Modest Proposals for a Lunar Base After 2024

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Research Question

What is an appropriate framework for a sustainable lunar base that is cost-conscious, ensures mission success, and holds 100 researchers to survive and study the Moon?

Abstract

As humanity's natural inclination to explore pushes society to advance, the National Aeronautics and Space Administration(NASA) plans to land humans back on the Moon in 2024 [1]. A research base situated on the Moon will bring humanity into a new phase of interplanetary civilization. Such a project will generate new frontiers for exploration, economic opportunities, and inspire a new generation of scientifically minded people [1]. A lunar base is proposed for construction after the completion of the Artemis III mission. Vital components required for supporting 100 permanent residents on the Moon include residence, transportation, satellites, and agriculture infrastructure. The south pole of the Moon is the location considered for this lunar base. The Foundational Surface Habitat (FSH), Lunar Terrain Vehicle (LTV), Habitable Mobility Platform (HMB), solar sail satellites, and the Gateway space station are main lunar technologies that will be used in the lunar base after 2024 [2, 3]. In the lunar base, the atmosphere composition of a pressurized residence facility must be oxygen/nitrogen based on abundance and cost. Nitrogen is best sourced from Earth through nitrogen generators due to its absence on the Moon, and oxygen is best sourced from cold ice traps on the south pole. Depending on the area of ice considered, the available amount for breathing varies from 240 years' worth to 3.9 millions years' worth of oxygen. The astronauts would receive food to meet a daily caloric requirement calculated per person based on biological measurements, and the World Health Organization (WHO) provides accurate mineral and vitamin intake information [4, 5]. The average required nutrients in calories for astronauts per male per day is 2968 kcal and per female per day is 2465.75 kcal. The base provides equipment and space such that astronauts can exercise at least 2 hours a day to counteract the weak gravity of the moon. Agriculture would employ hydroponics and aeroponics. Spinach, leek, and peas are recommended crops due to their high amounts of vital nutrients such as protein [6].

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Introduction: A New Age

Humans have an inclination to explore. Since spreading around the world from the African continent, humans have waged war on each other to gain territory and power. In 1492, Christopher Colombus sailed the ocean and opened up a new continent to the European population [7]. By the 20th century, most of the habitable places on Earth were colonized, and so, humanity looked towards the skies. In 1969, in the midst of the Cold War, the USA and Soviet Union pushed efforts to bring humanity's influence to space. Yuri Gagarin orbited the Earth, and America succeeded in landing humans on Earth's moon during the legendary Apollo 11 mission. Later, the US flew multiple missions to the moon with the latest in 1972. Since then, no one has set foot on the Moon [7].

NASA's next-generation lunar exploration program, the Artemis program, sets a goal to send humans to the moon in 2024, which would be the first time in 52 years a human set foot on another celestial body. The "Artemis Generation" will lead a new age where people will look to the moon at night and know that fellow humans reside there [1]. A return to the moon would lead mankind into a new age where humans spread influence to the Moon and beyond. The benefits for a lunar base are immense, some of which include technological innovation for application on Earth and economic gain. An economic impact report from NASA in 2019 shows that NASA generated $64.3 billion in economic output and created 312,000 jobs [3]. A lunar base will generate jobs for engineering, biology, astronomy and many more fields. New technologies innovated from space exploration include enhanced solar panels, implantable heart monitors, light-based anti-cancer therapy, and phone cameras [1,3].

Most importantly, a lunar base lays a foundation for future endeavors in space exploration by serving as a hub for further expansion. Humanity is already capable of transporting people to the moon. However, once that is achieved, it is unclear how we sustain them. NASA has, with the private sector, laid out in detail the intricacies of the former, such as the human transportation technology that will be used. These include the NASA SLS, Orion Spacecraft, and SpaceX HLS. Other parts are less clear, such as nutritious diet plans that include minerals and vitamins, how to form a breathable gaseous atmosphere, and the balance between transporting resources from Earth and self-sustenance. Within this problem lies complex dilemmas regarding sources for resources such as water or nitrogen, or problems such as selecting a few out of a significant variety of propulsion methods for space travel or orbital technology. The aim of this paper is to recommend multiple viable solutions to these problems and provide timelines or diagrams describing a plan coinciding with the Artemis missions. The structure of this paper is designed such that several suggestions are grouped into categories like transportation or nutrition, which mainly serve to split the ideas into different fields of study such as engineering, biology, or architecture.

