°S 166.0°W
	Illuminated time fraction	Over lunar year 2020	81%
		Minimum per lunar day	44%
		Maximum per lunar day	98%
	Notes	Even during the worst lunar day the longest period of darkness is ~7 Earth days, with shortest periods of light between darkness of ~3 Earth days	

Table 3.2 I Lighting conditions for lunar pole coordinates
Credit: Brand Griffin

Figure 3.3 presents six maps that were utilized to investigate the geography, geology, topography, and potential resources of the region between Shackleton and de Gerlache craters. These maps are based on data from the The Lunar Reconnaissance Orbiter (LRO), a robotic spacecraft operated by NASA that currently orbits the Moon and provides a precise global lunar topographic model and geodetic grid, which serves as a foundation for essential lunar understanding (Lunar and Planetary Institute 2017).

Shackleton crater is located in a region of the Moon's south pole that is known for its extreme and constantly changing lighting conditions - permanent light and permanent darkness, visible on the Figure 3.3-a. Both these features could affect future lunar exploration. The Moon's minimal axial tilt of 1.5° results in limited seasonal variations. Consequently, lunar polar peaks can experience almost continuous daylight, while some depressions may remain perpetually in shadow, never receiving sunlight. Years of research show ice deposits within Shackleton's shaded interior, preserved by extremely low temperatures (Fig. 3.3-b). From the perspective of human exploration, the presence of significant lunar ice reserves offers several advantages (Johnson 2022):

- **Oxygen to breathe:** Electrolysis, a straightforward electrical process, can split a water molecule (H2O) into oxygen and hydrogen gases. Astronauts could potentially produce their own air by collecting ice, melting it, and extracting the oxygen molecules.
- **Fuel:** Conversely, astronauts could utilize the hydrogen atoms released through electrolysis as a fuel source, whether for rocket propulsion or transportation across the lunar surface.



a) Topography and Permanently Shaded Regions

b) Near-Surface Temperatures Modeled; Maximum temperature (K)

c) Slope; 10 m elevation product

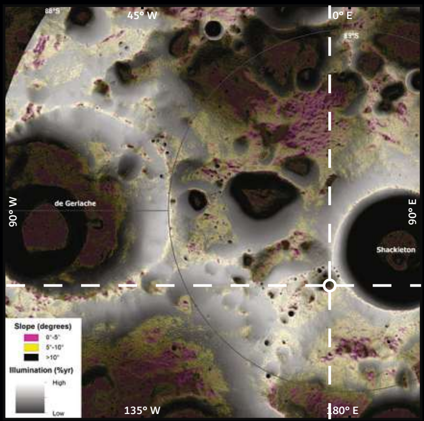
Fig. 3.3 I Lunar South Pole Atlas
Credit: LRO NASA

- **Water to drink:** If lunar ice is readily available, future astronauts could melt it to fulfill fundamental human requirements like drinking, cooking, and washing.

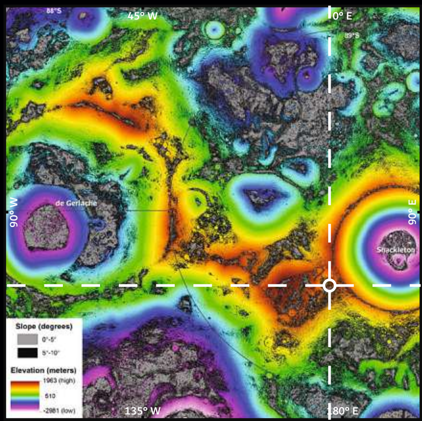
Sunlight is valuable not only for its illumination but also for the electricity it can generate (Figure 3.3-d). Space exploration relies on electrical energy, and although we can transport power from Earth, generating it on-site through solar panels is a more favorable option (Johnson 2022):

- **Constant power:** Shackleton Crater serves as an excellent site for harnessing uninterrupted sunlight and converting it into electricity. The initial infrastructure setup might pose a challenge, but once established, solar panels positioned along the rim of Shackleton Crater could efficiently produce electricity for a developing lunar base. Solar panels in this context would be even more efficient than those on Earth, owing to the consistently clear lunar sky.
- **Light:** Future astronauts planning extended stays can circumvent the challenge of enduring the prolonged lunar nights, which last for 14 days, by establishing their base at a location such as Shackleton.

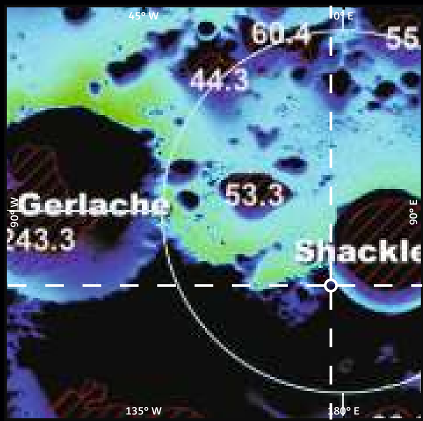
Furthermore, Shackleton crater is an attractive location due to its relatively flat floor (as seen in Fig. 3.3-e), which could serve as a safe and stable surface for spacecraft landings and the construction of lunar infrastructure.



d) Annual Illumination and Topographic Slope



e) Topography and Relatively Flat Areas



f) Earthshine Model

3.4 MISSION TIMELINE

In order to successfully land astronauts on the Moon as part of the Artemis mission in 2025, a lunar infrastructure will be necessary to support continuous and productive residence. Lunar base development will fall into four principal, broadly distinguishable phases, similar to those required in the settling of any radically new region: Precursor Phase, Pioneering Phase, Consolidation Phase and Settlement Phase (Eckart 1999, p. 223). The four principal phases of a lunar base development scenario and their properties are summarized in table 3.3. (Capellari 1972, Duke 1985) and shown on Fig. 3.5.

1

The Precursor Phase is the preliminary automated exploration done by robots. NASA is investigating the Moon in various ways, including through robotic missions, such as the Lunar Reconnaissance Orbiter, equipped with various scientific instruments and cameras to study the Moon's geology, topography, and mineral resources.

2

The Pioneering Phase of lunar exploration involves the preparation of the lunar base site. A lander with habitats, limited science facilities, and surface transportation will be deployed. The lunar exploration and habitation vehicle X-plor will be delivered to the lunar surface in this phase, ahead of the astronauts' arrival. In the same year, the first lunar habitat is planned to be delivered on the lunar surface.

3

The Consolidation Phase involves the establishment of extended surface facilities, including extended science capabilities, mining facilities, a lunar oxygen production plant, and the use of longer-range surface transportation. It will begin with the arrival of two astronauts under the Artemis III mission in December 2025 (Fig 3.4). The second X-plor is anticipated to land on the Moon in 2027, preceding the arrival of four astronauts as part of the Artemis IV mission in 2028.

4

The Settlement Phase is scheduled to begin after 2029, during which astronauts on the lunar surface will aim to reestablish a human presence on the Moon, demonstrate necessary technologies and business approaches, and prepare for future scientific studies and the eventual exploration of Mars.

	Elements	Tasks / Capabilities / Characteristics
Precursor Phase	Orbiters Robotic surface rovers	Lunar topographic mapping Site selection Resource assessment Subsurface data collection Gravity map production Seismic data collection Robotic surface surveys Sample return Experiment definition Instrument definition Space transportation system development
Pioneering Phase	Lander(s) with Habitats	Lunar base site preparation Limited science facilities Surface mining pilot plant Lunar oxygen pilot plant Instrument package emplacements Shortrange surface transportation
Consolida-tion Phase	Extended sur-face facilities	Extended science capabilities Extended mining facilities Lunar oxygen production plant Longer-range surface transportation
Settlement Phase	Fully operational lunar base	Advanced laboratories / Industrial research facilities Large-scale mining facilities Large-scale oxygen production / Oxygen export capabilities Lunar manufacturing facilities Satellite outposts Long-range surface exploration Resupply from Earth minimized Support of Mars missions and other exploration missions Expanding population base

Table 3.3 I Lunar Base Development Phases
Credit: Capellari 1972, Duke 1985

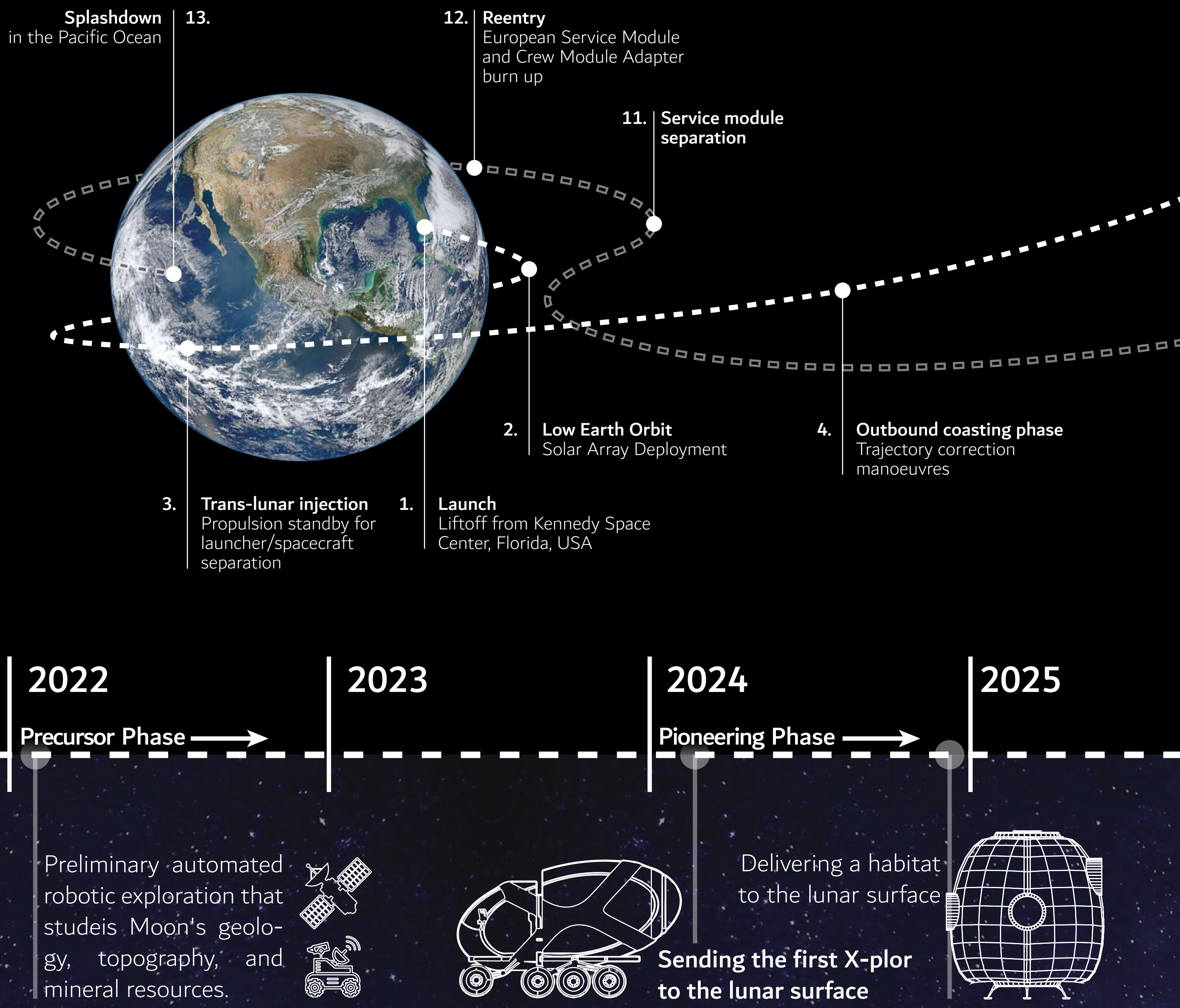


Fig. 3.4 I Artemis III Trajectory
Credit: Based on ESA Infographics

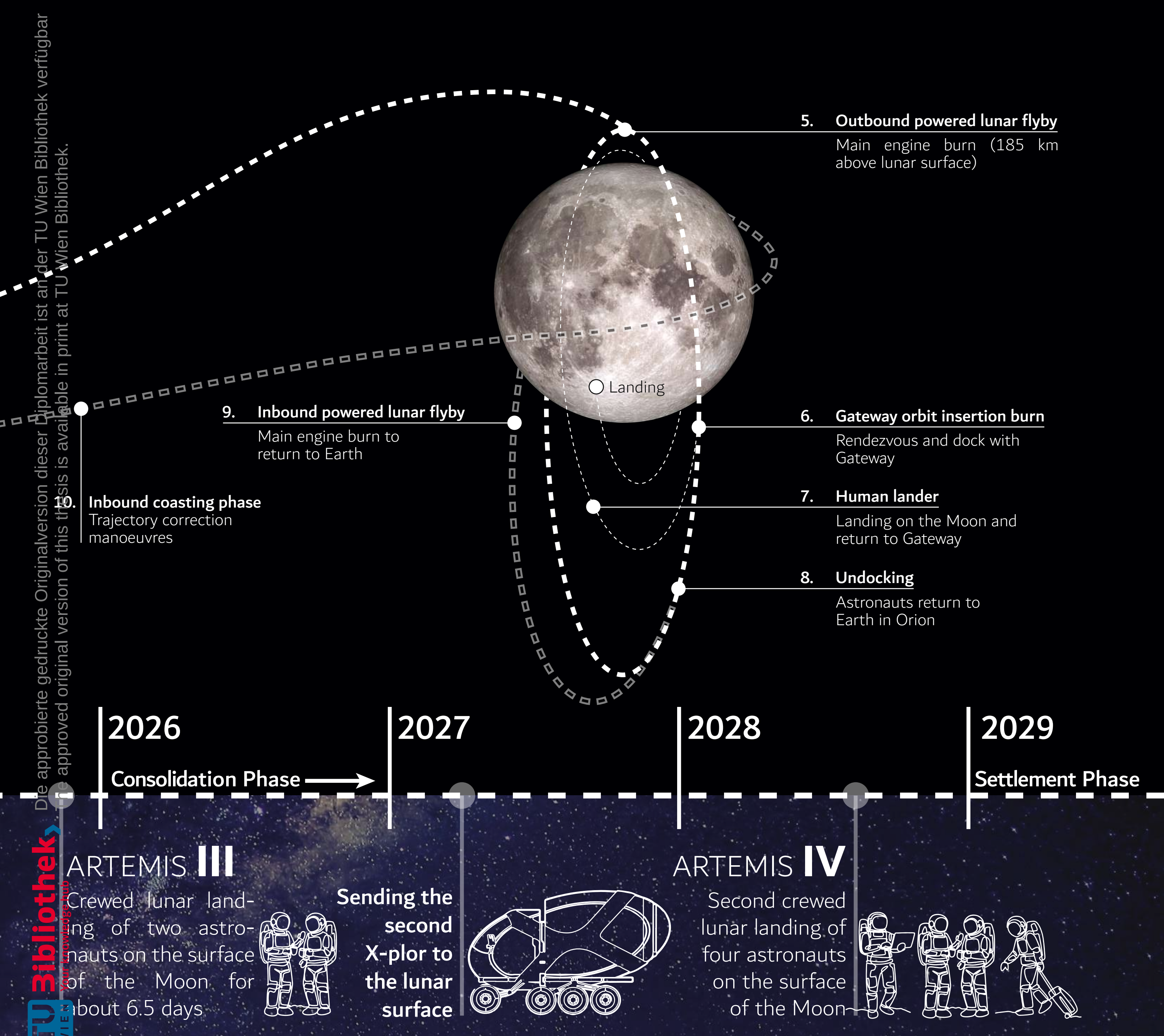
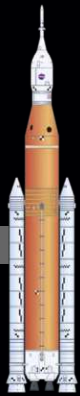


Fig. 3.5 I Artemis Timeline

3.5 MISSION COMPONENTS

The core elements of the Artemis program include the Space Launch System, Exploration Ground System, Orion Spacecraft, Gateway, Landing System, and Artemis Base Camp. These components will enable both robots and astronauts to engage in more extensive scientific exploration than ever before (NASA 2022).



SPACE LAUNCH SYSTEM (SLS)

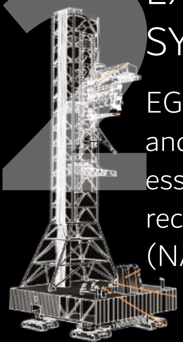
The SLS (Fig. 3.6) is the sole rocket capable of transporting Orion, astronauts, and cargo to the Moon within a single mission. Upon liftoff, the SLS will hold the distinction of being the world's most powerful rocket (NASA 2020-III).

GATEWAY

The Gateway (Fig. 3.9) is the spacecraft positioned in lunar orbit where astronauts will transition between the Orion spacecraft and the lander during routine Artemis missions. The Gateway is designed to stay in orbit for over a decade, serving as a residence and workspace while facilitating sustained scientific research and human exploration activities on and around the Moon (NASA 2021-IV).

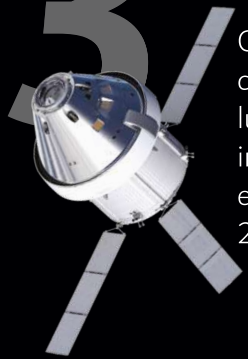
Fig. 3.6 I SLS Block 1
Credit: NASA

Fig. 3.9 I Gateway concept image
Credit: ESA



2 EXPLORATION GROUND SYSTEMS (EGS)

EGS refers to the infrastructure and facilities on the ground essential for astronaut launch and recovery, as shown on Figure 3.7 (NASA 2021-III).



3 ORION SPACECRAFT

Orion is NASA's dedicated spacecraft for transporting astronauts to lunar orbit and back to Earth, serving as the cornerstone of their lunar exploration efforts (Fig. 3.8) (NASA 2019-I).

5 HUMAN LANDING SYSTEM (HLS)

A lunar lander is a specialized spacecraft designed to convey astronauts and cargo from an orbiting spacecraft to the moon's surface, and subsequently return them to the orbiting craft (Fig. 3.10) (NASA 2021-V).

6 ARTEMIS BASE CAMP

The Artemis Base Camp concept (Fig. 3.11) encompasses a modern lunar cabin, a rover, and a mobile home to provide astronauts with a habitat for living and working on the Moon.

Fig. 3.7 I Exploration Ground Systems drawing
Credit: NASA

Fig. 3.10 I Human Landing System concept image
Credit: Lockheed Martin

Fig. 3.8 I Orion Spacecraft concept image
Credit: ESA

Fig. 3.11 I ATRIO as Artemis Base Camp
Credit: ATRIO authors

3.5.1 SPACE LAUNCH SYSTEM (SLS)

The Space Launch System (SLS) is an American super heavy-lift configuration developed by NASA (Fig. 3.12). As of 2022, it holds the record for the highest payload capacity of any operational rocket and the greatest liftoff thrust among all rockets. SLS serves as the key launch vehicle for the Artemis moon landing program, uniquely capable of delivering Orion, astronauts, and cargo directly to the Moon in a single mission (NASA 2020-III).

NASA's Space Launch System (SLS) rocket is designed in four planned versions, known as "blocks," each tailored for specific capabilities and mission objectives. Block 1, the initial version, is intended for the uncrewed Artemis I mission, encircling the Moon. Block 1B, configured for crew missions, will incorporate an Exploration Upper Stage (EUS) and serve for Artemis II, the first crewed SLS flight. Meanwhile, Block 1B for cargo and Block 2 versions will feature more potent core stages and enhanced engines, with Block 2 offering the highest lift capacity, up to 130 metric tons to low Earth orbit.

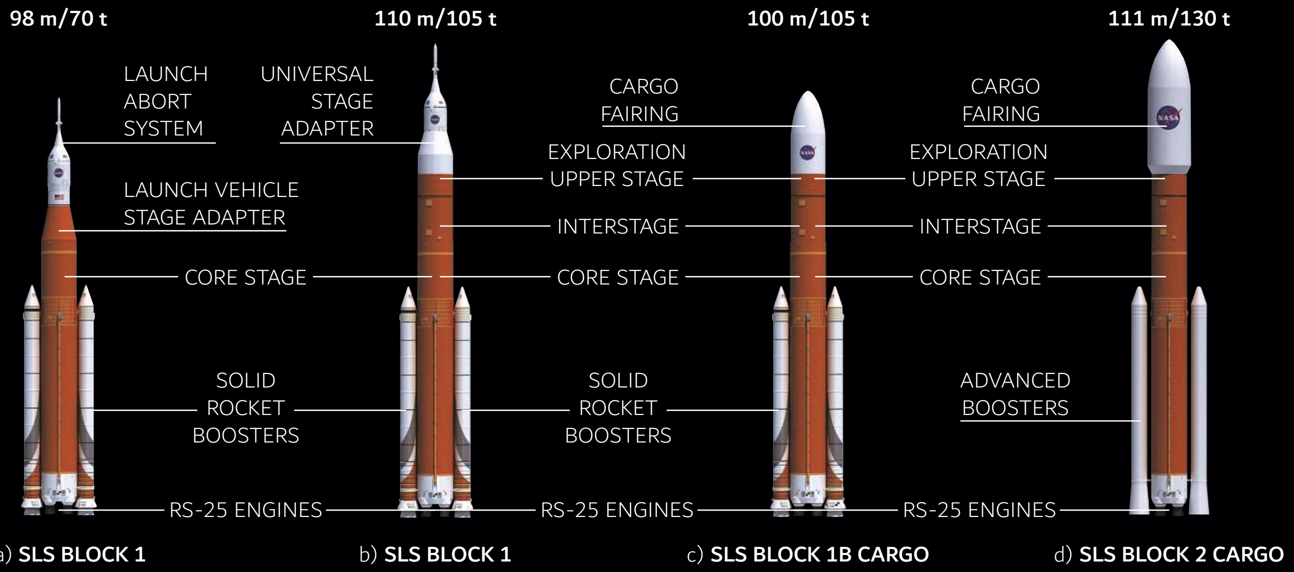


Fig. 3.12 I Space Launch System Configurations
Credit: NASA

The Space Launch System (SLS) Block 1B is a variant of the SLS rocket that is currently under development by NASA. It will be able to transport a range of payloads to the moon, including X-plor exploration and habitation vehicle in the year 2024.