Section 1: Terminology and Abbreviations

1-1: Transportation and Exploration

FSH: Foundational Surface Habitat.
HLS: Human Landing System.
HMP: Habitable Mobility Platform.
IKAROS: Interplanetary Kite-craft Accelerated by Radiation Of the Sun.
ISRU: In-situ Resource Utilization.
LTV: Lunar Terrain Vehicle.
SLS: Space Launch System.
TRL: Technology Readiness Level

1-2: Agencies

NASA: National Aeronautics and Space Administration.
SpaceX: Space Exploration Technologies Corporation.
JAXA: Japanese Aerospace Exploration Agency.

1-3: Nutrition

AF: Activity Factor.
BMR: Basal Metabolic Rate.
Bioavailability: The degree and rate at which a substance is absorbed into a living system or is made available at the site of physiological activity [39].
DEE: Daily Energy Expenditure.

Section 2: Getting to Luna

2-1: Brief Introduction of the Artemis Program

The last manned exploration of the lunar surface, since its iconic first occurrence in 1969, happened approximately 52 years ago in the Apollo 17 mission in 1972 [11]. Recently, NASA has implemented the President’s Space Policy Directive-1, which claims, “Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations" [12]. NASA states on its organization website that it “stands on the verge of commercializing low-Earth orbit,” and that “these experiences and partnerships will enable NASA to go back to the Moon in 2024 – this time to stay” [13]. NASA’s plan to send back humans to the moon in 2024 is called the Artemis Program, after the mythical Greek figure of Artemis, following the tradition of the first Apollo missions named after the brother of Artemis. The Artemis program is structured in 3 stages: Artemis I, Artemis II, and Artemis III, all which signify a notable step in initial lunar colonization. Artemis I, scheduled to take place on August 29, 2022, is a flight test of the Space Launch System (SLS) and the uncrewed Orion spacecraft to lunar orbit [11]. This mission will provide pivotal experimental proof for SLS’s transportation capabilities to the Moon and shall serve as the initiation into the “Artemis Generation,” which NASA refers to as the generation of current humanity who will all witness the totality of the Artemis Program taking action in their lifetime.

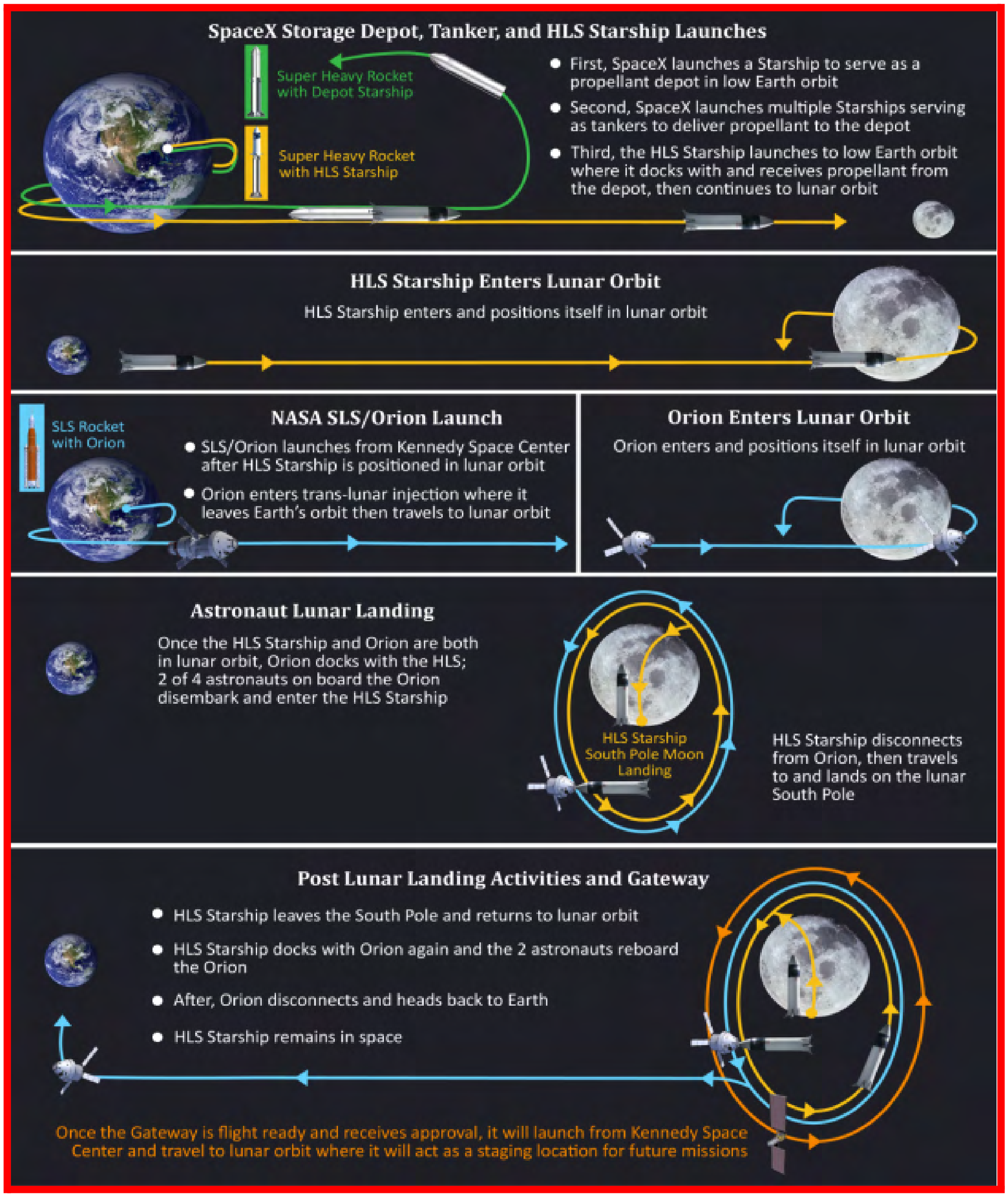
Artemis II will be the first mission to send crewed flights into lunar orbit with the SLS and Orion Spacecraft. With this mission, NASA will display the capability to consistently transport humans to lunar orbit and eventually the lunar surface. Artemis III, anticipated for 2024, will be the first time in 52 years that a human being sets foot on the lunar surface, carried by a SLS and Orion craft. Artemis III will be the catalyst to humanity's primary gateway to interplanetary civilization, the Moon. From an outpost built on the Moon, studies will commence on surviving in harsh conditions and transporting of humans to Mars, which in turn will officially begin the journey to interplanetary civilization. NASA has set 3 main lunar base technologies to be used after the success of Artemis III, which include habitable vehicles, convenient vehicles, and sitting bases which will be extensively covered later in this paper. Like these three future technologies, the scope of this paper is set past the Artemis III mission, to the time when NASA will be considering lunar base construction immediately. The Artemis program provides context for this goal, as by the time Artemis is completely successful, the next aim will be performing extended manned missions on the surface of the Moon. The moon bases will need a detailed infrastructure, transportation, and diet plan, all of which are considered.

2-2: Artemis III: SLS and HLS

Artemis III

The final goal of Artemis III is a demonstration mission that will illustrate the capability to land a crewed spacecraft on the Moon. The two main transportation technologies planned for Artemis III are the NASA SLS and SpaceX HLS. SLS and HLS will be used cooperatively in the mission.

Below is a detailed plan of Artemis III, where HLS provides a transition for the astronauts from the SLS in Lunar orbit to lunar surface touchdown [14].



SpaceX Storage Depot, Tanker, and HLS Starship Launches

- First, SpaceX launches a Starship to serve as a propellant depot in low Earth orbit
- Second, SpaceX launches multiple Starships serving as tankers to deliver propellant to the depot
- Third, the HLS Starship launches to low Earth orbit where it docks with and receives propellant from the depot, then continues to lunar orbit

HLS Starship Enters Lunar Orbit

HLS Starship enters and positions itself in lunar orbit

NASA SLS/Orion Launch

- SLS/Orion launches from Kennedy Space Center after HLS Starship is positioned in lunar orbit
- Orion enters trans-lunar injection where it leaves Earth's orbit then travels to lunar orbit

Orion Enters Lunar Orbit

Orion enters and positions itself in lunar orbit

Astronaut Lunar Landing

Once the HLS Starship and Orion are both in lunar orbit, Orion docks with the HLS; 2 of 4 astronauts on board the Orion disembark and enter the HLS Starship

HLS Starship disconnects from Orion, then travels to and lands on the lunar South Pole

Post Lunar Landing Activities and Gateway

- HLS Starship leaves the South Pole and returns to lunar orbit
- HLS Starship docks with Orion again and the 2 astronauts reboard the Orion
- After, Orion disconnects and heads back to Earth
- HLS Starship remains in space

Once the Gateway is flight ready and receives approval, it will launch from Kennedy Space Center and travel to lunar orbit where it will act as a staging location for future missions

Figure I. The detailed mission plan for Artemis III, set to 2024 [14].