The SLS Block 1B cargo (Fig. 3.13.) is designed to carry large payloads to the Moon, such as the Lunar Gateway modules, and support future crewed missions to deep space destinations like Mars. It will have a more powerful upper stage, the Exploration Upper Stage (EUS), which will provide greater performance and mission flexibility compared to the Block 1 variant. In terms of cargo capacity, the SLS Block 1B will be able to carry up to 45 metric tons of payload to the moon and the rocket will have a height of approximately 98 meters. The cargo fairings are planned to be between 5-8.4 meters in size, and there are plans for even larger fairings in later stages. The Block 1B launches will feature an 8.4 meter diameter fairing that is 19.1 meters or 27.4 meters in length, with an internal cargo diameter of 7.5 meters (Donahue 2017).

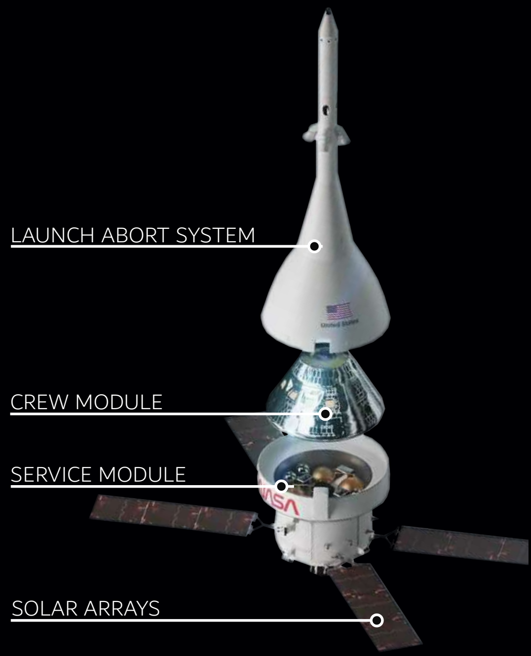
3.5.2 EXPLORATION GROUND SYSTEMS

NASA's Kennedy Space Center's Exploration Ground Systems Program manages the development and operation of systems and facilities crucial for rocket and spacecraft assembly, transport, and launch. Its objective is to evolve the space center from a government-exclusive launch site into a versatile space-port capable of accommodating diverse spacecraft, whether government or commercial. This initiative is laying the groundwork to support multiple spacecraft, including NASA's Space Launch System (SLS) rocket and Orion spacecraft for Artemis I, with the goal of cost reduction and long-term sustainability by opening up processing and launch infrastructure to multiple users (NASA 2021-III).

Fig. 3.13 I SLS Block 1B cargo

3.5.3 ORION SPACECRAFT

Orion (Fig. 3.14) is a partially reusable crewed spacecraft designed to support a crew of four to six beyond low Earth orbit. Its mission includes transporting astronauts to the Moon's surface, the lunar Gateway, and eventually Mars. As an exploration vehicle, Orion features emergency abort capabilities, sustains astronauts during missions, and ensures their safe re-entry from deep space return velocities. Equipped with solar panels, an automated docking system, and glass cockpit interfaces, it can launch atop various vehicles, but it is primarily intended for use with the SLS rocket, featuring a tower launch escape system (NASA 2019-I).



3.5.4 GATEWAY

The Lunar Gateway (Fig. 3.15) represents humanity's inaugural space station orbiting the Moon. It is designed to act as a solar-powered communication hub, a scientific laboratory, and a storage facility for rovers and other robots. Its additional mission involves providing essential support functions to ensure the well-being of astronauts, including pressurized living and working space for mission preparation, scientific activities, meal preparation, exercise, and rest. This pressurized living space is furnished by two modules: the Habitation and Logistics Outpost (HALO) module from Northrop Grumman and, in subsequent missions, the International Habitation (I-HAB) module from ESA (NASA 2021-IV).

Fig. 3.14 I Orion Spacecraft
Credit: Based on NASA

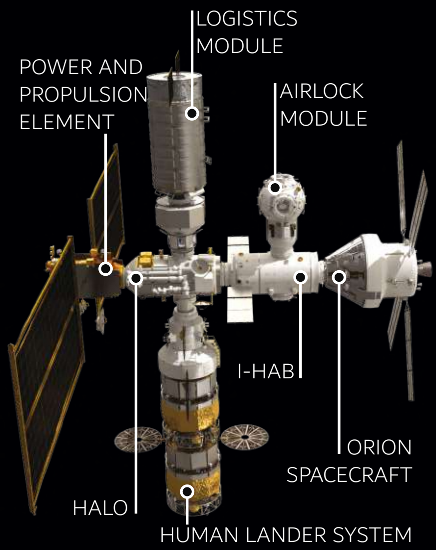
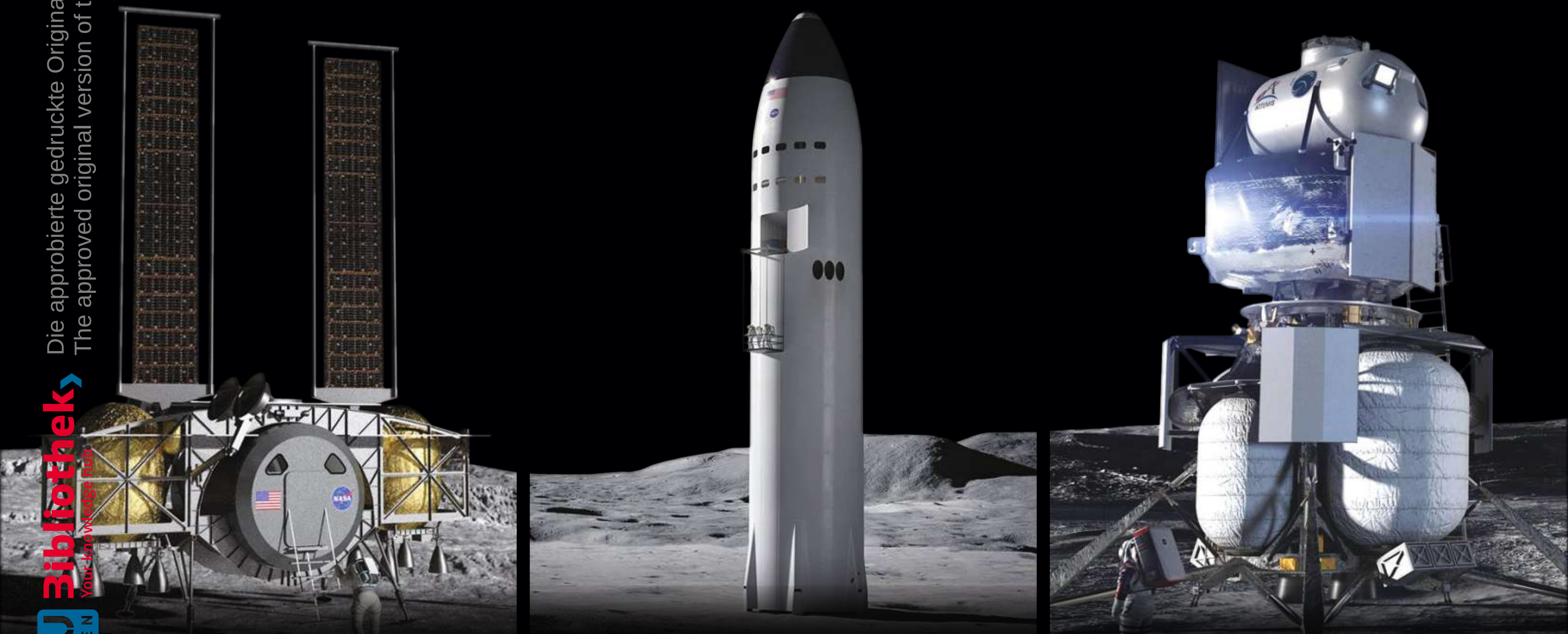


Fig. 3.15 I Gateway
Credit: Based on ESA

3.5.5 HUMAN LANDING SYSTEM (HLS)

NASA is planning to use the Human Landing System (HLS) for its upcoming Moon landing missions, which will include both crewed and uncrewed landers. Human landing systems of the Artemis era will need to be equipped to meet the challenges of complex missions. Required capabilities include docking with multiple systems and astronaut and cargo landing in a range of geographic regions. To achieve these goals, NASA is partnering with three companies to develop and test lunar lander concepts; Blue Origin, Dynetics and SpaceX (Popular Mechanics 2020)(NASA 2021-V).

- **Dynetics' Human Landing System (HLS):** Dynetics' HLS design (Fig. 3.16-a) consists of two elements: a crew module and a descent stage. The crew module will carry up to four astronauts, while the descent stage will provide propulsion and landing capabilities. The Dynetics HLS will use a variety of propulsion systems, including engines fueled by liquid oxygen and liquid methane.



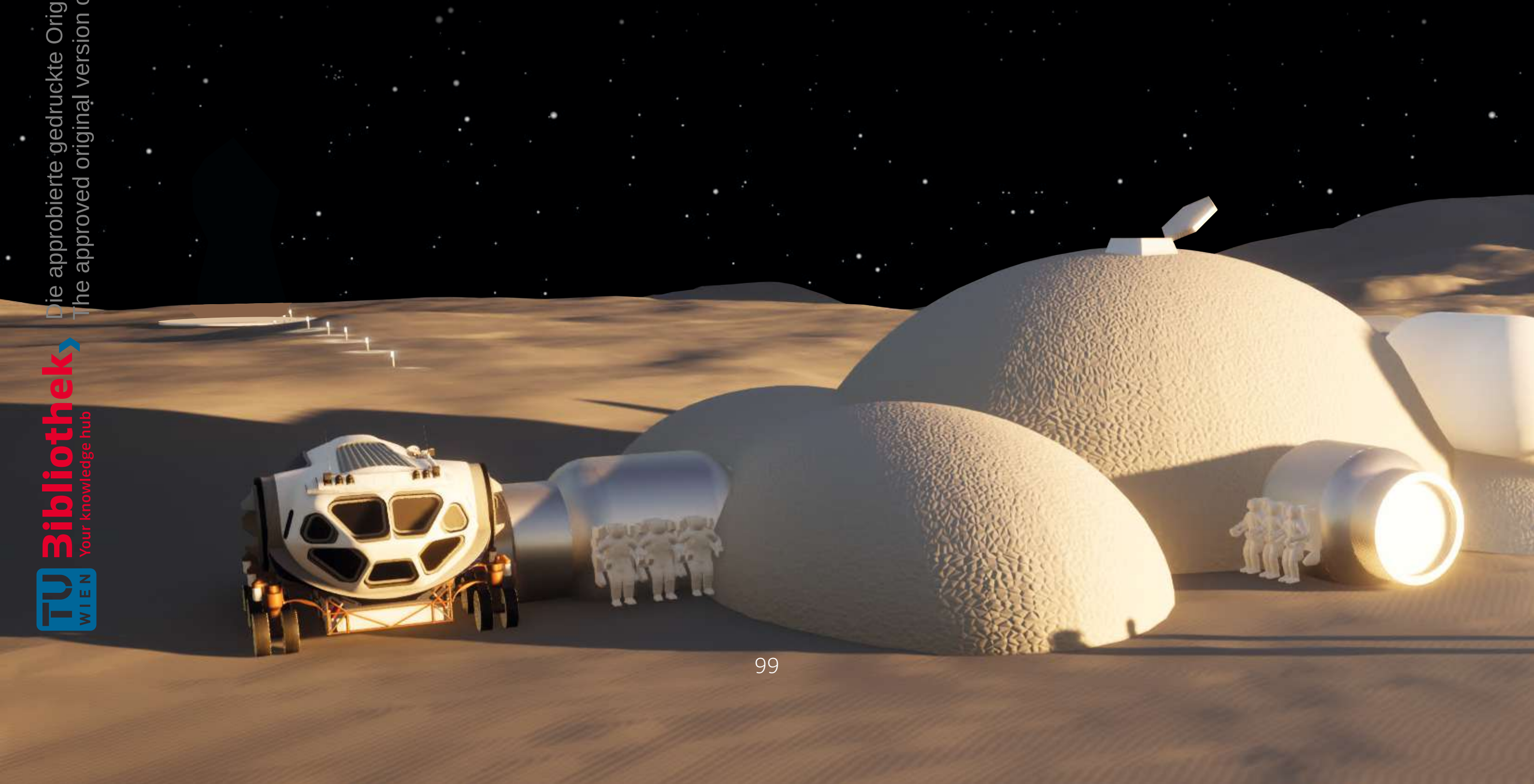
a) Dynetics lander　b) SpaceX lander　c) Blue Origin's lander

Fig. 3.16 I Lunar lander concepts
Credit: Dynetics, SpaceX and Blue Origin

- **SpaceX's Starship:** SpaceX's Starship (Fig. 3.16-b) is a fully reusable spacecraft designed for missions to Earth orbit, the moon, Mars, and beyond. The Starship HLS will be a modified version of the spacecraft, with additional fuel tanks, landing legs, and other specialized equipment for lunar missions. SpaceX plans to launch the Starship HLS atop its own Falcon Heavy rocket.

- **Blue Origin's Integrated Lander Vehicle (ILV):** Blue Origin is developing the three-stage ILV (Fig. 3.16-c), which will use a descent stage, an ascent stage, and a transfer stage to transport astronauts and cargo from lunar orbit to the surface of the moon and back again. The ILV will be powered by Blue Origin's BE-7 engine, which uses a mixture of liquid hydrogen and liquid oxygen for fuel.

Blue Origin's ILV is a lander of choice for landing X-plor to the lunar surface. It is a strong contender for a lunar landing system for several reasons. Firstly, the ILV's three-stage design, along with its docking and landing capabilities, make it versatile and suitable for complex lunar missions. Secondly, Blue Origin is an experienced and respected aerospace company with a proven track record in developing advanced rocket technologies. Finally, Blue Origin is collaborating with other organizations to develop key technologies, which could ensure the ILV is developed in a cost-effective and sustainable manner.



3.5.6 ATRIO AS ARTEMIS BASE CAMP

As already mentioned, ATRIO lunar habitat (Fig. 3.17) has been chosen as the lunar habitat for the Artemis Base Camp. ATRIO is a research facility that explores the relationship between humans and plants, with an emphasis on discovering the full potential of plant development in a micro-gravity environment (Kugic A., Radic V., Alkaabi A., Ayman M., Saeed F., Zrik K. 2021).

ATRIO would be a hub for human exploration and scientific research on the Moon. It would serve as a central location for astronauts to live and work during extended missions to the lunar surface. The concept envisions an inflatable structure that could be expanded and upgraded over time, with the ability to support a range of activities and experiments.

It is designed as a sustainable and resilient research facility that explores the relationship between humans and plants, with a focus on using local resources such as water ice to produce fuel, oxygen, and other necessary materials. This would reduce the need for resupply missions from Earth and make long-term lunar exploration more feasible.

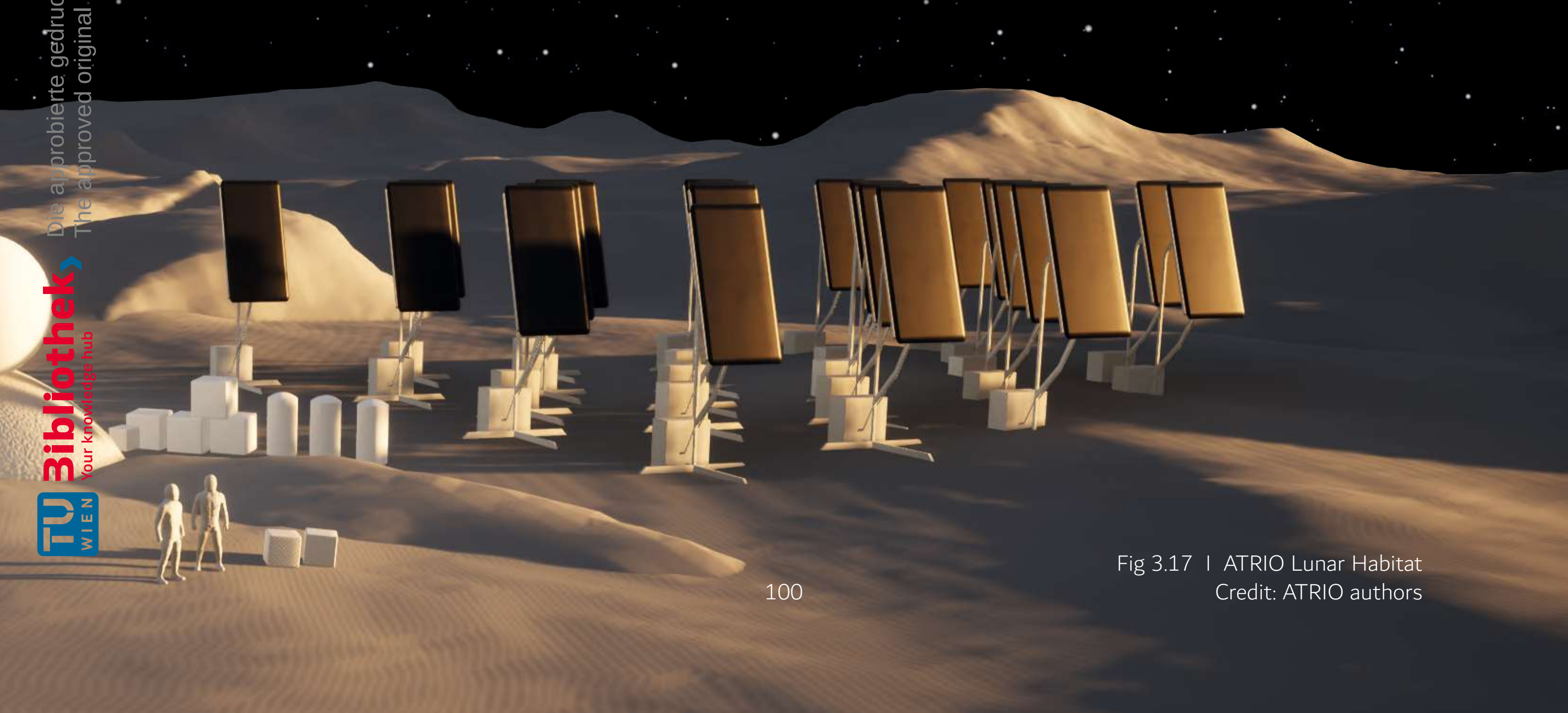


Fig 3.17 I ATRIO Lunar Habitat
Credit: ATRIO authors

The lunar facility can accommodate six crew members, where the plant research will allow a creation of a self-sustainable settlement and help the inhabitants to reach full nutritional independency from Earth. The implementation of plants in the living areas of the habitat will help to maintain the mental health and reduce stress and anxiety, which can often occur in confined environments. Sustainability and habitability are the main tools, which help develop an independent and an agreeable living environment on the lunar surface. By improving the physiological, sociocultural factors, as well as the environmental factors the inhabitants will experience an increase in the quality of life and professional performance, which will be reflected on their overall wellbeing.

3.5.6.1 ATRIO Site Plan

The ATRIO site plan is a layout concept of a ridge in Shackleton crater, which is essential for planning, designing, and optimizing the infrastructure layout of ATRIO. Additionally, it is also significant for the X-plor habitation vehicle landing concept. It shows the components placed on the lunar surface, such as the inflatable habitat, greenhouses for food production, and solar panels for electrical energy production, that are essential for sustaining life and enabling long-term habitation on the Moon. The inflatable habitat provides a living and working space for the crew, while the greenhouses allow for the production of fresh food, reducing the need for resupply missions from Earth. The solar panels are crucial for generating electrical power to support life-support systems and scientific experiments.

Water and oxygen are also essential components for human survival and will be extracted from the nearby Shackleton crater and regolith. The proximity of these resources makes it feasible to sustain a lunar settlement without relying heavily on Earth for supplies.

In addition to these key components, a landing pad located 1.5 km away from the habitat will enable the crew to receive supplies and equipment via pressurized lunar vehicles. This infrastructure will provide a crucial lifeline for the settlement, allowing for regular resupply and maintenance missions to ensure the safety and well-being of the crew (Kugic A., Radic V., Alkaabi A., Ayman M., Saeed F., Zrik K. 2021).

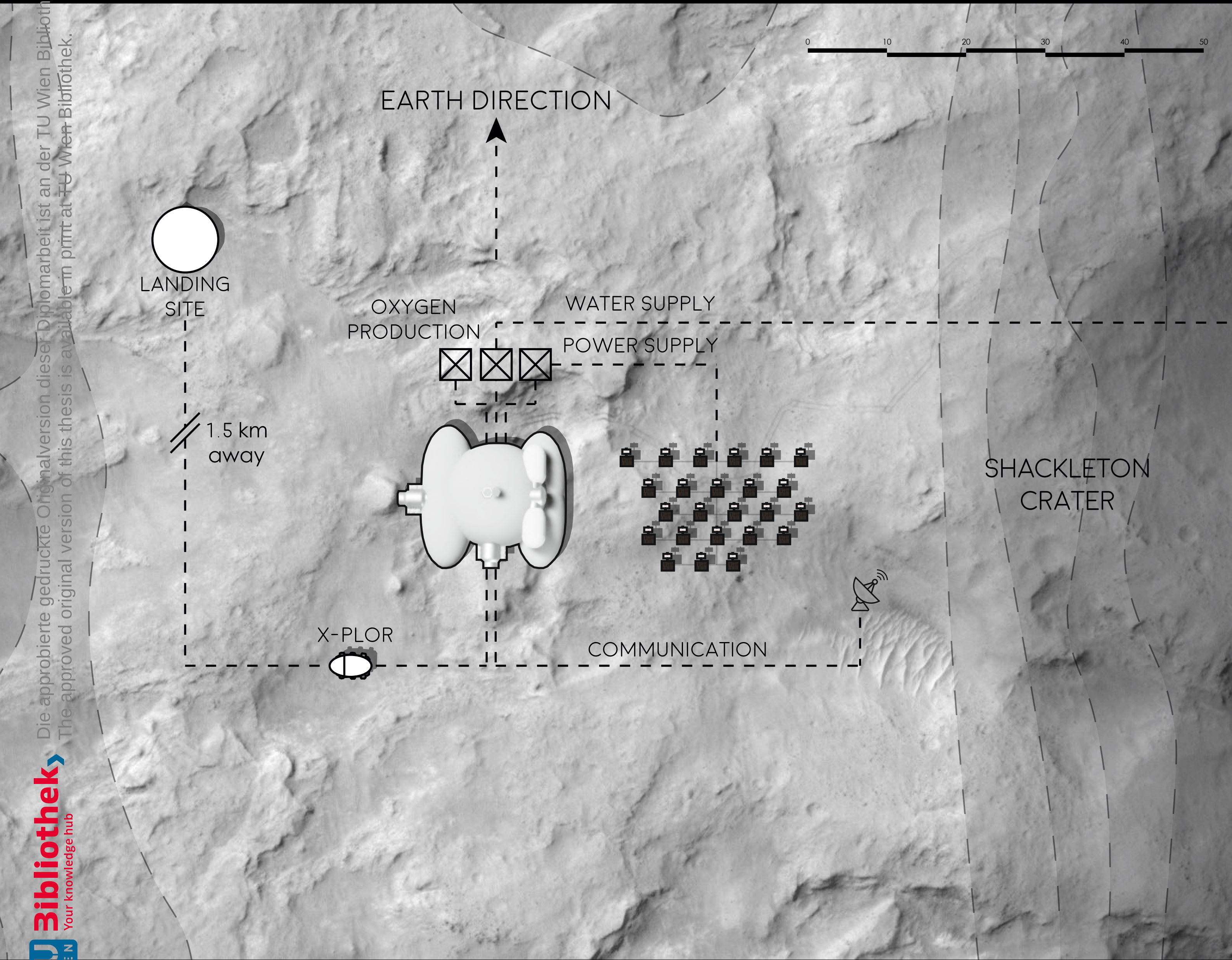


Fig 3.18 I ATRIO Site Plan
Credit: ATRIO authors

3.6 LUNAR ROVER RATIONALE

	REQUIREMENTS
CREW CAPACITY	• 2 astronauts + 2 more in case of emergency
MISSION DURATION	• 2 weeks for short term missions • Support at least 10 years of the Artemis Program
LUNAR ENVIRONMENT SURVIVABILITY	• Survive extreme temperatures of the Lunar South Pole • Operate for at least 2 hours in a Permanently Shadowed Region
PERFORMANCE CHARACTERISTICS	• Modular design and transformable architecture • Reach a top speed of 15 km/h • Capable of traversing cratered highlind terrain and operable over a max slope of ± 20° • Nominal transport of 800 kg, consisting of crew (550 kg) and payload (250 kg)
ROBOTIC MANIPULATION	• Robotics manipulator to support science exploration • Robotically exchangeable end-effectors
REMOTE OPERATIONS	• Operable by on-board and remote crew on lunar surface or Earth • Supervised autonomous operations required, development path to increase levels of autonomy desired
RECHARGE CAPABILITY	• Traverse 100 km on single charge • Capable of recharging itself and external power exchange

Table 3.4 I Requirements and Rationale List
Credit: Author

RATIONALE
• Prioritizing crew safety and mission resilience, aiming to enhance the overall well-being of the crew and implement measures to mitigate risks and ensure successful mission outcomes.
• Minimizing the commute back to base at the end of each day • NASA's decade-long program for lunar exploration emphasizes long-term vision, sustainability, and the maximization of scientific, technological, and operational benefits from the Artemis missions, ultimately establishing a robust lunar presence.
• Ensuring the resilience and effectiveness of equipment and systems in the challenging lunar conditions. • Conducting scientific investigations and exploring areas that receive little to no direct sunlight. By meeting these requirements, exploration efforts can ensure mission success and longevity.
• Flexibility in mission design, coupled with the ability to enhance mission adaptability, versatility, and operational efficiency • Enhancing productivity and enabling astronauts to cover more ground within a given timeframe, maximizing the scientific output and exploration capabilities. • Ensuring mobility and maneuverability in challenging lunar environments, along with a greater radius of exploration. The system's capability to navigate such uneven and rough terrains allows for detailed scientific investigations and search of valuable resources. • Ensuring efficient and effective transportation, supporting the needs of lunar missions and enabling the realization of scientific discoveries and operational goals on the lunar surface.
• Enhancing the capabilities, efficiency and diversity of scientific research during lunar missions • Ability to swap or replace different tools or instruments at the end of the robotic arm provides flexibility for efficient reconfiguration and customization of its capabilities to meet specific mission requirements.
• Expanding the capabilities, enhancing safety, optimizing mission operations, and leveraging the expertise and support available from both on-site and remote personnel. • Increasing levels of autonomy to enhance operational efficiency, reduce the workload on human operators, and enable the system to adapt to dynamic lunar environments.
• Enablling extended range mobility and enhance mission efficiency during lunar exploration. • Ensuring continuous operation, adaptability, and mission resilience. Enhancing autonomy, reducing logistical constraints, and increasing ability to adapt to different mission scenarios.

Lunar Rover Rationale, visible in Table 3.4 serves a crucial purpose in the context of lunar rover development and mission planning. By listing the requirements, it establishes a framework for the rover's design and functionality, guiding the design and development process.

3.6.1 COMPARISON LIST

PARAMETERS	THE LUNAR CRUISER	LUNAR TERRAIN VEHICLE	ATHLETE
DIMENSIONS [m]	vehicle: 6.0 m L x 5.2 W x 3. 8 m H	habitat: 4.5 m L x 3.0 m W x 3.0 m H	habitat: 3.66 m L x 2.34 m Wx 2.34 m H
HAB. VOLUME [m^3]	13 m^3	approx 10 m^3	approx 14 m^3
WEIGH T [kg]	UNKNOWN	4000 kg	850 kg + 450 kg cargo
PRESSURIZED	YES	YES	YES
NUMBER OF PEOPLE	2 (+2 in emergency)	2 (+2 in emergency)	UNKNOWN
SPEED [km/h]	UNKNOWN	10 [km/h]	10 [km/h]
RANGE [km]	10 000 km	125 km	UNKNOWN
RANGE [weeks]	6 weeks	2 weeks	UNKNOWN
MIS SIO N LENGHT	10 years	UNKNOWN	10 years
MODULAR	NO	YES	YES
AUTONOMOUS	YES	NO	NO
SUITPORT	YES	YES	UNKNOWN
POWER SUPPLY	FCEV (hydrogen fuel cells)	FCEV (hydrogen fuel cells)	Solar
WHEELS	6 wheels	12 wheels, can pivot 360°	6 DoF limbs
ROBOTIC ARM	UNKNOWN	YES	YES, robotic limbs

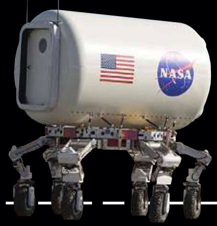



Table 3.5 I Comparison List - expanded
Credit: Author

The comparison list (Table 3.5) between the **Lunar Cruiser**, **Lunar Terrain Vehicle** and **Athlete** allows for a comprehensive evaluation of the different vehicles used in lunar exploration. By comparing their parameters, features, and capabilities, we can gain valuable insights into their strengths, weaknesses, and suitability for various mission requirements.

Through the comparison, it is possible to identify areas where each rover excels and where improvements or innovations can be made. It provides valuable insights that can be used to inform the design and development of new rovers, ensuring that future missions benefit from advancements and optimizations in rover technology.

X-PLOR

habitat: 10.40 m L x 4.90(6.90) m W x 6.00 m H (veh.)
min. 46 m³
5500 kg
YES
2 (+2 in emergency)
15 [km/h]
100 - 150 km
2 weeks
min. 10 years
YES
YES
YES
FCEV (hydrogen fuel cells) + RTG
6 wheels rocker bogie + 2 cockpit +1 robotic
YES

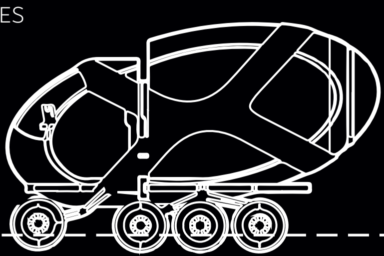


Figure 3.19 depicts Kennedy's graph "Habitable Volume for Increasing Crew Size," where X-plor is positioned between the **preferred** and **performance limit** points with his habitation volume of 46 cubic meters. Nonetheless, it is considered acceptable in light of the mission's relatively short duration, lasting only 2 weeks. X-plor's position within this range reflects the specific considerations taken into account for its design and mission objectives.

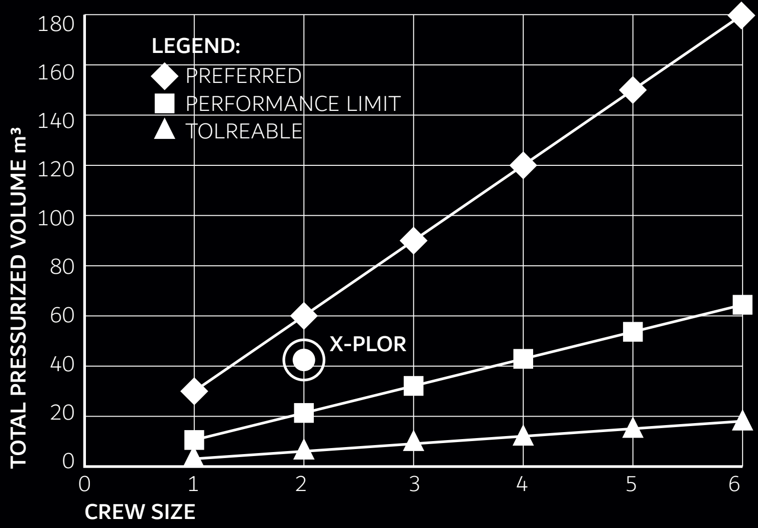


Figure 3.19 | Habitable Volume for X-plor
Credit: Based on Kennedy 2007

04 DESIGN PROPOSAL

"It suddenly struck me that that tiny pea, pretty and blue, was the Earth. I put up my thumb and shut one eye, and my thumb blotted out the planet Earth. I didn't feel like a giant. I felt very, very small."

Neil Armstrong, 1969.

4.1 INTRODUCTION

In order to successfully explore the Moon and beyond, novel approaches to planetary surface exploration by astronauts are planned to be developed, as the challenges of returning to the Moon and exploring Mars differ significantly from the Apollo program's achievements.

The heart of the concept is X-plor; an innovative approach to lunar exploration and habitation resulting from a comprehensive design study. It represents a groundbreaking method for enhancing the safety and performance of astronauts during their missions on planetary surfaces. It can house two astronauts under normal circumstances (with an emergency capacity for two additional astronauts) in a comfortable, shirt-sleeve environment while they traverse the planetary surface. By facilitating extended missions and eliminating the need for daily return to the outpost or lander, X-plor maximizes the productivity of suited crew time.

Through the integration of autonomy and modularity, X-plor addresses the rigorous demands during lunar missions on challenging terrains. Its primary goal is to enable efficient operations by offering exceptional mobility, flexibility, and habitability on the Moon. Its self-deployment architecture allows for customizable appearance and size, tailored to mission requirements and duration, representing a significant leap forward in human planetary surface exploration. This achievement is made possible by the self-deployable transit and habitation system, optimizing X-plor for four distinct configurations: **launch**, **mobile**, **habitation**, and **separated configuration**.

It is planned to put two of those vehicles on the moon in current decade, augmented with scientific equipment for geological observations. Dual rover strategy significantly increases the number of field sites that can be investigated from a single landing site. They are designed to have an extended exploration range that is at least ten times greater than that of the Apollo rovers, and potentially up to 1000 km. Each rover serves as a backup for the other and can accommodate up to four crew members in case of a contingency return to the base, thereby providing a greater range capability than a single, larger pressurized rover.

Fig. 4.1 I X- plor Concept Idea

4.2 VEHICLE HABITATION CONCEPT

The Vehicle Habitation Concept, depicted in Figure 4.2, took its initial form through hand-drawn sketches, serving as the first step towards the creation of a suitable lunar habitation vehicle. These early designs explored the idea of a modular structure, incorporating a distinctive curved and ellipsoid body intended to withstand internal pressure and mitigate the potential hazards of lunar dust on the exterior. The sketches embody an attempt to harmoniously fuse engineering principles with artistic aesthetics, reminding us that the design principles for space exploration are not solely driven by engineering methodologies, but also by the synergy of creative living and design.

Space architects have the important job of turning visions and aspirations into actual structures. They use their knowledge and skills in design, engineering and planning to create spaces that are pleasing, functional and meet the needs of individuals and the environment.

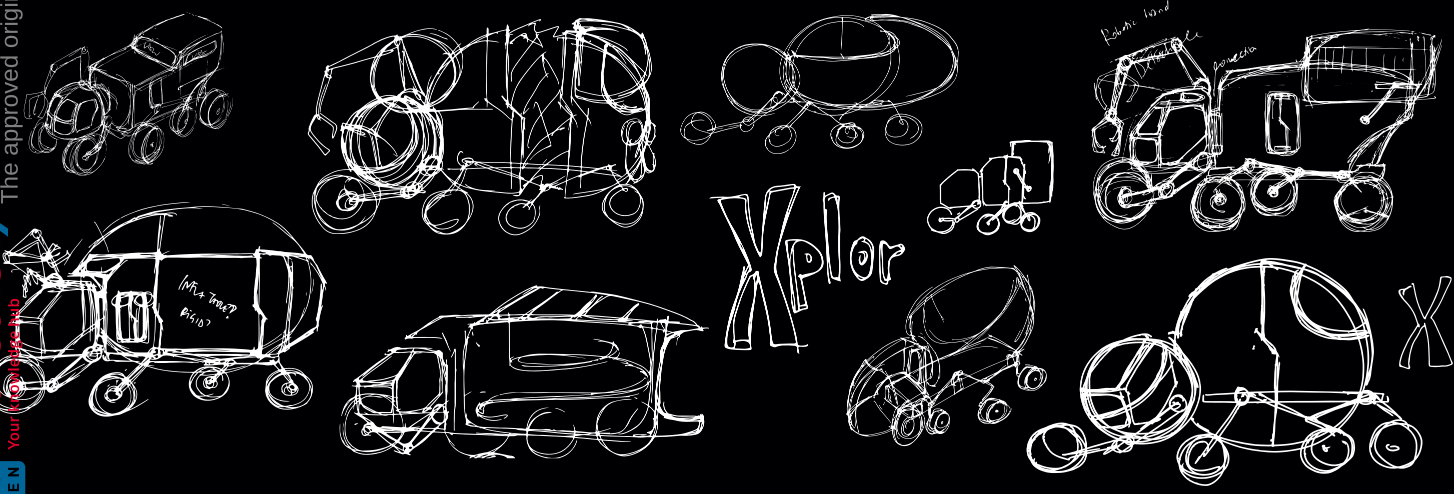


Fig. 4.2 I Vehicle Habitation Concept

4.2.1 VEHICLE LOGIC

The vehicle logic of X-plor is characterized by a modular design and an adaptable architecture. It comprises three primary elements (Fig. 4.3-a): the cockpit, chassis, and payload, which can be arranged and configured in various ways to cater to the specific requirements of astronauts on the lunar surface (Fig. 4.3-b). The transformation of the vehicle occurs depending on its state, whether it is in motion or stationary, leading to distinct mobile and stationary configurations. This flexibility and versatility enables seamless transitions between different operational modes, ensuring optimal performance and functionality throughout lunar missions (Fig. 4.3-c).

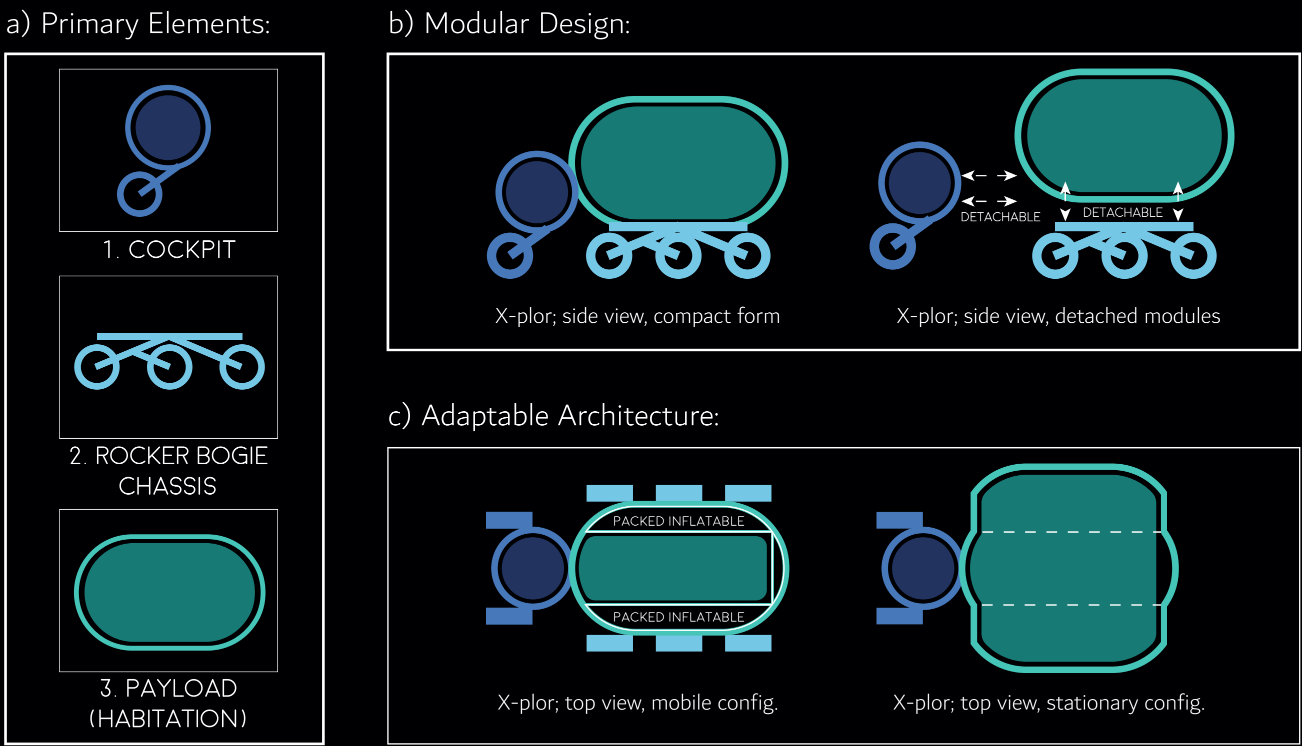


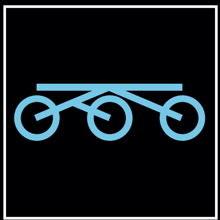
Fig. 4.3 I Vehicle Logic Concept

4.2.2 ENABLING DESIGNS AND TECHNOLOGIES

PRIMARY ELEMENTS: The essential components of the X-plor vehicle consist of the **Cockpit**, **Rocker-Bogie Chassis**, and **Payload**, often serving as a **Habitation Module**. All these elements are carefully designed to create a versatile and adaptable platform for astronauts on the lunar surface, enabling them to achieve their mission objectives while prioritizing their safety and well-being.

1. COCKPIT:

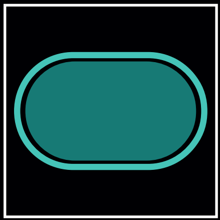
The pressurized cockpit, equipped with two seats, serves as a control center for maneuvering the chassis and payload across the lunar surface. It features a hatch door for seamless connectivity to the habitat module or lunar base and incorporates two suitports for easy ingress and egress. Beyond its driving capabilities, the cockpit also serves as a multifunctional space for mission planning, communication with the lunar base and Earth, and houses its own power supply and air ventilation system. Additionally, it can function independently as a standalone vehicle for specific exploration purposes.



2. ROCKER BOGIE CHASSIS:

A rocker-bogie chassis is a type of suspension system used in rovers or planetary exploration vehicles. It consists of a set of six wheels, a series of rocker arms and bogie assemblies that provide stability and flexibility, allowing the rover to traverse uneven terrain while keeping all wheels on the ground (Verma et al).

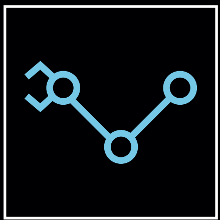
On X-plor, it serves as a versatile platform that can be connected to the cockpit and utilized for transporting various types of cargo. However, its primary function is to serve as the chassis for the habitation module, providing a stable and reliable foundation for lunar surface operations.