SpaceX's multiple Starships will provide a propellant depot and tanker for the main HLS starship to use. The HLS Starship will then continue to lunar orbit, where it will meet with the SLS. After, SLS will launch with the Orion Spacecraft from Kennedy space center, and Orion will be launched to lunar orbit. From lunar orbit, Orion will dock on the HLS, and 2 people will board the HLS for descent onto the lunar surface. After the astronauts have completed their tasks on the Moon, they will return with HLS to Orion and then to Earth, while HLS will remain in orbit.

Later, the Gateway space station will launch to lunar orbit to serve as a station for future manned missions.

Availability

NASA's SLS has been delayed at least sixteen times according to Wikipedia and The Planetary Society, both of which link a timeline of delays [15, 16]. The first launch of SLS, planned in December 2016, has been delayed sixteen times, adding five years to the original schedule. On the other hand, SpaceX's HLS is planned for 2023 and has not seen any major delay yet. Although the HLS's timeline is relatively abstract, the SLS has seen an excess of delays which undermines the value of a concrete timeline. This increases the credibility of the HLS to perform at the planned deadline compared to the SLS.

Comparison

The Block 1 design of the Space Launch System (SLS) has a payload of 27 metric tons(t) or 59,500 pounds (lbs). It has a maximum thrust of 8.8 million lbs, which is 15 percent more thrust than the Saturn V rocket [17]. In contrast, the Starship Human Landing System(HLS) by SpaceX has a payload of 150 metric tons(t), and the HLS will produce 17 million pounds of thrust at liftoff [15].