3. PAYLOAD (HABITATION MODULE):

The habitation module, designed to be placed on the Rocker-Bogie chassis and connected to the cockpit, serves as a vital living space for astronauts during their missions in the lunar south pole region. Equipped with two hatch doors, one for the cockpit and another for connection with lunar base or other X-plor vehicles, the habitation module provides easy access and mobility. It is equipped with two space suits for emergency exits through the Airlock.
The habitation module is specifically designed to fulfill all essential habitation needs. It includes sleeping pods, a functional kitchen, and a wet compartment for hygiene requirements. Moreover, the module offers additional sleeping spaces for two astronauts, ensuring preparedness for emergencies and adaptability to varying crew sizes. Additionally, it features a fully equipped science laboratory to support various scientific in-situ endeavors.

SECONDARY ELEMENTS: The X-plor rover incorporates various secondary elements to enhance its functionality and support astronauts in their lunar exploration missions. These elements are: robotic arm, glovebox, suitports, docking hatch, deployable walls, cockpit window, wheels and solar arrays.

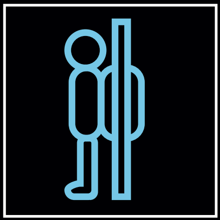


ROBOTIC ARM:

The X-plor is equipped with a robotic arm that provides additional dexterity and manipulation capabilities. It can be used for various tasks, such as collecting samples, deploying scientific instruments, or assisting in maintenance operations. It can serve as a transformative component, functioning as a wheel for the cockpit and transforming it into a vehicle with enhanced mobility and maneuverability.

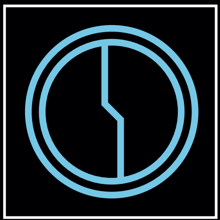
GLOVEBOX:

The glovebox, located in the Science laboratory of the X-plor, provides a secure workspace for astronauts to handle samples and conduct experiments with precision and safety. It relies on the robotic arm, which is connected to the cockpit, for sample collection and manipulation during lunar exploration.



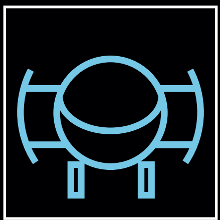
SUITPORTS:

The X-plor rover features two suitports integrated into the cockpit, providing secure entry and exit points for astronauts in their spacesuits. These suitports offer several advantages, including efficient and rapid ingress/egress during extravehicular activities, minimizing therisk of contamination from lunar dust, and facilitating easy transitions between the pressurized vehicle and the lunar surface. Additionally, the suitports ensure the crew's safety by maintaining a controlled environment and preventing the loss of valuable resources such as breathable air. Suits are securely housed in a closed compartment, safeguarded from dust and other contaminants by sliding doors.



DOCKING HATCH:

The X-plor rover is equipped with docking hatches in standardized dimensions, providing convenient and secure connections between various components. The cockpit features one docking hatch, while the habitation module is equipped with two, enabling connections to both the cockpit and lunar base. They ensure compatibility and ease of integration, allowing for efficient transfer of crew members, equipment, and supplies between different modules of the X-plor vehicle and the lunar base.



DEPLOYABLE WALLS:

The X-plor rover incorporates two expandable walls as integral components of its structural design. This innovative design allows for a 1-meter expansion, effectively increasing the overall volume of the rover and creating additional habitable space. These expandable walls provide flexibility, as they can be utilized when needed to accommodate specific mission requirements or activities. This dynamic feature optimizes the utilization of space, ensuring that resources are allocated efficiently and allowing for a more comfortable and functional environment during specific phases of lunar missions.

COCKPIT WINDOW

The X-plor features a single window on the cockpit, designed with shutters for protection against thermal and radiation effects. In addition to its primary purpose of providing a view outside, the window also functions as an augmented reality (AR) screen, allowing astronauts to access digital information and visualizations. Furthermore, the window can be utilized as a telescreen, enabling communication and video transmissions between the vehicle and external sources.

UNIQUE WHEEL DESIGN

The X-plor rover features custom wheels designed for lunar exploration. Traditional air-filled tires are unfit for the Moon's unique conditions due to a lack of atmosphere, extreme temperatures, and potential for meteoroid impacts. These factors make air-filled tires unreliable for weight support, traction, and durability, posing the risk of immobilization or pressure fluctuations. Consequently, the X-plor's wheels are manufactured using a specialized approach reminiscent of the Lunar Roving Vehicle used during the Apollo missions. These wheels feature a construction consisting of a woven mesh crafted from zinc-coated piano wire, complemented by titanium treads meticulously riveted onto the mesh in a chevron pattern. This unique design ensures that the wheels do not sink into the soft lunar soil, providing enhanced traction and stability. (Smithsonian 2020).

ROLL OUT SOLAR ARRAYS

X-plor incorporates the use of Roll-Out Solar Arrays (ROSA), which are positioned between the cockpit and habitat module. ROSA presents a novel and advanced solution compared to traditional solar array technologies. It boasts a compact design, increased affordability, and autonomous features that greatly enhance various scientific and commercial missions. By harnessing the energy from the sun through ROSA, X-plor maximizes its operational potential and reduces reliance on external power sources, making it a self-sustaining and versatile lunar exploration vehicle (NASA 2022).

4.2.3 TRANSPORT AND MODULAR DESIGN

The X-plor is designed to be launched into space using the SLS Block 1B Cargo, which features an internal cargo diameter of 7.5 meters (NASA 2021). Despite its compact design, the X-plor measures only 5x6 meters in diameter when vertically positioned (Fig. 4.4). This optimized size allows for efficient transportation and integration into the launch vehicle, while still providing ample space for the necessary components and functionalities required for lunar exploration and habitation.

The modular design enables primary elements, such as the cockpit, chassis and payload (habitation module) to be easily interconnected or detached based on mission requirements. This modular design enhances the vehicle's versatility, as it can be customized and reconfigured to meet specific needs, making it well-suited for diverse exploration scenarios and optimizing the utilization of resources. Additionally, the modular design of the X-plor enables the integration of various secondary elements, as illustrated in Figure 4.6.

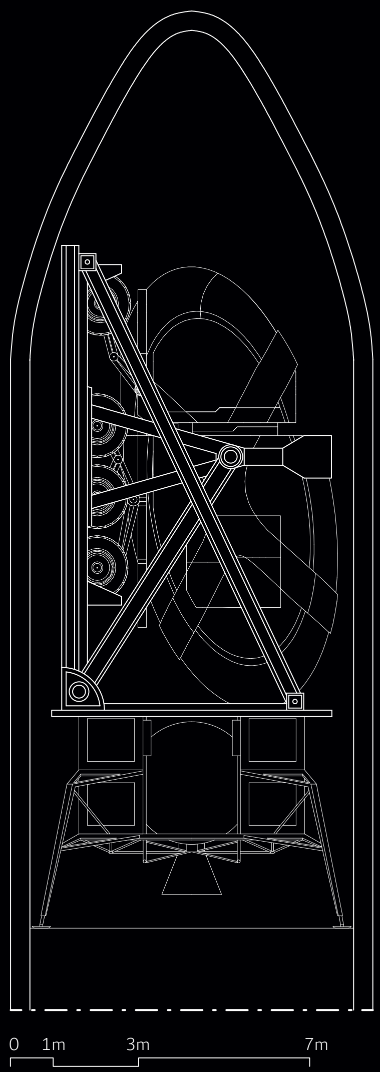


Fig. 4.4 I X-plor in transportation vehicle

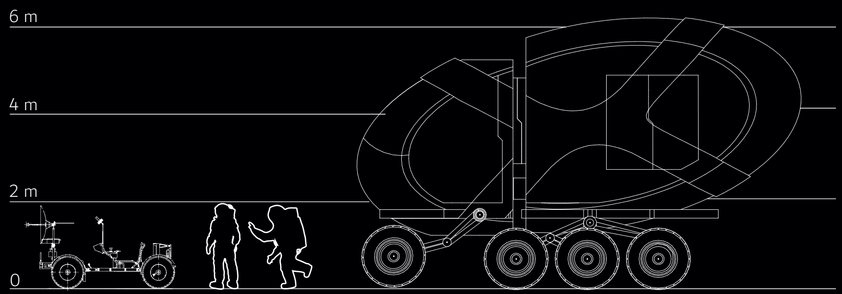


Fig. 4.5 I X-plor and Apollo rover size comparison

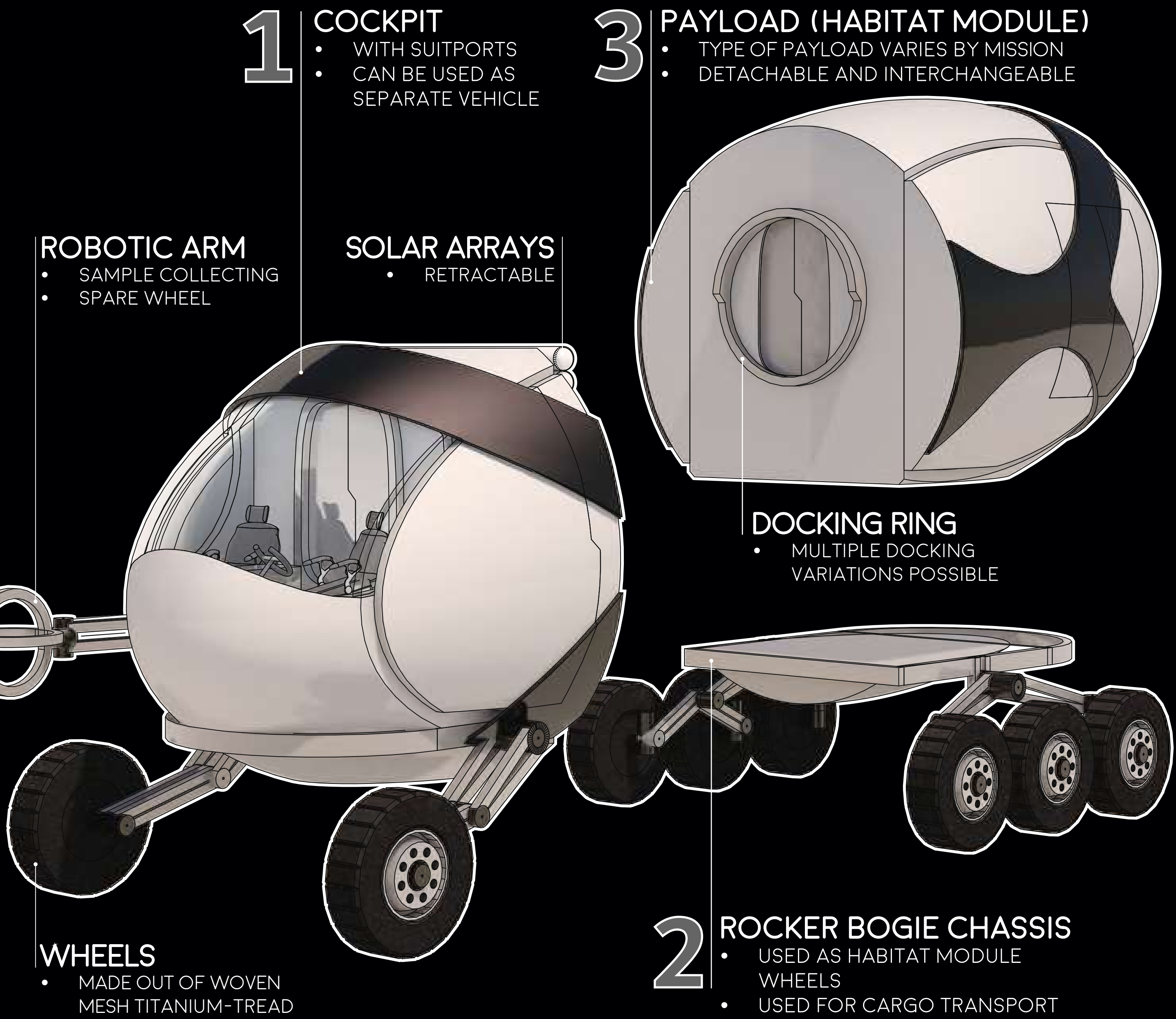
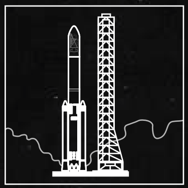


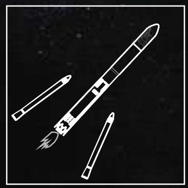
Fig. 4.6 I X-plor Modular Design

4.2.3.1 Transit to the Moon



LAUNCH

X-plor launch from NASA's Kennedy Space Center in Florida in SLS Block 1B Cargo



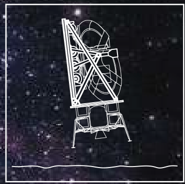
BOOSTER SEPARATION

After boosters have burned out their fuel, they are no longer needed to propel the rocket

Fig. 4.7 I X-plor automatic offloading

CARGO DEPLOYMENT

Release of X-plor with lander from the SLS rocket once it reaches its designated location



LUNAR LANDING

The successful touchdown of the Blue Origin lander carrying X-plor

4.2.4 ADAPTABLE ARCHITECTURE

In the context of adaptable architecture, X-plor offers four different configurations (Fig. 4.8). This ability to transform allows X-plor to flexibly respond to specific operational requirements and adapt to different mission objectives. By providing versatile options, X-plor enhances efficiency and maximizes the utilization of the vehicle during lunar missions.

A

Mobile Configuration: The mobile configuration of X-plor represents a compact form in which the cockpit is connected to both the chassis and the habitation module. This configuration is specifically designed for efficient travel across the lunar South Pole, allowing astronauts to navigate challenging terrains while maintaining a streamlined and maneuverable vehicle. The mobile configuration ensures optimal mobility and agility, enabling the exploration and traversal of diverse lunar environments during the mission.

B

Habitation Configuration: This configuration of X-plor is utilized when the vehicle is stationary for a certain period of time to facilitate extravehicular activities (EVA) and conduct in-situ scientific research. In this configuration, the walls of the habitation module have the capability to expand, allowing for an increase in habitable volume and the establishment of a dedicated scientific laboratory. This configuration provides a comfortable and spacious environment for astronauts to carry out their research tasks and scientific investigations while ensuring their safety and well-being on the lunar surface.

C

Cargo Transport: In the cargo transport configuration, the cockpit of X-plor is connected to the chassis, allowing for the efficient loading and transportation of cargo using the robotic arm. This configuration expands the vehicle's capabilities to facilitate the delivery of vital supplies and scientific equipment to various locations on the lunar surface, enabling comprehensive exploration and resource utilization missions.

D

Separated Configuration: In the separated configuration, the cockpit of X-plor is detached from the rest of the rover, utilizing the robotic arm as a third wheel. This configuration enables the cockpit to operate as an independent vehicle, offering increased speed and agility compared to when it is connected to the chassis and habitation module. The separated configuration provides flexibility for specific mission requirements, allowing for rapid exploration or targeted scientific investigations in locations that may be inaccessible to the fully assembled vehicle.

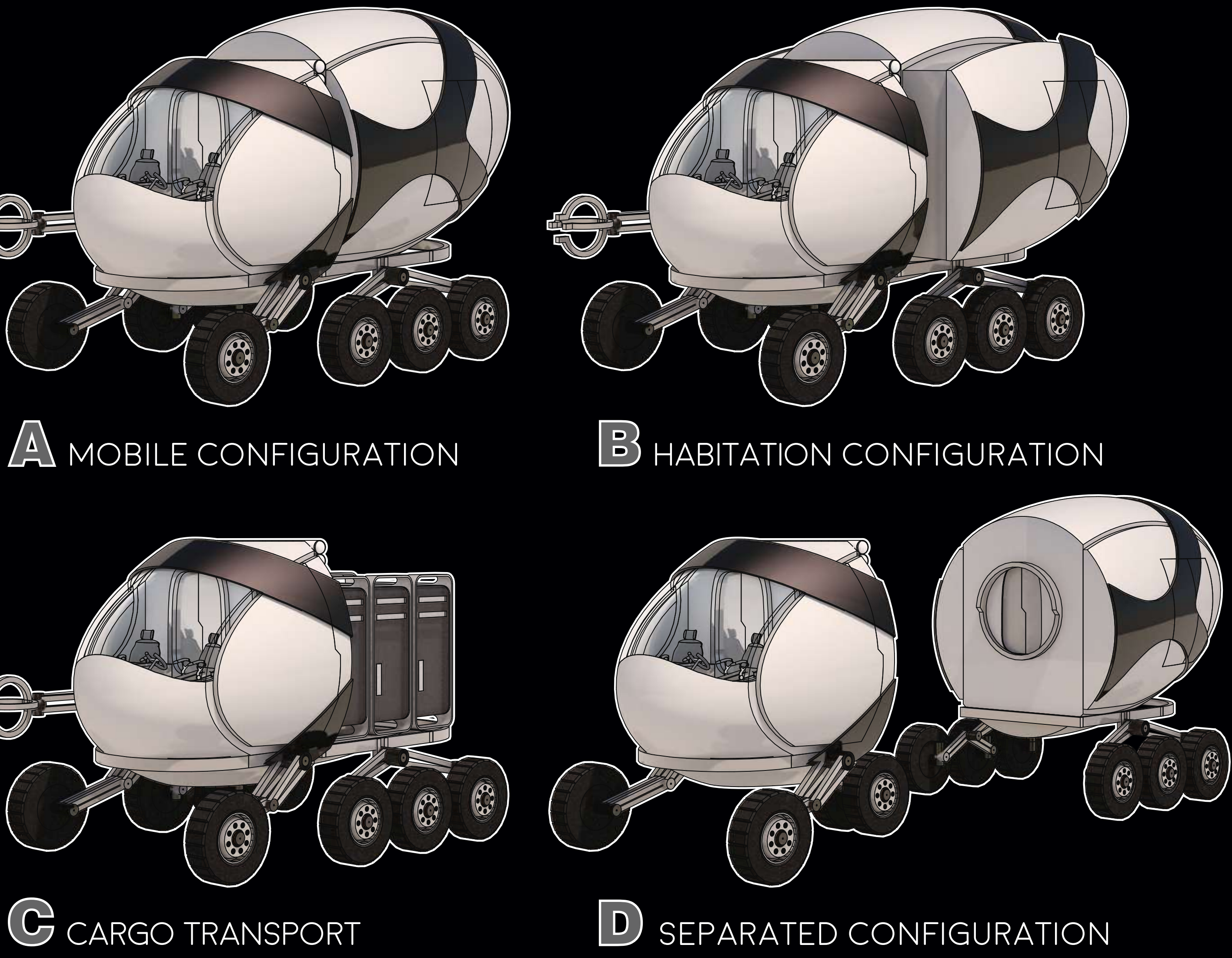
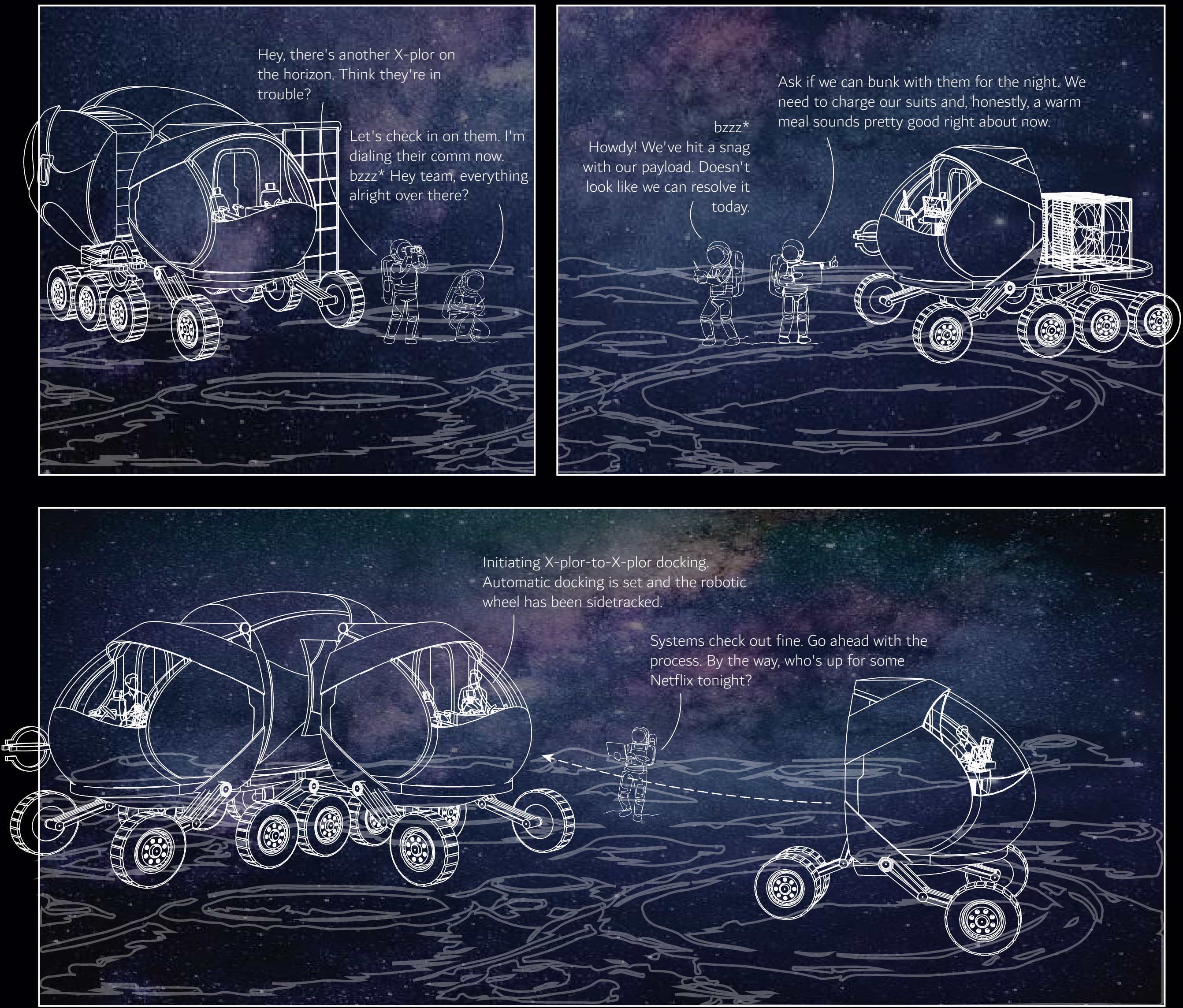
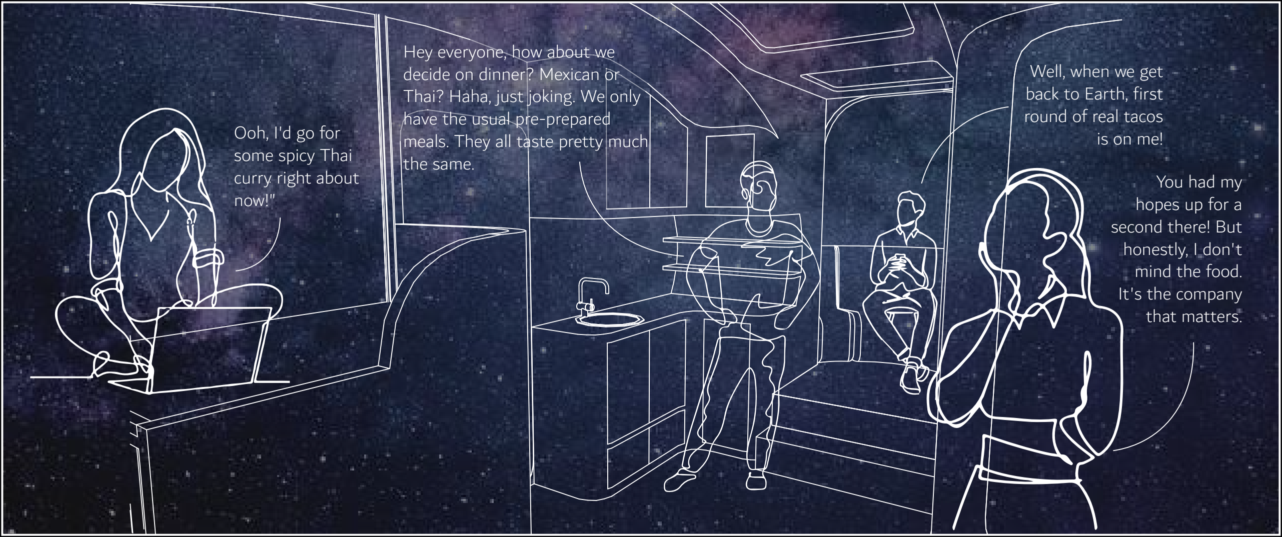
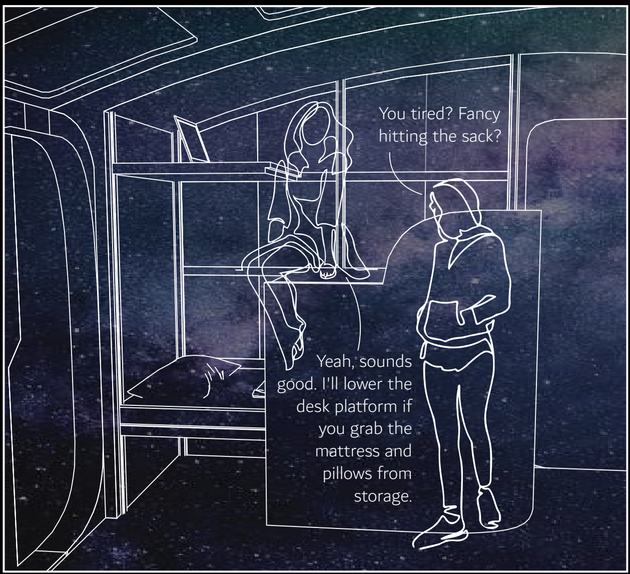