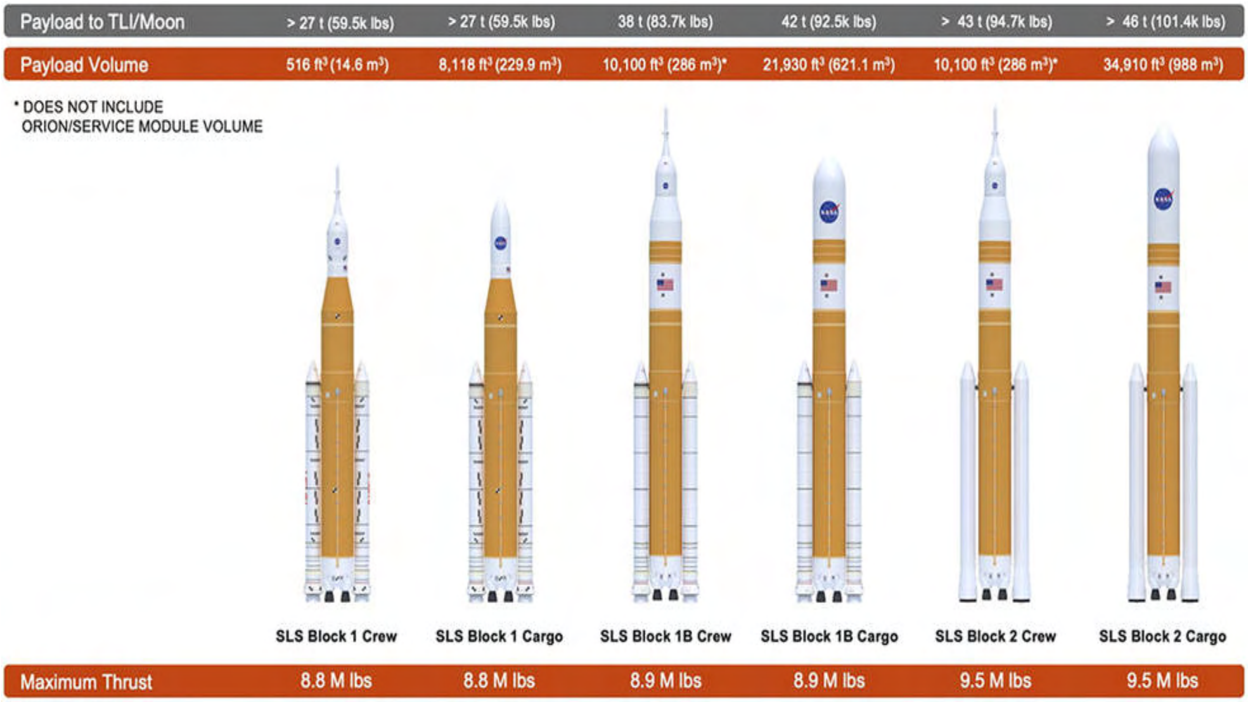


Figure II. The proposed development progression of the SLS is detailed above, with the only version currently being developed the Block 1 Crew and Block 1 Cargo [16].

With the two most recent transportation technologies from NASA and SpaceX, the final Artemis III mission will set the background for further missions that will eventually lead to the construction of a lunar base.

Section 3: Setting Infrastructure

3-1: Atmosphere Composition

Introduction

The lack of atmosphere on the Moon requires manned missions with spacesuits. To build a base that does not require humans to be in a suit, a habitable atmosphere must be provided indoors. This section will include justification for the use of an oxygen/nitrogen system like that of Earth, compared to a novel oxygen/argon system, as well as sourcing costs for nitrogen and oxygen transported to the Moon. All conversions are done with the following sources [18, 19, 20].

The Use of Nitrogen Versus Argon

Earth's atmosphere is composed of 78 percent nitrogen, 21 percent oxygen, 0.9 percent argon, and 0.1 percent other gasses [17]. Because of the abundance and low prices that arise from said abundance, nitrogen is more available for transportation to the Moon than argon.

Nitrogen Sourcing

Humans breathe 2000 gallons of air a day [19].
= 9092.18 liters(7.571m^3)
= 909,218 liters(757.082m^3) of air required per day for 100 humans
78% of that air is nitrogen.
= 709,190 liters(590.52m^3) of nitrogen.
. Nitrogen, unlike oxygen, is not altered during respiration processes, and will not have to be replaced continuously [20].

Gaseous nitrogen generation only costs are electricity if generated by a nitrogen generator on Earth, which at Merritt Island, Florida, NASA already possesses [21]. The generator's electricity use costs 9.18¢/kWh in Florida [22]. It cannot be known how much electricity NASA's generator uses. As an estimate, Peak Scientific, a successful nitrogen generator maker, has a highest performing machine of 70L/min flow rate which consumes 2530VA, which is about 1514W [23, 24].

To generate 709,190 liters (590.52427m^3), one unit would need to operate for 169 hours.
1514W *169 hours = 255.86 kWh
9.18¢/kWh in Florida ⇒ $23.49 to generate 590.52 m^3 of nitrogen on Earth for 100 people to breathe on the Moon, resulting in a negligible price for nitrogen generation.

1 Nm^3 of Nitrogen = 1.25 kg
590.52 m^3 = 738.50 kg

SLS Block 1 is planned to have a minimum payload to lunar orbit of 57,000 lbs or 25854.76 kg [15]. This is at least 35 times the amount needed for 100 people to breathe. With about $2 billion per launch for the SLS block 1 [25], the cost, approximately, of sending 100 people worth of nitrogen from the Earth to the Moon is
$23.49 + ($2 billion/35.009) = $57,128,190

Notice that the cost of generation is 0.00004% of the cost to send the nitrogen to the Moon, and that the total cost mostly depends on the price of one launch of the rocket used for transportation.

Oxygen Sourcing

Oxygen primarily exists on the Moon in the form of water, where it is bonded with hydrogen in a 2:1 molecular ratio of H_2O. Ice, the solid form of H_2O, has been observed to be "trapped in large permanently shadowed regions in the Moon's polar regions, due to their extremely low temperatures," according to a team of researchers who published their findings on the science website, *Nature Astronomy*. The micro cold traps, which contribute to approximately 10–20% of the cold-trap area vary in diameter from 1 km to 1 cm, which results in a total area for cold traps on the Moon of ~40,000 km^2. The south area of the Moon holds approximately 60% of these cold traps [9].

To emphasize the abundance/uncertainty of oxygen available for extraction that this provides, we calculated a pessimistic estimate of the amount of oxygen available for respiration after water was put away for drinking use, along with the initial cold trap area being considered only for the micro-trapped areas. The thickness of the cold traps will be estimated as 1mm. We additionally assume that the cold traps are not 100% water, and use an estimate of 100 to 400 $\mu g\, g^{-1}$ H_2O which was made by Honniball and others for "observations of the Moon… using the NASA/DLR Stratospheric Observatory for Infrared Astronomy (SOFIA)" [10]. A full, optimistic estimate which includes the remaining cold-trap areas and if the cold-traps are pure water, is also calculated.

With the results, we conclude that oxygen shall be extracted through electrolysis on the Moon, as there is a great abundance of it.

Pessimistic Estimate

If 15% of the total cold trap area is micro cold traps,
Water trap area = 6000km^2
If the cold traps are 1mm thick,
volume total = 0.006km^3 of ice = 0.00552km^3 of water = $5.52 * 10^6 m^3$ of water.
250ppm = 0.250kg/m^3
$0.250 * 5.52 * 10^6 m^3 = 1.38 * 10^6$kg of water 1kg of water = 1L of water.

For 100 people, 2.5L a day for each person, we need 250L of water a day for consumption. If we were to put 100 years of drinking water aside, then we have $1.355 * 10^6$Lof water left.
= $1.355 * 10^6$kg of water
= $1.195 * 10^6$kg of O_2
= 836337.98m^3(1 kg = 0.6998m^3)
$8.36 * 10^8$L of O_2 (1 cubic meter = 1000liters)
$8.36 * 10^8$L/9546.789(liters of oxygen used per day for 100 people)
= 87604.11 days worth of O_2.
= 240 years worth of O_2

Optimistic Estimate

40,000 km^2 of cold traps that are 1 mm thick = 0.04 km^3 of ice = 0.0368 km^3 of water
= 3.68 * 10^{10} kg of water = 3.68 * 10^{10} L of water.
For 100 people, 2.5 L a day for each person, we need 250L of water a day for consumption. If we were to put 1000 years of drinking water aside,
=3.68 * 10^{10} L of water left
=3.68 * 10^{10} kg of water
= 3.25 * 10^{10} kg of O_2
= 2.27* 10^{10} m^3
= 2.27* 10^{13} L of O_2
2.27* 10^{13}L/9546.789 (liters of oxygen used per day for 100 people)
= 2.38 * 10^9 days worth of O_2.
= 6.5 million years worth of O_2
If the south pole holds 60% of the cold traps
= 3.9 million years worth of O_2 in the south polar region of the Moon for future lunar bases to use for respiration.

3-2: Building Infrastructure

Basic Info [28]:

A day on the Moon is 27.2 Earth days, and it takes about 3 Earth days for a spacecraft to reach the Moon. The Moon has a diameter of 2,159 miles (3,476 kilometers) and is about one-quarter the size of Earth. The Moon weighs about 80 times less than Earth. The Moon is at an average distance of 238,855 miles (384,400 kilometers) away from Earth, which is about the width of 30 Earths. The moon revolves around Earth as fast as it spins on its axis, and so one side of the moon faces earth at all times. The tilt is minimal unlike Earth's 23.4 degrees, which disallows any significant seasonal temperature changes. When the moon orbits the Sun, from that perspective, it meets the sunlight at the same angle every time it orbits the earth in the same position. Such orbital details and physical traits of the Moon give information on the ideal spot for a lunar base. A beneficial spot may be a location where sunlight is available for most of the year.

At the poles, there are spots where there is always the same amount of light at a given point. The data from the Lunar Reconnaissance Orbiter (LRO) shows that certain locations on the edge of the Shackleton Crater are lit for most of a lunar year. The longest period that Shackleton is eclipsed is less than 2 days.

"The Lunar Reconnaissance Orbiter Camera (LROC) provides… imaging of the north and south polar regions. From our analysis of the LROC images, we identified localized regions where the lunar surface remains illuminated for nearly 94% of the year with the longest eclipsed period lasting only 43 h" [26]. These factors are able to inform a long-term habitation site, namely that Shackleton crater is the ideal spot for a permanent lunar base.