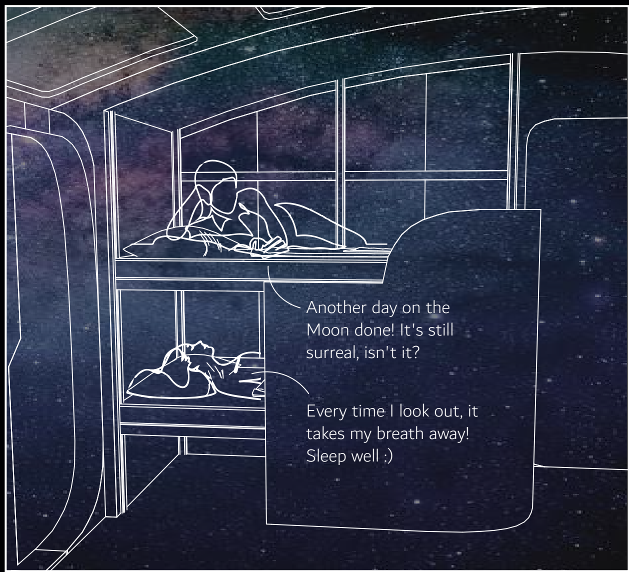
Fig. 4.8 I X-plor Configurations

4.2.4.1 Storyboard




Ooh, I'd go for some spicy Thai curry right about now!"
Hey everyone, how about we decide on dinner? Mexican or Thai? Haha, just joking. We only have the usual pre-prepared meals. They all taste pretty much the same.
Well, when we get back to Earth, first round of real tacos is on me!
You had my hopes up for a second there! But honestly, I don't mind the food. It's the company that matters.


You tired? Fancy hitting the sack?
Yeah, sounds good. I'll lower the desk platform if you grab the mattress and pillows from storage.


Another day on the Moon done! It's still surreal, isn't it?
Every time I look out, it takes my breath away! Sleep well :)

4.2.5 HABITATION AND ORGANIZATION REQUIREMENTS

The current configuration of X-plor was designed with the human factors and habitability considerations described in chapter no. 2 "Space Architecture", while also taking into account certain constraints associated with the existing modules of the vehicle. As already mentioned, the round (oval) shape of the X-plor vehicle serves a dual purpose, providing structural strength to withstand internal pressure and provides protection against the potential hazards posed by lunar dust on its exterior surface. Additionally, this geometric design includes features that enhance the perception of spaciousness, promoting a comfortable and productive environment for the crew. The smaller volume at foot level in opposition to the larger volume at standing height increases the perceived volume of this small space (IHMC 2008).

Designed for two astronauts on two-week-long lunar journeys, the habitable rover incorporates various functional and habitable areas crucial for supporting the crew's mission. These designated areas are strategically divided into **work**, **social**, and **private spaces**, with invisible transitions and encouraging interactions between them (Fig. 4.9). The division of habitable areas, along with their activities, functions, and rationale, is comprehensively presented in Table 4.1.

In the X-plor vehicle, the circulation is designed to facilitate movement and access between different areas. The main entrance, located at the side of the habitat module, features hatch doors that dock with other X-plor vehicles or lunar bases, ensuring crew transfer and efficient resource exchange. Upon entering the rover, there is a division point that branches off into three directions. To the left are the sleeping pods and eventually the cockpit. On the right side, there is the kitchen and lounge area. In front of the division point is the science lab.

- **THE COCKPIT:** The cockpit functions as a central hub for navigation and control, providing a space for piloting and operating the rover. However, it can also be utilized for relaxation and dining purposes, offering a versatile and multi-functional area within the rover. It is also equipped with two suitports, which serve as another exit and entry points for astronauts. Between the cockpit and the

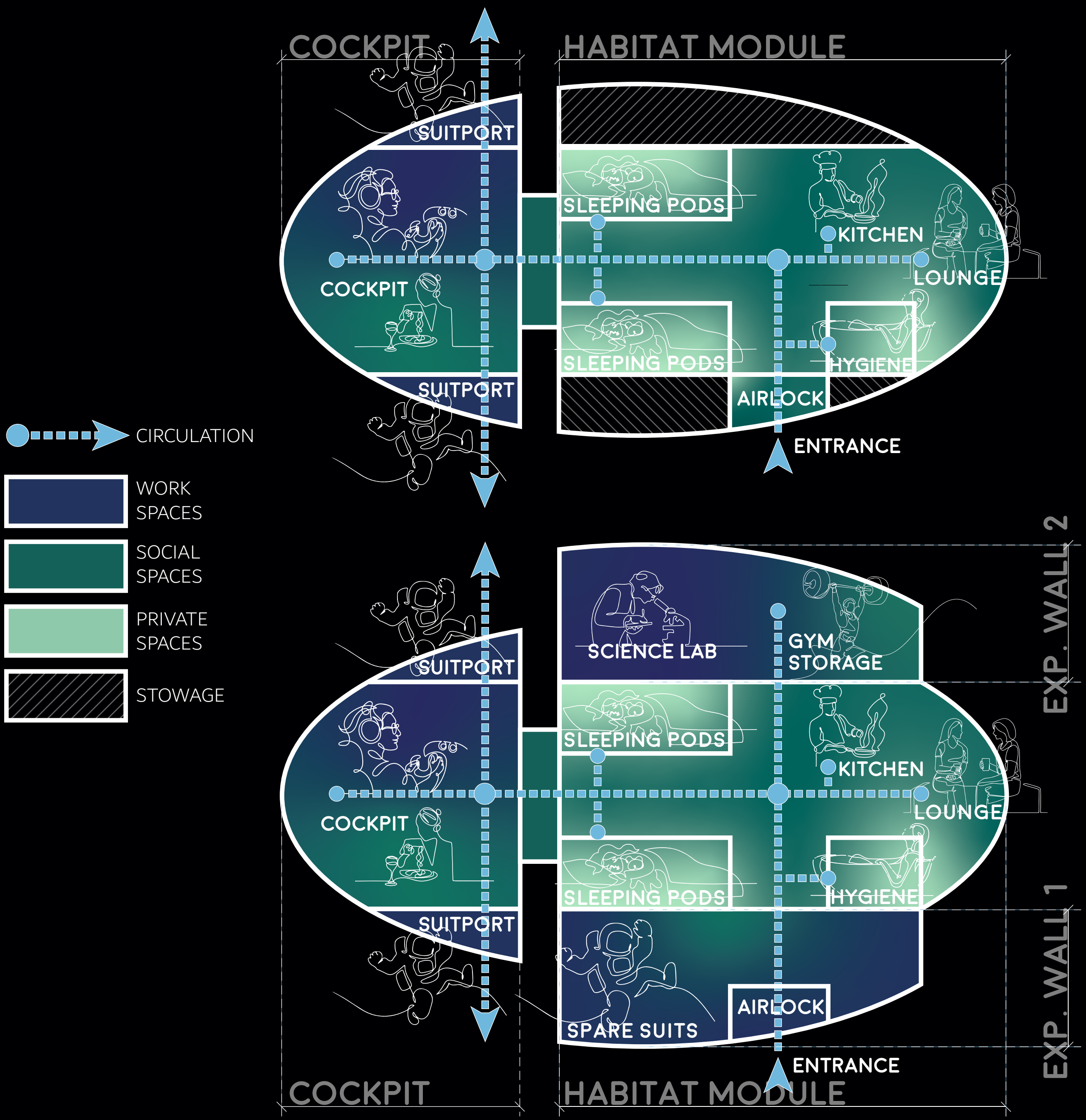


Figure 4.9 I Habitable Area and Circulation

DIVISION	HABITABLE AREA	ACTIVITY	AREA	FUNCTION
WORK SPACES	**COCKPIT**	Driving Communication center Mission planning	5.20 m2	Serves as the central control and operational hub, providing astronauts with a pressurized environment for listed activities.
	SUITPORTS/AIRLOCK	Exits and entrances Suit maintenance	total 6.05 m2	Provide a secure and controlled transition between the pressurized and unpressurized environments.
	SCIENCE LAB	In-situ scientific research Med bay	4.70 m2	Equipped with advanced scientific instruments and tools, providing a controlled and sterile environment for conducting experiments and analyzing lunar samples.
SOCIAL SPACES	**COCKPIT**	Dining AG window used for movies	5.20 m2	Used for leisure time because it provides comfortable seating arrangements and entertainment systems for movie watching, creating a relaxing and enjoyable environment.
	LIVING	Socializing Relaxing	7.85 m2	Serves as a space for socializing and relaxation with a welcoming atmosphere for astronauts to connect and unwind during their mission.
	KITCHEN	Food storage and preparation	1.40 m2	Provides a functional space for astronauts to prepare meals and store food, ensuring their nutritional needs are met during their mission.
	GYM	Workouts	1.10 m2	Serves as a space for physical exercise and maintaining physical well-being of the crew.
PRIVATE SPACES	**SLEEPING PODS**	Sleeping Relaxing	1.90 m2	The sleeping pods offer not only a comfortable sleeping place but also serve as storage compartments for the astronauts' personal belongings during their mission.
	HYGIENE	Toilet Body washing	0.90 m2	The wet compartment provides the necessary facilities for personal hygiene and bathing activities for the astronauts.

Table 4.1 I Habitable Space Division and Rationale

Lorem ipsum

RATIONALE

Workspaces in X-plor serve multiple purposes, including efficient task execution, easy organization and accessibility of tools, ensuring safety and ergonomics, facilitating task specialization and collaboration, and effective information and data management. These workspaces are designed to optimize efficiency, safety, collaboration, and information management during lunar missions.

Social spaces are vital in the X-plor habitat as they encourage connection and relaxation, strengthening the bond between crew members and enhancing their well-being during lunar exploration. These spaces facilitate collaboration, shared meals, and recreational activities, fostering a positive and supportive environment for the astronauts on board the X-plor habitat.

Private spaces are crucial to ensure personal privacy, rest, and rejuvenation. These spaces provide a retreat where astronauts can unwind, have personal time, and maintain their mental and emotional well-being in the demanding and communal environment of the lunar exploration mission.

habitat module, is a hatch door that seals off these two sections, ensuring separation when needed. This allows for independent access and operation of each area.

- **HABITAT MODULE:** The sleeping pods within the habitation module are designed to be transformable in size, providing customizable personal spaces for the astronauts. Additionally, in emergency cases, the sleeping pods can be converted into additional beds, maximizing the utilization of available space. The kitchen and hygiene (wet compartment) are positioned across from each other for convenience and efficient use of plumbing connections. Located at the rear of the rover, the lounge provides a semi-circular space designed for socializing and enjoying leisure time together. The custom-made furniture inside the X-plor habitat features rounded edges to prioritize safety, ensuring the well-being and comfort of astronauts while preventing potential injuries during movement.

- **EXPANDABLE WALLS:** The habitation module of the X-plor vehicle incorporates two expandable walls that allow for an increase in habitable volume. One wall expansion creates a dedicated scientific laboratory and a med bay, featuring a glove box and a small hatch door. Additionally, storage for gym equipment is conveniently located there, promoting crew exercise and physical well-being during lunar missions. On the opposite side of the rover, there is another wall expansion that serves as storage for two space suits. These suits are specifically reserved for emergency situations and are only used when necessary. In the event of an emergency, the deployable-wall expands, creating an airlock where crew members can safely put on the suits. Once fully suited up, the crew members can exit the rover through the hatch doors, which are primarily utilized for docking with lunar bases or other X-plors.

4.2.5.1 Net Habitable Volume

The Net Habitable Volume of a habitat is an important metric that takes into account the available usable space for the crew. It considers factors such as the loss of volume due to equipment, stowage, and other structural inefficiencies that may decrease the functional volume. By accounting for these factors, the Net Habitable Volume provides a more accurate representation of the actual space that the crew can utilize for various activities (IHMC 2008).

In the case of the X-plor vehicle, the calculated volumes for different areas within the habitat can be found in Table 4.2. This table offers a quantitative breakdown of the interior space, providing valuable information about the distribution of usable volume and the allocation of resources within the vehicle. These calculations are crucial for effective mission planning, as they allow for a better understanding of the available space and its optimization for different functions and activities.

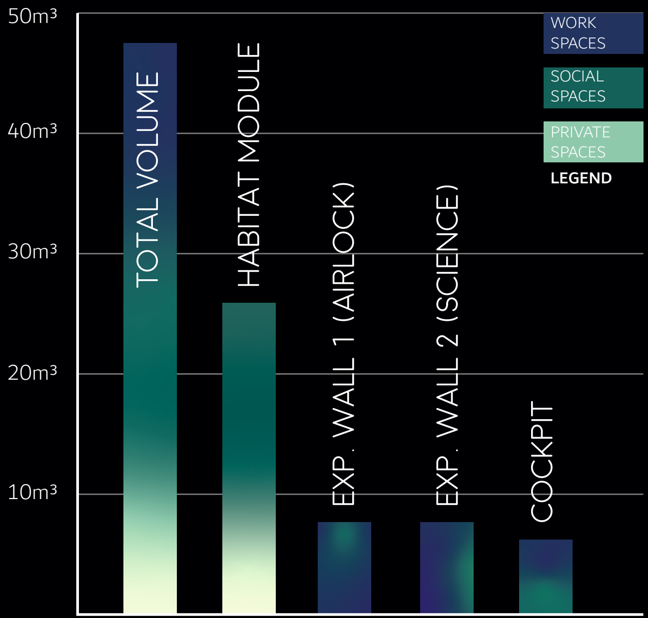


Table 4.2. I Net Habitable Volume

The total Net Habitable Volume of the habitat is measured to be 46 m3, as indicated in Table 4.2.

The habitat module occupies a volume of 25 m3, providing a significant portion of the overall space for the crew's activities and living quarters.
The cockpit, with a volume of 6 m3, and both expandable walls contribute a total volume of 7.5 m3 each, providing additional space per needs of the crew.

The color coding system employed within the habitat helps visually distinguish and divide the different areas based on their intended functions; **Private spaces**, **Work areas**, and **Social spaces**.

4.2.5.2 Promoting Habitability

Integrating habitability aspects into a lunar exploration rover involves considering the needs and well-being of astronauts during their missions. Some key considerations are:

1 **Ergonomics and Comfort:** The X-plor's interior is designed to prioritize astronaut comfort and usability. Smooth, continuous interior surfaces increase perceived volume and crew safety during travels. The interior setup is designed to follow a logical spatial hierarchy and ensure fluid circulation, allowing for efficient movement and organization within the space.

2 **Crew Accommodation:** The sleeping pods provide adequate space for crew members to rest, sleep, and relax during their missions. They are designed with privacy features, extra radiation protection, storage compartments for personal belongings and dedicated areas for personal care activities.

3 **Communication and Connectivity:** Reliable communication systems are implemented within the cockpit to facilitate effective communication between the crew, mission control, and their friends and family. The rover also incorporates spaces that serve as versatile environments for both work and socializing.

4 **Human-Machine Interface:** The design incorporates user-friendly interfaces and displays for easy interaction with the rover's systems. An augmented reality screen in the cockpit window offers clear visual feedback, while informative displays enhance situational awareness.

5 **Psychological Well-being:** Psychological well-being is prioritized by incorporating design elements that aim to reduce stress and foster a positive environment. This includes the integration of lounge area, recreational spaces, and access to entertainment options, as well as facilitating communication with loved ones during the mission.

6 **Safety Features:** Safety measures are integrated into the rover to protect the crew during hazardous situations, including emergency response systems, fire suppression mechanisms, radiation shielding, and emergency escape provisions.

LOUNGE:

- X-plor lounge design prioritizes user relaxation and support
- Promotes socializing with its inviting design
- Designed to blend into the living space

STOWAGE:

- Modular compartments for equipment storage
- Climate-controlled sections for sensitive instruments
- Secure latch mechanisms for rough terrains

HYGIENE:

- Serves as the primary bathroom facility.
- Designed for efficient body washing.

ROSA:

- Roll Out Solar Arrays
- Extendable solar panels designed for efficient energy capture

SCIENCE LAB:

- Serves as a central hub for scientific investigations, functioning as an on-the-go mobile laboratory.
- Designed for efficient sample collection and analysis.
- Glovebox optimized for coordination with the external robotic arm
- Deployable

ROBOTIC ARM:

- Functions as a primary device for the science laboratory, aiding in experiments and sample collection
- Doubles as a spare wheel for the cockpit when detached, ensuring mobility

COCKPIT:

- Serves as the main hub for mission control and navigation.
- Used as space for communication, work and socializing
- Detachable

Fig. 4.10 I X-plor Perspective Section 1

COCKPIT WINDOW

- Transforms into an augmented reality screen that provides real-time info on lunar terrain, location, navigation and other features

KITCHEN

- Equipped with space-efficient appliances for meal preparation
- Designed for easy access and storage of food supplies.