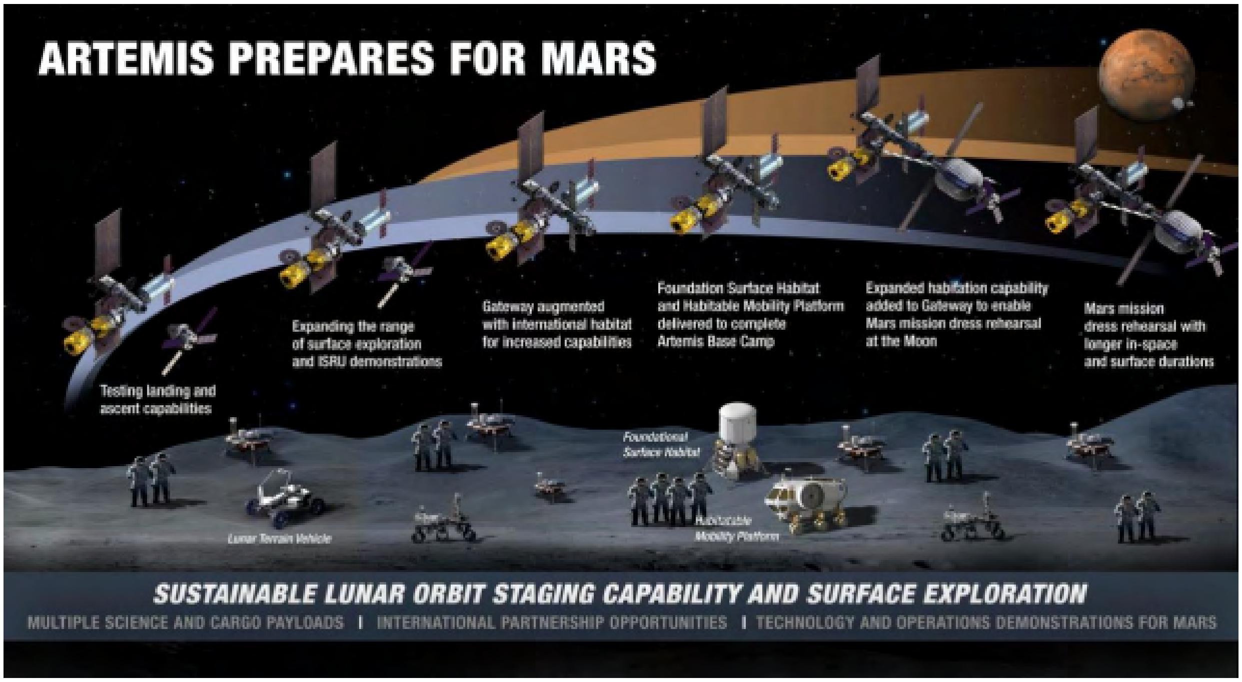


Figure III. NASA's Plan for Sustained Lunar Exploration and Development provides an image of the continual progress that the Artemis missions will overlook [3].

Radiation

The Moon receives 60 microsieverts (Sv) of radiation per hour, 200 times that of Earth's surface [8, 9]. A solution may not be needed in the short term where astronauts go on short missions that last less than a month, but to create a lasting settlement, putting as much mass between radiation from the Sun and people as possible is important. We propose placing lunar soil on the base as extra padding to somewhat mitigate radiation, and NASA is researching the exact effects of sources of large radiation like the Sun's flares or a coronal mass ejection (CME) [9].

Asteroids

The Moon possesses no atmosphere, thus giving a higher risk of asteroids. The solution is natural shelter, like a crater can provide [3]. The accompanying image is Figure 5 of NASA's Plan for Sustained Lunar Exploration and Development. This image shows potential sites near permanently shadowed regions. These sites offer long sunlight exposure and terrain that will be convenient for future missions.