AIRLOCK:

- Designed for docking with other X-plors or bases
- Stores two emergency suits
- Can be used as exit in emergency cases
- Suit maintenance equipped

SUITPORTS:

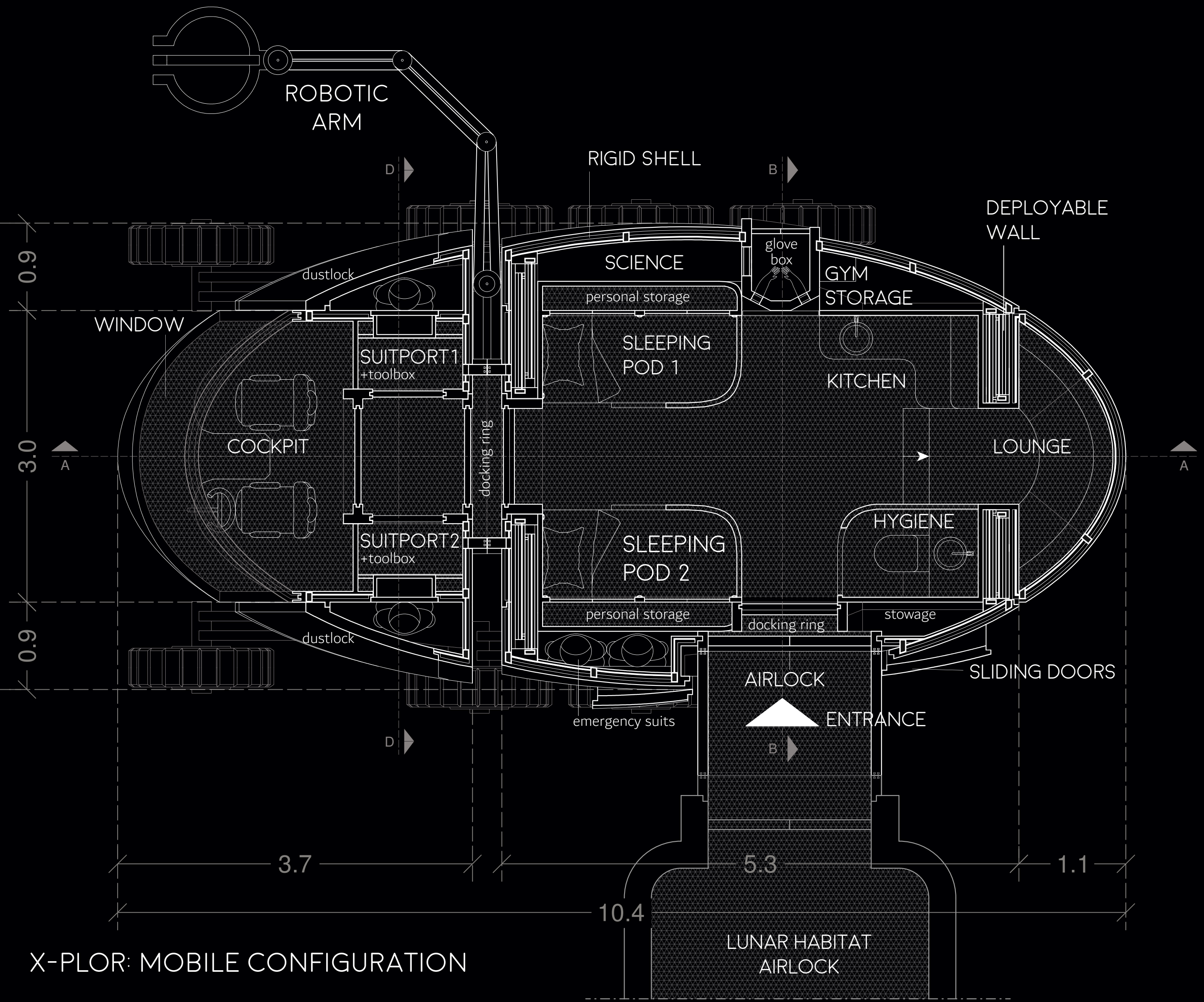
- Enables easy suit donning/doffing
- Provides secure suit storage and mitigates external contamination
- Saves atmosphere
- Optimizes crew time usage and conserves power

SLEEPING PODS:

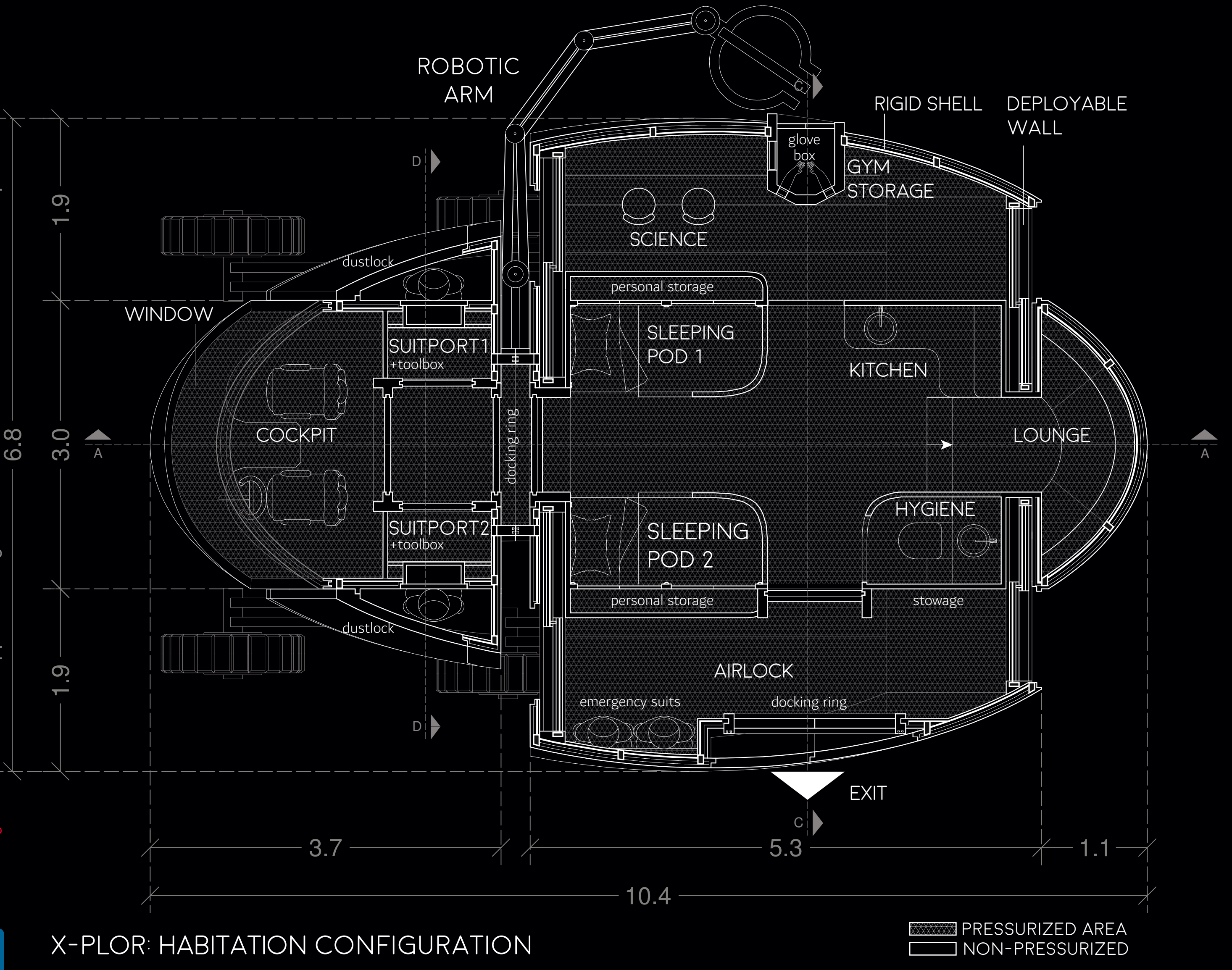
- Provides space for rest and relaxation
- Features built-in privacy elements
- Offers enhanced radiation protection
- Contains storage for personal items
- Bed design includes a sliding element for versatility in use

Fig. 4.11 I X-plor Perspective Section 2

4.3 FLOORPLANS



X-PLOR: MOBILE CONFIGURATION



X-PLOR: HABITATION CONFIGURATION

The X-plor rover has two distinct configurations for lunar missions. The first is the mobile configuration when it is docked to a lunar habitat, enabling crew movement between the two. The second is the habitation configuration with fully expanded walls, providing extra interior space for improved living and working conditions.

4.3.1 MATERIALS AND CONSTRUCTION

The utilization of carbon materials in the field of space exploration has opened up a range of groundbreaking opportunities. The X-plor rover stands out by incorporating these materials into its design, showcasing their vast benefits for space missions. Derived from extensive research, including pivotal insights from the paper "Carbon Radiation Shielding for the Habot Mobile Lunar Base" by Marc M. Cohen (2004), this rover's design offers a fresh perspective against the conventional metallic space vehicles, raising the bar in both safety and efficiency.

Moving away from the confines of traditional aluminum alloys, the introduction of carbon components brings forth a range of distinct benefits. Among these is the outstanding capability for radiation shielding. Comprehensive research has underlined the unmatched potency of carbon in this domain, with all-carbon composite habitable structures standing out for their heightened protection against radiation, surpassing the safeguards offered by conventional materials. Furthermore, one of the intrinsic qualities of carbon materials is their adeptness at thermal regulation. This characteristic ensures that spacecrafts remain resilient against the harsh and fluctuating temperatures of space, particularly the demanding lunar cycles with their intense temperature swings. The danger posed by micrometeoroids and space debris is significant. Yet, carbon-based materials demonstrate their worth by providing enhanced protection against such risks, ensuring the safety of both the sophisticated equipment and the precious human lives onboard.

In terms of architectural and structural design, the X-plor is built with a foundational **primary structure** at its core. This primary structure is complemented by an inner **secondary framework** that provides

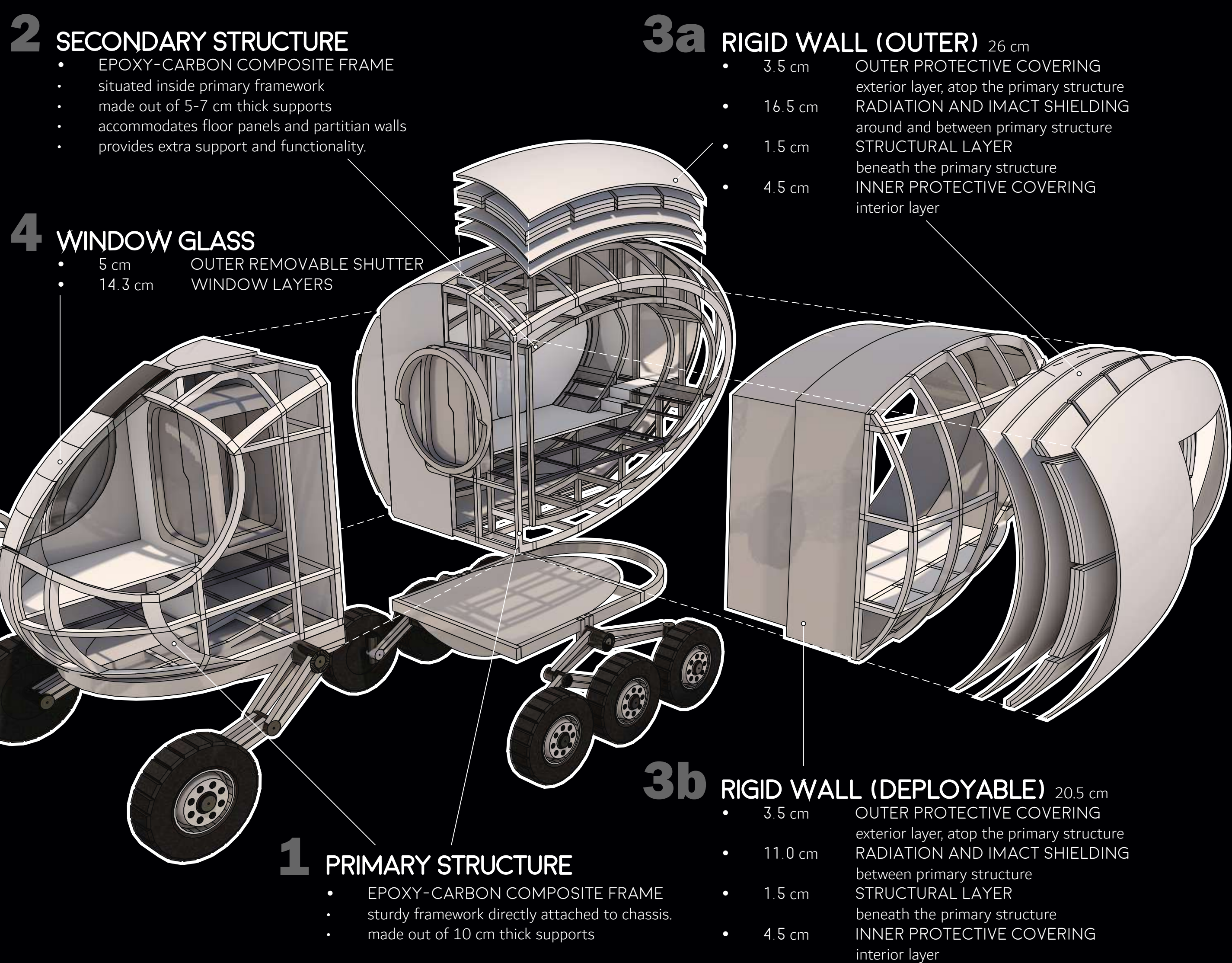


Fig. 4.12 I X-plor Materials and Construction

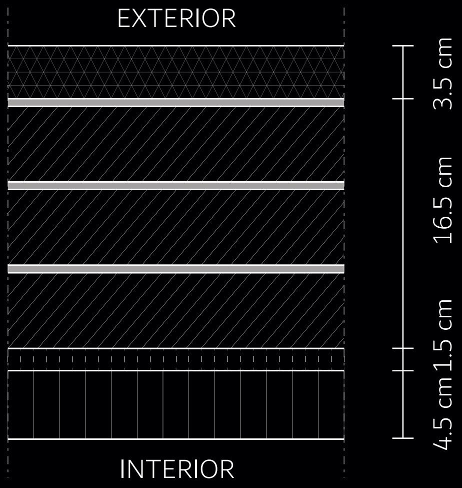
additional strength and stability. The X-plor is further enhanced by its **rigid exterior walls** and a specially-designed **cockpit window**. This strategic designensures X-plor's robustness and durability when traversing the challenging lunar terrain.

- 1 **PRIMARY STRUCTURE:** The primary structure is a sturdy vehicle framework directly connected to the chassis, guaranteeing balanced load distribution and maintaining overall stability. While the cockpit remains permanently connected to the chassis, the habitation module is designed to be detachable, allowing for mission-specific configurations. Made from **epoxy-carbon composite**, this structure offers resilience against the harsh lunar environment, serving as the central framework that underpins all of the rover's components. It's also crafted to synergize with other structures, such as the rover's rigid wall, to enhance aerodynamics, aesthetics, and overall functionality.

- 2 **SECONDARY STRUCTURE:** The secondary structure is located within the primary framework, offering an additional layer of support and utility. Although the primary structure determines the rover's foundational stability and overall form, the secondary layout enriches the internal design features. This structure holds floor panels and walls, dividing the inside into areas like science lab, hygiene compartment, storage, equipment housing and sleeping pods. Additionally, the design incorporates sturdy fixtures, ensuring that all furnishings, devices, and storage compartments remain securely anchored during lunar movements.

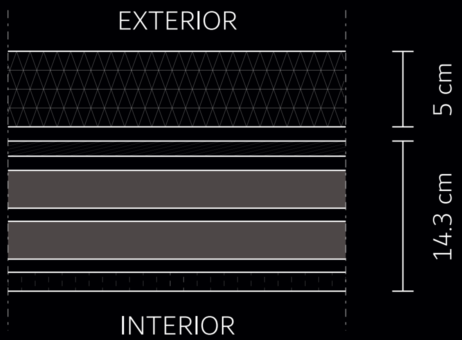
- 3 **RIGID WALL:** The X-plor rover utilizes carbon-based materials for the rigid construction of its (both outer and deployable) wall layers, tailored for the challenges of lunar exploration and inspired by Marc M. Cohen's 2004 "Habot Mobile Lunar Base." It is crafted with multiple layers, each serving a crucial purpose. Starting from the outside, a 3.5 cm layer of **ORNL Carbon Radiator over a Thermal Blanket** acts as an outer protective covering. It's not just about protection, as this layer also manages the rover's temperature, ensuring the right thermal conditions inside. Just below that, there's a 0.5 cm layer of **Carbon Filled-Carbon**. It's there to offer an extra shield against the harsh radiation and other dangers that come with space exploration. Moving inward, a 5.0 cm thick **Vitrified Carbon Foam** serves as a buffer and structural spacer that offers protection against micrometeoroids and space debris impacts. These two layers are replicated three times to achieve the intended overall thickness of the section. Then comes 1.5 cm Pressure Vessel Shell made of **epoxy-carbon composite**, which holds the structural integrity of the rover that provides strength and prevents the internal environment from being exposed to the vacuum of space. Lastly, on the innermost side, a 4.5 cm

Interior LET Attenuator is used as additional radiation protection, specifcally targeting low-energy transfer (LET) radiation (M. Cohen 2004). The composite layers reach 26 cm for the outer wall and 20.5 cm for the deployable wall, as layers for impact and radiation protection are duplicated only twice.



3.5 cm	**Outer protective covering:**		
	ORNL Carbon Radiator over Thermal Blanket		
16.5 cm	**Radiation and imact shielding:**		
	0.5 cm	Carbon Filled-Carbon	x3
	5.0 cm	Vitrified Carbon Foam	x3
1.5 cm	**Structural layer:**		
	Pressure Vessel Shell: epoxy-carbon composite		
4.5 cm	**Inner protective covering:**		
	Interior LET Attenuator: polyethylene		
26.0 cm	**TOTAL**		

- **WINDOW GLASS:** The window glass allows the rover's operators and astronauts to have a clear view of the surrounding lunar terrain during driving maneuvers. It enables them to observe and navigate through potential obstacles, evaluate the terrain's characteristics, and make informed decisions regarding the rover's path and trajectory. The window glass of the X-plor rover is composed of multiple layers: (Häuplik-Meusburger, Bannova 2016, p. 191)



5 cm	**Outer removable shutter**
1 cm	**Outer meteoroid pane**
2.5 cm	**Redundant pressure pane**
2.5 cm	**Primary pressure pane**
1.2 cm	**Inner scratch pane**
14.3 cm	**TOTAL with air layers between**

Fig. 4.13 I X-plor Wall and Window Glass sections

4.3.1.1 Radiation Protection

The Moon is exposed to high-energy particles, including GCR and SEPs, leading to a radiation-rich environment. Secondary radiation is generated through interactions with the lunar surface. Proper radiation protection is crucial to address these radiation sources. Further details on this topic can be found in chapter 1.2.3.2 "Radiation" of this thesis.

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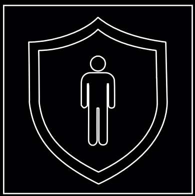
CARBON

The X-plor lunar rover is designed to integrate advanced radiation shielding within its rigid wall structure. Carbon-based materials are predominantly used in these layers, ensuring maximum protection from harmful space radiation. Moreover, specialized layers have been added around the sleeping pods to provide astronauts with an additional safeguard during their rest periods. In radiation protection, the Z/A ratio, indicating the Atomic Number to Atomic Weight, is crucial for evaluating neutron production. Carbon (Z=6) is notably more efficient than materials like aluminum (Z=13) at blocking primary particles and minimizing secondary neutron generation.

Drawing inspiration from the Habot Mobile Lunar Base Project conducted at NASA-Ames Research Center, it's found to be beneficial to position the shielding on the rover's exterior as opposed to the interior. The ISS traditionally uses polyethylene for shielding, but it can't handle lunar temperature shifts. Conversely, carbon-carbon composites resist these thermal extremes, making them suitable for external lunar applications, unlike water or polyethylene (Cohen 2004).


SAFE HAVEN

During a solar particle event (SPE), which refers to the release of high-energy particles from the Sun, it is crucial to ensure the safety of astronauts and equipment. In such an event, the X-plor rover would follow a protocol to return to the lunar base. This precautionary measure aims to minimize the potential risks posed by increased radiation exposure during SPEs. By returning to the base, astronauts can seek shelter in more protected habitat and wait for the SPE to subside before resuming their exploration activities.

4.3.2 DOCKING RING

Docking refers to the process of connecting two spacecraft or vehicles together, allowing for the transfer of crew members, equipment, or resources between them. The docking ring plays a crucial role in maintaining the pressurized environment of a spacecraft during docking operations. It serves as a secure connection point between two spacecraft, ensuring an airtight seal and preventing the loss of air or pressure (NASA 2010-I).

The X-plor vehicle is designed with docking ports that adhere to established docking standards and protocols (Fig. 4.14). These docking ports provide a secure connection point for linking the X-plor vehicle to other X-plor vehicles or the lunar base. Two X-plor vehicles have the capability to dock with each other using a docking ring located on the side of each vehicle or to a docking port on the cockpit. The two docking mechanisms engage and lock together, creating a sealed connection, which allows for the transfer of personnel, supplies, and information between the vehicles. The docking ring on the X-plor is equipped with sliding doors that remain closed to protect against lunar dust until the docking ring is ready to be utilized.

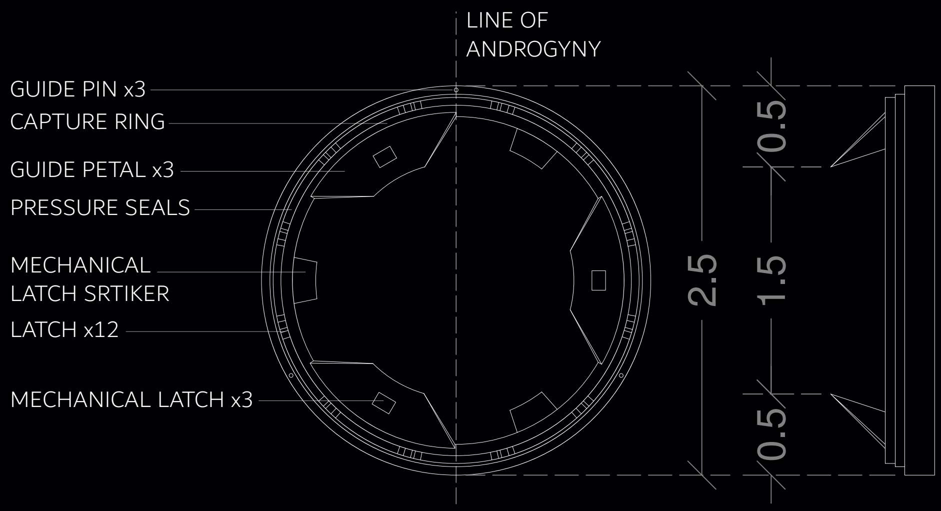
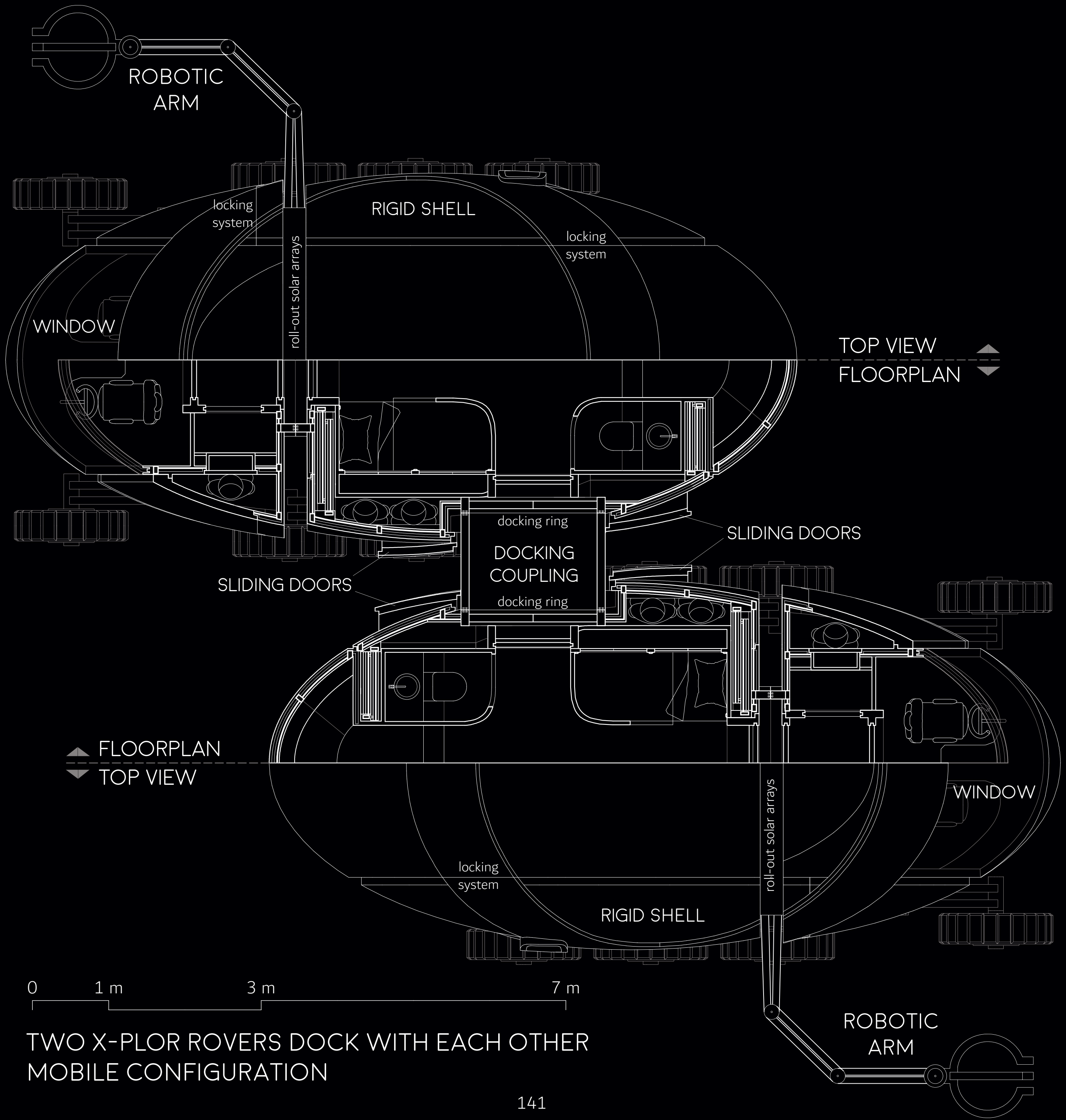
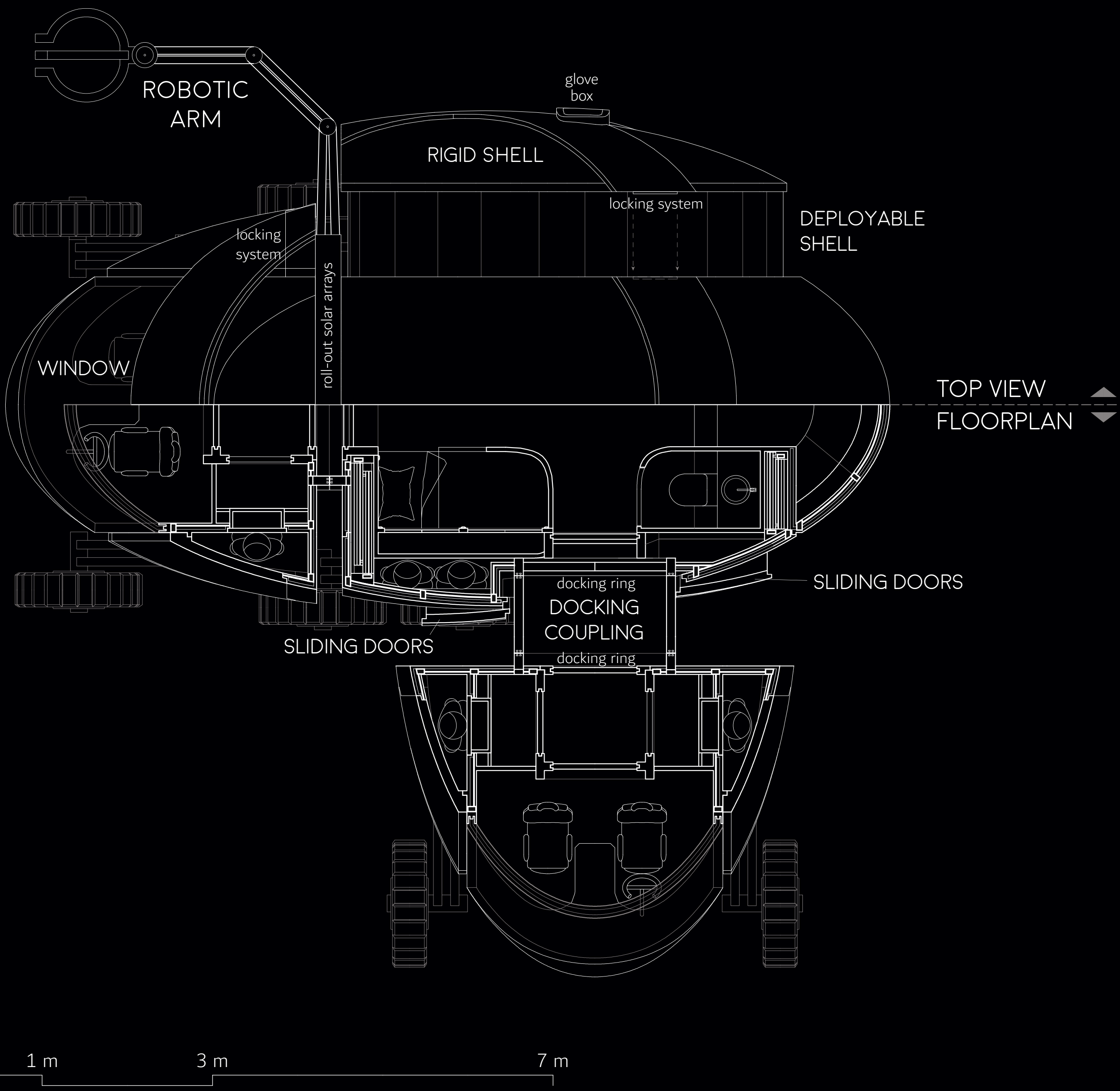


Figure 4.14 I X-plor Docking Ring

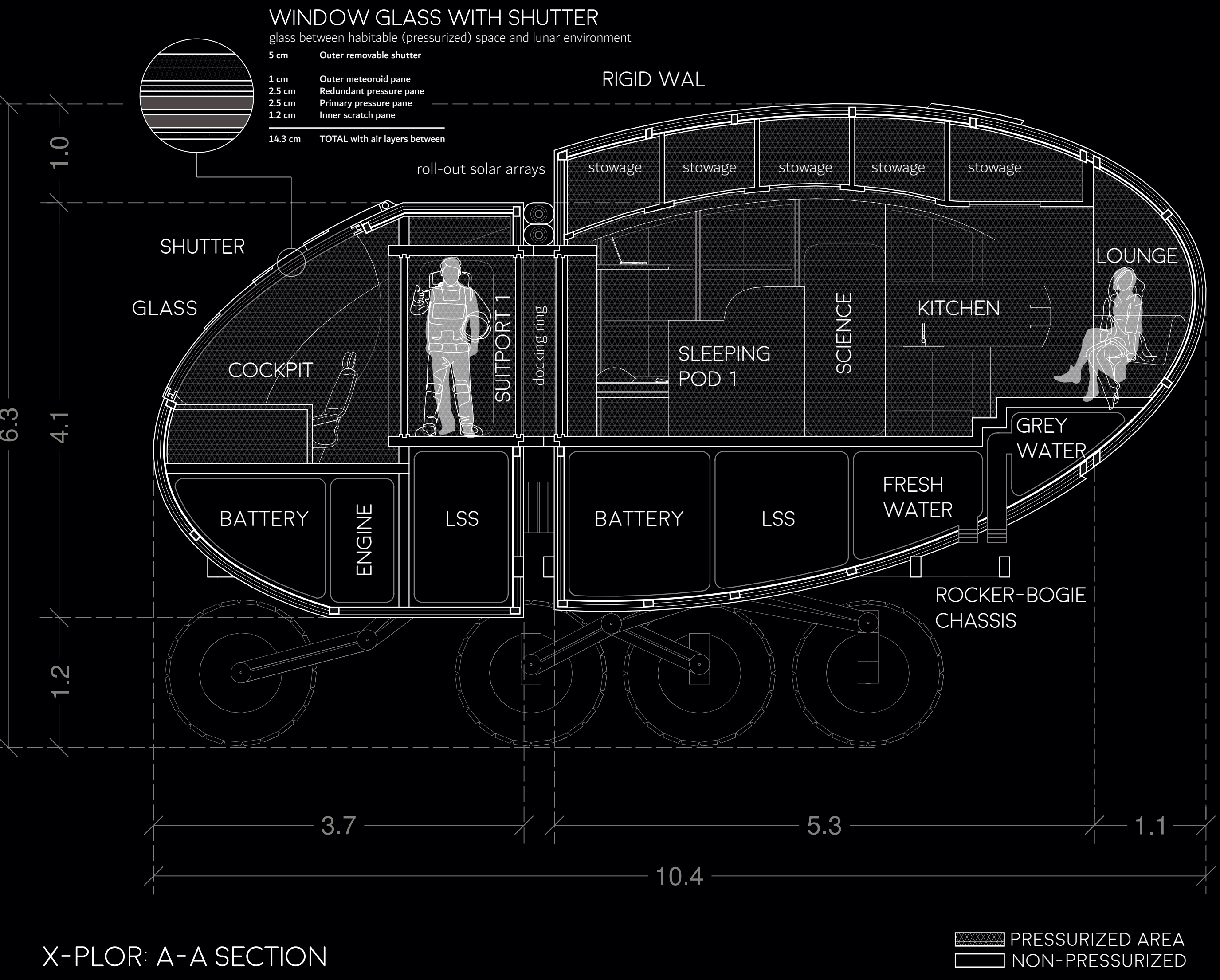


TWO X-PLOR ROVERS DOCK WITH EACH OTHER
MOBILE CONFIGURATION



X-PLOR DOCKED WITH COCKPIT
HABITATION CONFIGURATION

4.4 SECTIONS



X-PLOR: A-A SECTION

Section **A-A** of the X-plor lunar rover shows a connection between the cockpit and habitation module, joined by a versatile docking ring that allows for detachment of modules if required. Within this section, the roll-out solar arrays, which are strategically packed, can be seen, highlighting their importance in providing power during lunar missions.

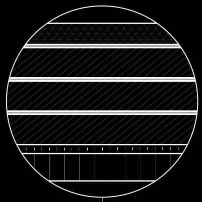
The cockpit serves as more than just a driving area. It incorporates two suitports, providing astronauts with a means to exit the rover for extravehicular activities. The cockpit and habitation module are thoughtfully divided into two distinct sections, with the pressurized area located on top and the Life Support System (LSS) situated at the bottom, ensuring a secure and habitable environment for the crew. The reason for the separate placement of the Life Support Systems (LSS) in both the cockpit and habitation module is their ability to detach from one another, which is driven by the distinct functions and requirements of the rover.

The habitation module is designed to cater to the astronauts' needs during their mission. It features sleeping pods, offering a comfortable space for rest, a well-equipped kitchen for food preparation, dedicated hygiene facilities for personal care, and a lounge area that supports social interaction and relaxation during the demanding lunar missions.

By looking at **B-B** and **C-C** sections, the rover's versatility becomes evident as different configurations and adaptations come into focus. The habitation configuration showcases the deployment of the walls, extending by 1 meter to create additional room for a science laboratory and an airlock on the opposing side. Telescopic beams are utilized to ensure robust structural support, capable of withstanding the weight of crew members and equipment

The airlock, positioned within this sections, features a protective mechanism in the form of sliding doors, ensuring that the docking ring remains shielded from lunar dust. The doors are opened selectively, preserving the integrity and operational efficiency of the docking mechanism.

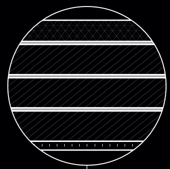
The detailed depiction of Section A-A, along with the variations seen in Sections B-B and C-C, highlights the rover's modular design and adaptability. It emphasizes the importance of efficient space utilization, providing astronauts with comfortable living quarters, essential amenities and the necessary infrastructure to conduct scientific research and exploratory activities on the Moon.



RIGID WALL. TYPE 1

wall between habitable (pressurized) space and lunar environment

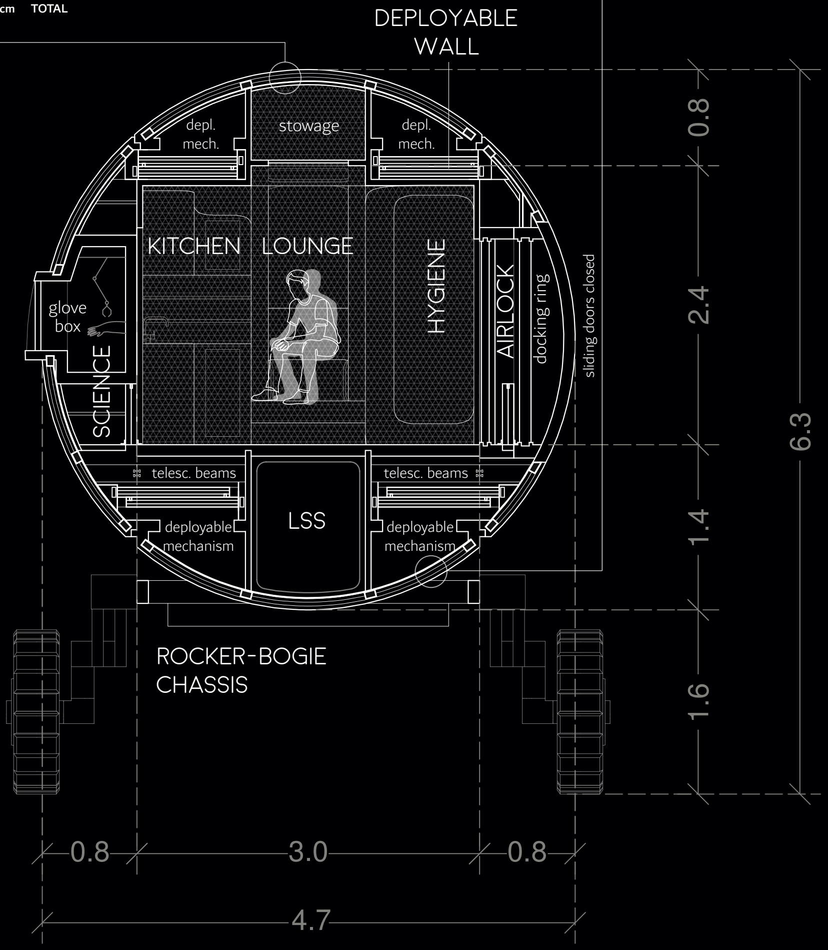
3.5 cm	**Outer protective covering:** ORNL Carbon Radiator over Thermal Blanket
16.5 cm	**Radiation and imact shielding:** 0.5 cm Carbon Filled-Carbon x3; 5.0 cm Vitrified Carbon Foam x3
1.5 cm	**Structural layer:** Pressure Vessel Shell: epoxy-carbon composite
4.5 cm	**Inner protective covering:** Interior LET Attenuator: polyethylene
26.0 cm	TOTAL



RIGID WALL. TYPE 2

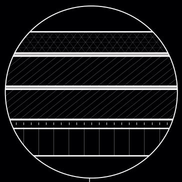
wall between non-habitable (non-pressurized) space and lunar environment

3.5 cm	**Outer protective covering:** ORNL Carbon Radiator over Thermal Blanket
16.5 cm	**Radiation and imact shielding:** 0.5 cm Carbon Filled-Carbon x3; 5.0 cm Vitrified Carbon Foam x3
1.5 cm	**Structural layer:** Pressure Vessel Shell: epoxy-carbon composite
21.5 cm	TOTAL



X-PLOR: B-B SECTION. MOBILE CONFIGURATION

PRESSURIZED AREA
NON-PRESSURIZED



DEPLOYABLE WALL

wall between habitable (pressurized) space and lunar environment

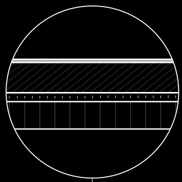
3.5 cm **Outer protective covering:**
ORNL Carbon Radiator over Thermal Blanket

11.0 cm **Radiation and imact shielding:**
0.5 cm Carbon Filled-Carbon x2
5.0 cm Vitrified Carbon Foam x2

1.5 cm **Structural layer:**
Pressure Vessel Shell: epoxy-carbon composite

4.5 cm **Inner protective covering:**
Interior LET Attenuator: polyethylene

20.5 cm **TOTAL**



INTERIOR WALL AND FLOOR

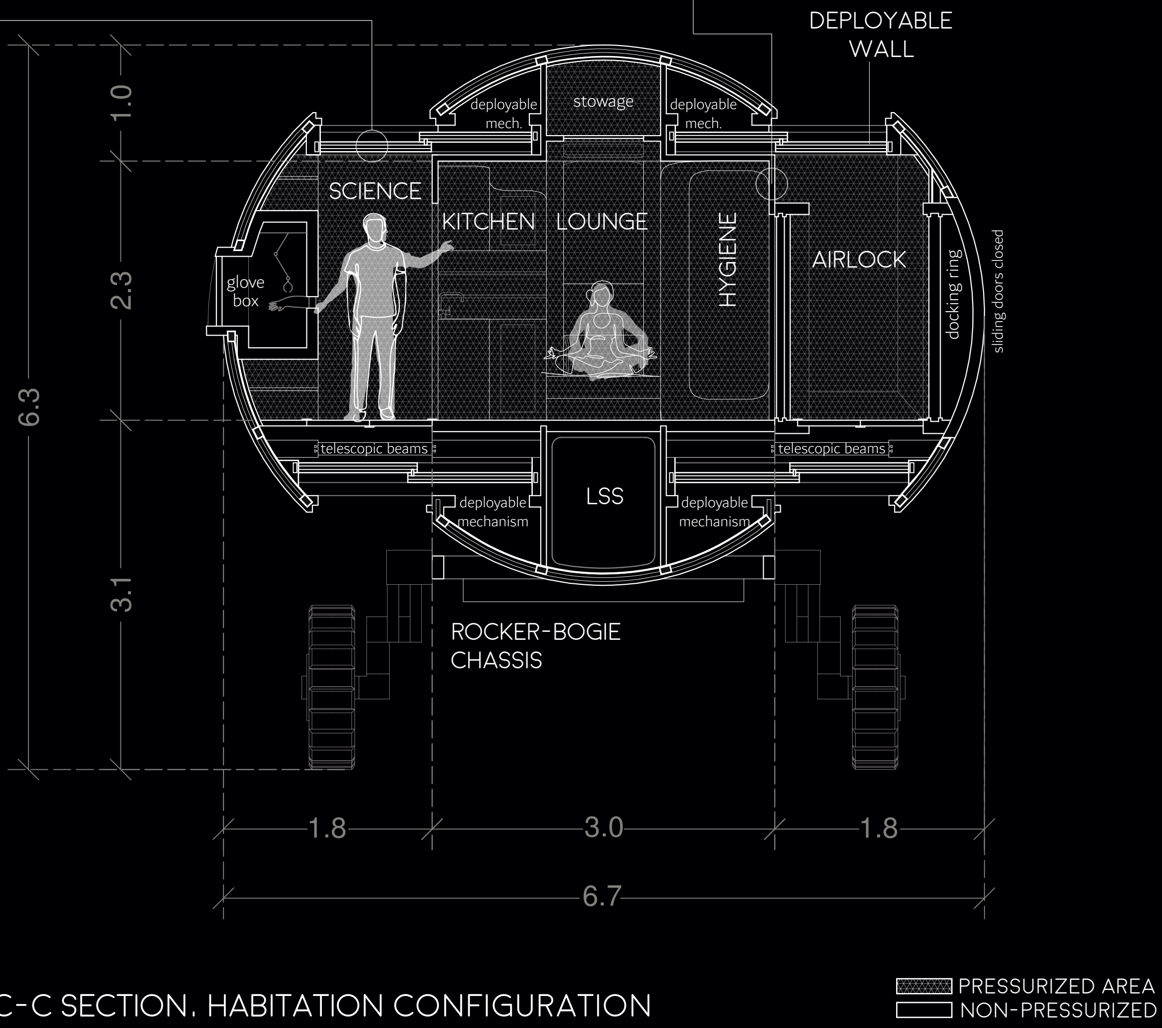
walls and floors inside pressurized environment

5.5 cm **Radiation and imact shielding:**
0.5 cm Carbon Filled-Carbon
5.0 cm Vitrified Carbon Foam

1.5 cm **Structural layer:**
Pressure Vessel Shell: epoxy-carbon composite

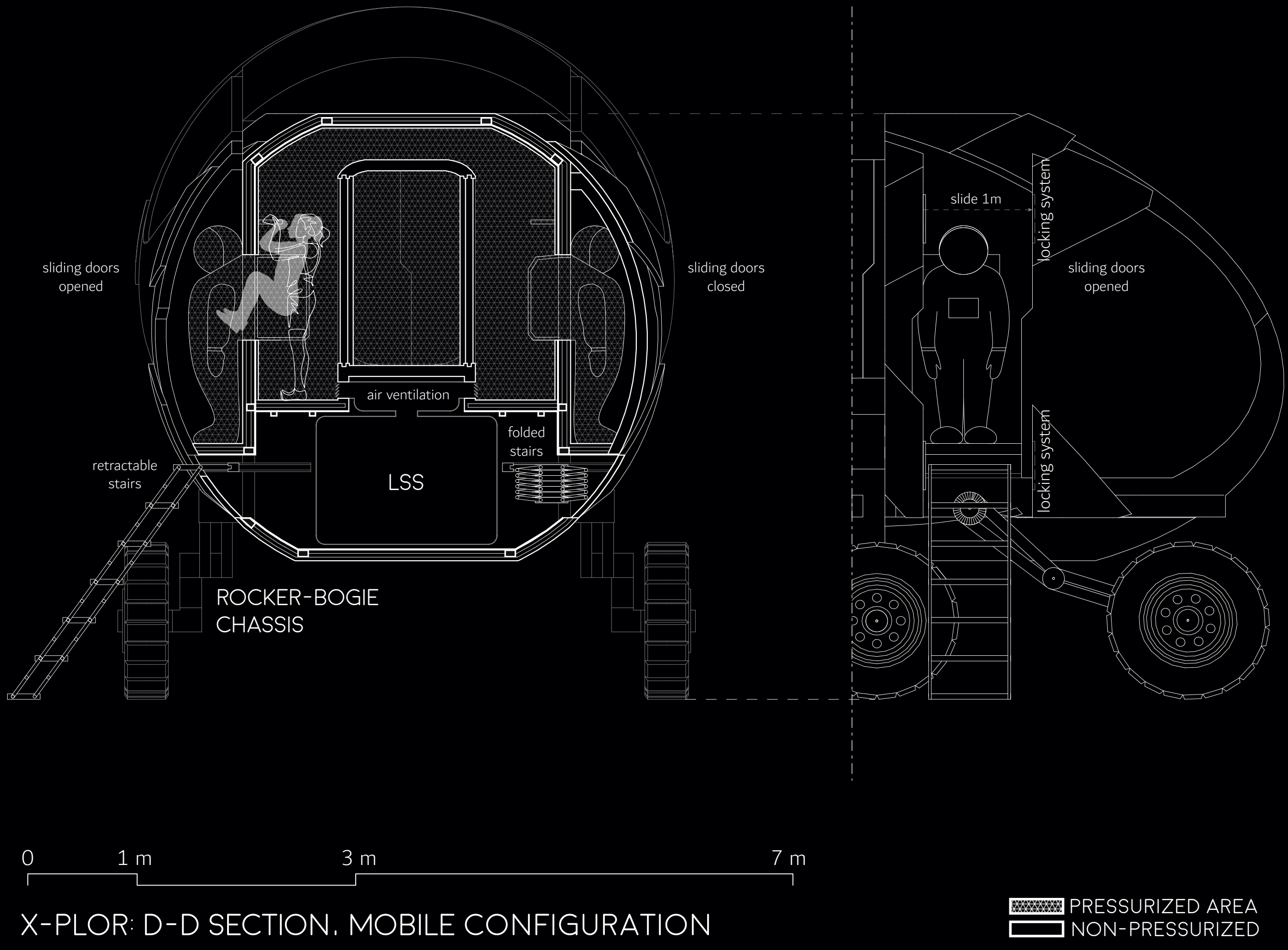
4.5 cm **Inner protective covering:**
Interior LET Attenuator: polyethylene

11.5 cm **TOTAL**



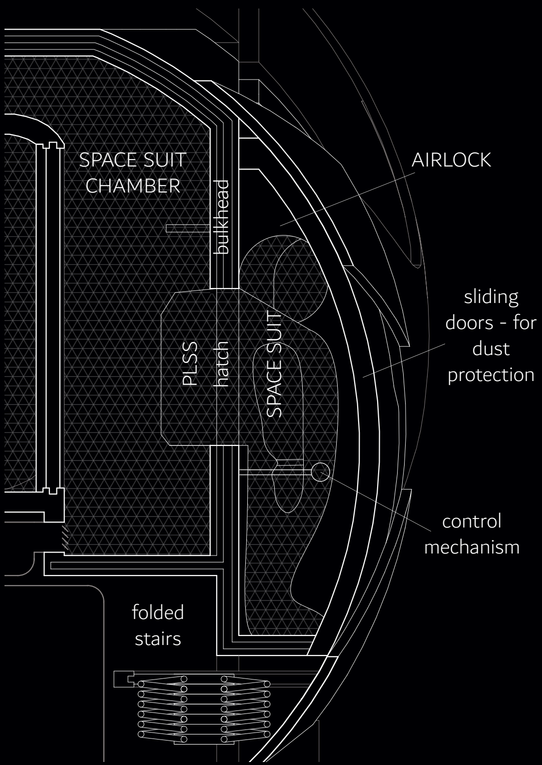
X-PLOR: C-C SECTION. HABITATION CONFIGURATION

4.4.1 SUITPORT

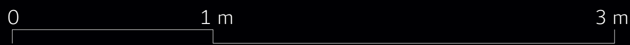


X-PLOR: D-D SECTION, MOBILE CONFIGURATION

To facilitate easy entry and exit from the X-plor, the spacesuits are equipped with suitports, which directly dock to the rear of the cabin and open into the vehicle interior. This design allows for rapid ingress and egress, minimizing the intrusion of lunar dust into the rover's interior. Sliding doors are employed to shield the suits from dust and ensure their protection. To maintain a safe and controlled environment, an inner hatch, accompanied by appropriate procedural controls, ensures that the use of suitports carries no greater risk of rover depressurization than traditional airlocks or suitlocks. Prior to use, the suits undergo a pressure and leak check at 8 psi, with both the suit hatch and suitport hatches securely closed. Upon successful completion of the pressure and leak check, the suitport hatch and suit hatches are opened, enabling the astronaut to step into the rear-entry suit (IHMC 2008) as depicted in section D-D.



In a space station access system, a module is divided into a suit chamber and an airlock by a bulkhead. A space suit with a portable life support system (PLSS) interface on its back can be attached to the bulkhead via a hatch. The PLSS is mounted in a hatch cover, which can pivot away from the hatch, allowing an astronaut to enter the suit through the open hatch and interface. Once inside the suit, the astronaut closes the hatch, connects the PLSS to the suit using a glove-connected control mechanism, and initiates the airlock's pumpdown process. After completing the pumpdown, the astronaut opens a hatch, disconnects the PLSS from the hatch cover, pivots the control's pressure vessels to one side on their supports, disconnects the glove portions from the pressure vessels, and proceeds with the extra-vehicular activity (EVA) (Cohen 1989).



X-PLOR: D-D SECTION. ENLARGED

4.4.2 LIFE SUPPORT SISTEM

X-plor is a self-contained vehicle equipped with essential life support systems to ensure the survival of its occupants. These systems will encompass:

- **Air Supply:** The vehicle maintains a constant and breathable air composition, regulating oxygen levels and removing carbon dioxide through advanced air circulation and filtration systems.

- **Water Supply:** X-plor has plumbing to store and distribute water for drinking, hygiene, and other essential purposes. Water recycling and purification technologies are implemented to maximize efficiency and minimize resource consumption. X-plor incorporates specialized containers for fresh water that have the capability to establish connections with the lunar base, allowing for the replenishment of freshwater reserves.

- **Electricity:** The vehicle features power generation and distribution systems to meet the electrical needs of the crew and onboard equipment. This includes Roll-Out Solar Arrays (ROSA) and fuel cells.

- **Food Production and Delivery:** To sustain the crew during their mission, food for the X-plor lunar rover will be meticulously packed and stored prior to the mission, guaranteeing a suitable provision to sustain the crew throughout their expedition.

- **Temperature Control:** Maintaining a comfortable temperature range within the habitat is vital. Climate control systems, insulation, and thermal regulation technologies are employed to mitigate extreme lunar temperature variations.

- **Waste Management:** Proper disposal and management of solid and liquid waste generated by the crew is a priority. X-plor has integrated waste containment systems and greywater, which can be emptied when connected to a lunar base.

4.4.3 POWER SUPPLY

X-plor incorporates fuel cell technology as its primary energy source. Fuel cell technology operates by harnessing the chemical reaction between hydrogen and oxygen to generate electricity, with water being the resulting product. Since both hydrogen and oxygen are in gaseous form, they can be stored and transported in tanks for extended periods. Fuel cells, weighing approximately one-fifth the mass of lithium-ion batteries and occupying about 20 percent less volume, emerged as the optimal choice. Initially, for the mission, hydrogen and oxygen will be transported from Earth, and the rover will sustain its operation by exchanging tanks. The water produced during electricity generation can serve multiple purposes, such as coolant or drinking water, enhancing the rover's self-sufficiency. Considering these factors and more, fuel cells prove to be the most suitable energy source for this mission. Furthermore, solar photovoltaic panels can be utilized for electrolysis, separating hydrogen and oxygen for storage as fuel, which can then be utilized to generate electricity, with water serving as a byproduct once again. This water can be utilized for various purposes, including sustaining life or even as an additional source of electricity (Toyota 2019).

X-plor incorporates a cutting-edge solar power solution known as Roll-Out Solar Arrays (ROSA). These compact arrays possess the unique ability to roll up like a carpet, allowing for easy stowing during launch and enhancing transportability while still providing a substantial surface area for power generation. ROSA, despite its smaller size compared to traditional solar arrays, demonstrates remarkable performance, capable of producing more than 30 kilowatts per panel, depending on its size. This impressive output is achieved through the utilization of highly efficient solar cells, and future iterations of ROSA even explore the incorporation of concentrators to further enhance its power-generating capabilities.
In addition to their exceptional power generation, ROSAs are designed with structural durability in mind. The composite booms utilized in their construction provide robust rigidity, enabling them to withstand the challenges of a dynamic environment, a broad range of frequencies, and potential encounters with debris or micrometeoroids. This resilience ensures reliability for long-duration missions, making ROSA a promising and dependable solar solution for X-plor's energy needs (NASA 2022.)

4.4.4 ROCKER-BOGIE CHASSIS

The Rocker-Bogie Mobility system exhibits the ability to overcome obstacles approximately the size of a wheel and enables traverse over rugged lunar terrain.

The term "rocker" refers to the larger links present on each side of the suspension system that provide a rocking motion. These rockers are interconnected with each other and the vehicle chassis through a modified differential, maintaining balance.

On the other hand, "bogie" refers to the joined links with drive wheels attached at each end. Bogies are commonly utilized to distribute loads over terrain, such as in army tanks' tracks or trailers of semitrailer trucks. To maintain the vehicle's center of gravity, when one rocker moves upward, the other moves downward. The chassis plays a crucial role in maintaining the average pitch angle of both rockers according to the situation, ensuring stability and control (Verma et al 2017).

The rocker bogie suspension system in the X-plor rover ensures stability, traction, and flexibility while minimizing wheel slippage and

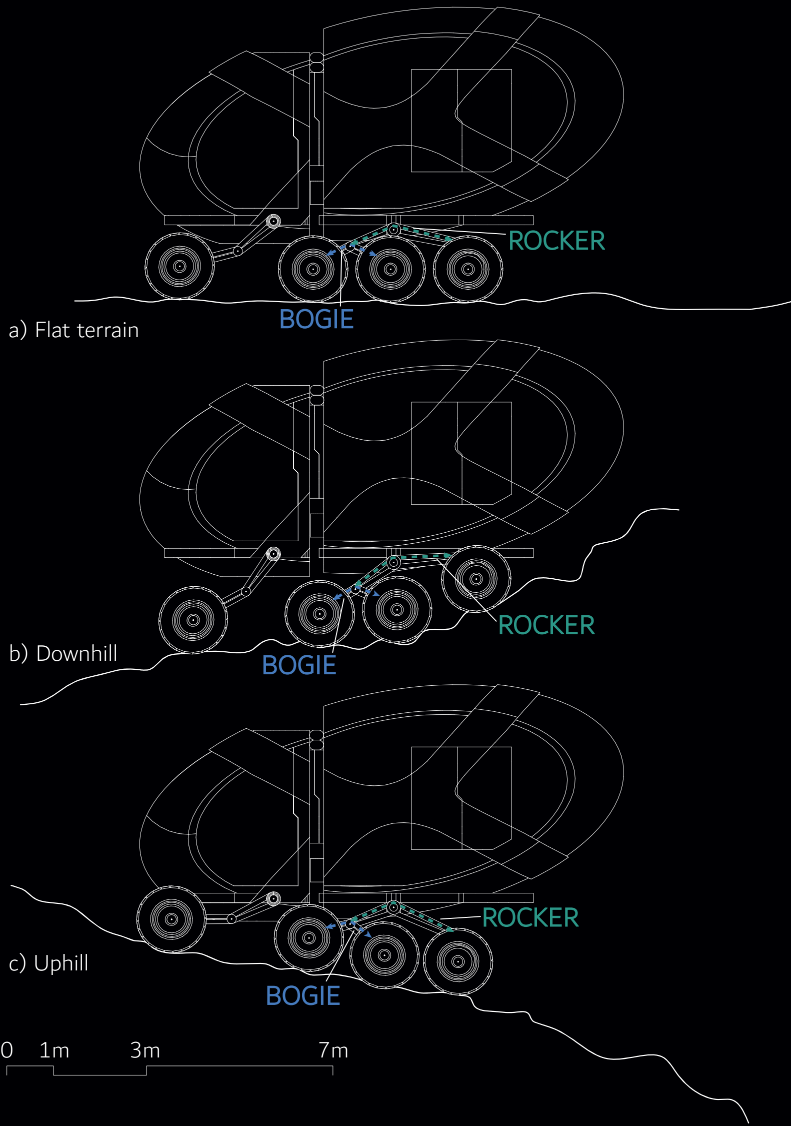
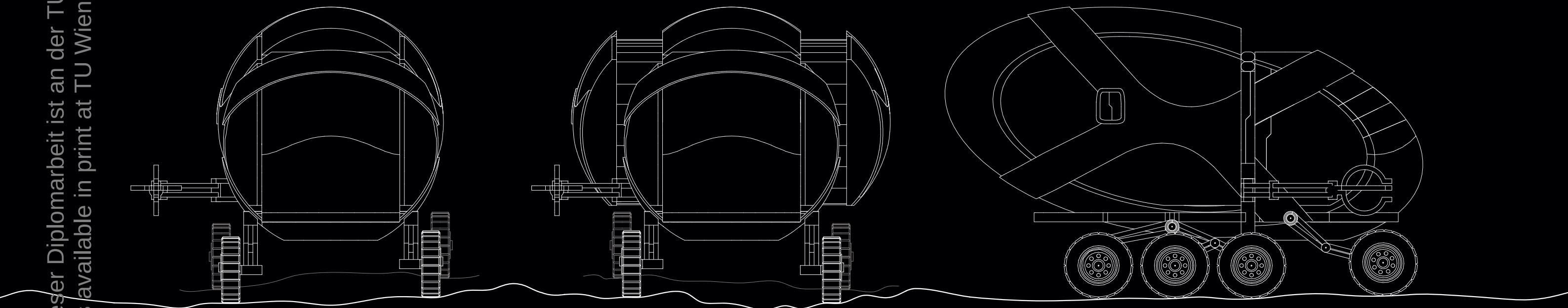


Fig. 4.15 I Various Rocker-Bogie motions according to the terrain



a) Front view: Mobile configuration b) Front view: Habitation configuration c) Side view

absorbing shocks. It enables the rover to handle uneven terrain, navigate obstacles, and offer a smooth, reliable performance during lunar exploration.In Figure 4.15, the left side of the X-plor vehicle is depicted, illustrating the wheel positions during flat, downhill, and uphill drives. Figure 4.16 showcases the front side of the X-plor vehicle in both Mobile and Stationary configurations, including the right side as well.

There are several benefits that are attributed to this system, including:

- The design incorporates independent motors for each wheel. There are no springs or axles, making the design simpler and more reliable.
- Rocker Bogie Suspension can withstand a tilt of at least 500 in any direction without overturning, which is the biggest advantage of heavy loaded vehicle.
- It can move in harsh environment
- It can work in place which are beyond human reach
- Rocker-Bogie consisting of no spring and stub axle in each wheel which allows the chasis to climb over any obstacle such as rocks, ditches, sands etc. that are up to double the wheels diameter in size while keeping all the wheels on ground for maximum time (Verma et al 2017).

Figure 4.16 I Various aspects of the X-plor rover in context of the Rocker-Bogie system

4.5 CONCLUSION

In conclusion, the Xplor lunar exploration rover represents a remarkable achievement in the pursuit of lunar exploration, combining both functionality and habitability for future missions. Designed with the goal of enabling extended human presence on the Moon, the Xplor rover incorporates essential features to ensure the well-being and comfort of astronauts during their stay. Its habitable module provides a safe and comfortable environment, equipped with life support systems, radiation shielding, and efficient thermal control mechanisms.

By prioritizing habitability, the Xplor rover not only addresses the physical needs of astronauts but also recognizes the importance of psychological well-being in prolonged space missions. The inclusion of ergonomic designs and human-centric interfaces fosters a sense of connection and enhances crew morale, crucial factors for the success of lunar exploration endeavors.

Furthermore, the Xplor rover's adaptability to different lunar terrains, its advanced mobility system, and its integration of state-of-the-art technologies position it as a reliable platform for conducting scientific research and resource utilization on the Moon. It opens up possibilities for groundbreaking discoveries, contributing to our understanding of the lunar environment and its potential for supporting future human settlements.

As we look towards the future of lunar exploration, the Xplor rover exemplifies our commitment to pushing the boundaries of human exploration and expanding our presence beyond Earth. It serves as a testament to the ingenuity and determination of scientists, engineers, and astronauts, who continue to advance our knowledge and capabilities in exploring the lunar landscape. The Xplor rover is poised to play a vital role in shaping the future of lunar exploration, paving the way for unprecedented discoveries and unlocking the full potential of our cosmic neighbor.

Figure 4.17 I X-plor on lunar surface

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CHAPTER 1

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Fig. 1.2 I Moon
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Fig 1.8 I Apollo 11 Mission
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Fig. 1.10 I Partner Agency Logos
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Fig. 1.11 I Lunar South Pole landing sites of interest
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CHAPTER 2

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Fig. 2.1 I Moon Village
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Fig. 2.4 I The Habitability system
Credit: Häuplik-Meusburger, Bishop 2021.
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Fig. 2.5 I ATRIO Library
Credit: ATRIO Authors
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Figure 2.6 I Habitable Volume for Increasing Crew Size
Credit: Kennedy 2007.
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Figure 2.7 I ISS Node 2 (Harmony) under construction
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Fig. 2.8 I Inflatable Habitat, Langley Research Center
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Fig. 2.9 I Lunar Roving Vehicle
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Fig. 2.10 I Lunar Roving Vehicle: Front and Side View
Credit: Boeing LRV 1971
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Fig. 2.11 I Daylight Rover
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Fig. 2.12 I Nomad Explorer VLTV
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Credit: A. Scott Howe
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Fig. 2.14 I Moonwalker
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Fig. 2.15 I Lockheed Martin's LTV concept
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Fig. 2.16 I NASA's LTV concept
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Credit: ATRIO authors
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Fig. 3.12 I Space Launch System Configurations
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Fig. 3.14 I Orion Spacecraft
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Fig. 3.15 I Gateway
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Fig. 3.16 I Lunar lander concepts
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Fig 3.17 I ATRIO Lunar Habitat
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Fig 3.18 I ATRIO Site Plan
Credit: ATRIO authors
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