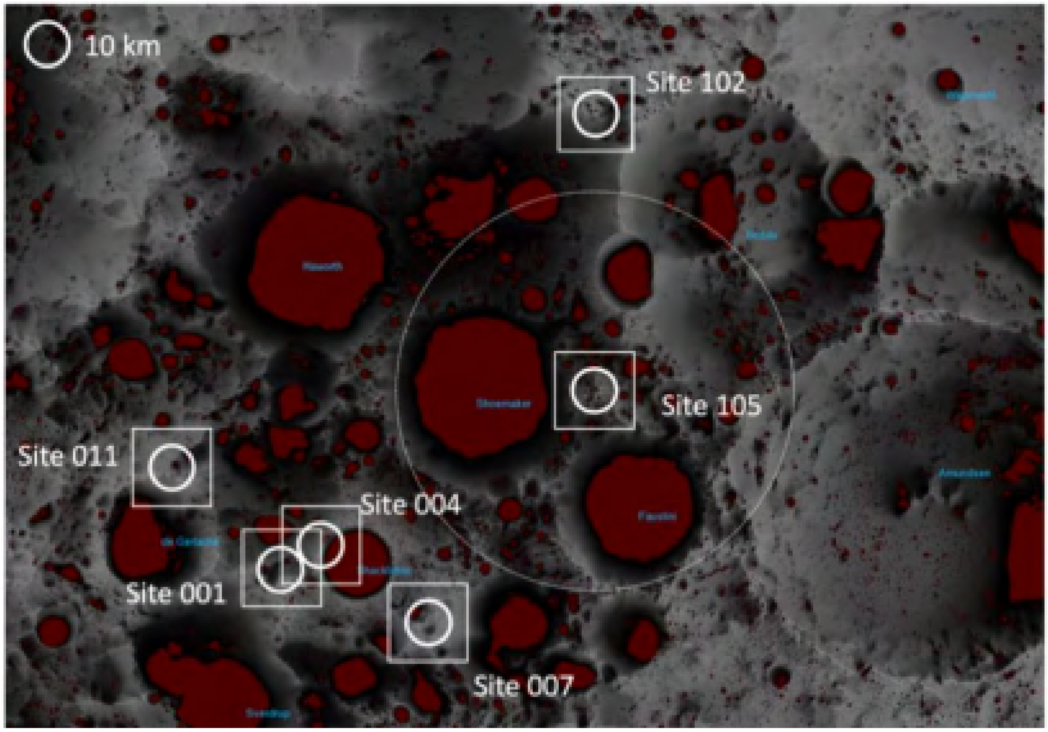


Figure IV. The noted areas are all located near the lunar south pole, where there is nearly eternal sunlight and low chance of asteroid collision compared to the rest of the lunar surface [3].

Weak Gravity

The danger that weak gravity, specifically about 1.62 m/s² on the Moon, poses is bone and muscle atrophy. A solution is constant exercise to counteract the atrophy's effects. See Section 4.

Long Day and Big Temperature Difference Between Day and Night

The average temperature on the Moon (at the equator and mid latitudes) varies from -298 degrees Fahrenheit (-183 degrees Celsius), at night, to 224 degrees Fahrenheit (106 degrees Celsius) during the day [10]. The south pole sites on the moon have long periods of sunlight (Figure IV above).The lack of atmosphere extremizes the temperature difference between day and night. The moon's temperature can reach a boiling 250° Fahrenheit (120° Celsius or 400 Kelvin) during lunar daytime at the moon's equator [10]. The surface temperature of the Moon varies greatly by latitude and position of the Sun.

Daytime temperatures vary from ~387–397 K at the equator, to dropping ~300 K to around 95 K before sunrise. The average maximum temperature in the poles of the Moon is ~200 K with average minimum temperatures of ~50 K [27].

Exploration/Research Infrastructure

NASA's LTV and HMP are two technologies that NASA has revealed plans for a future lunar base. NASA has revealed three proposers of LTV so far. Lockheed Martin's proposal sees the most amount of companies cooperating on the project, including a historic lunar tire maker, Goodyear. None of the proposing companies have revealed designs so far.

Residence

The permanent residence technology planned by NASA's Artemis mission is named the Foundation Surface Habitat, which will support a crew of up to four on the lunar surface, the lunar surface power systems, ISRU demonstrations, and pilot plants [3].

Agriculture Infrastructure

Hydroponics is defined as growing plants in a nutrient solution root medium and is a growing area of commercial food production. Aeroponics is "the process of growing plants in an air or mist environment without the use of soil or an aggregate medium" [28].

Water Usage: Soil>Hydro>Aero [29]
Growth Speed: Aero

Hydroponics can become waterlogged, where air struggles to vent in soil.
In aeroponics, suspended aeroponic plants receive 100% of the available oxygen and carbon dioxide to the roots zone, stems, and leaves, thus accelerating biomass growth and reducing rooting times. NASA also concluded that aeroponically grown plants require ¼ the nutrient input compared to hydroponics [29]. We propose aeroponics as the main agricultural method for the above reasons.

3-3: Satellite Propulsion Methods and Gateway

Needs for Satellites on the Moon

Satellites will have many uses on the Moon such as topography analysis, real time communication, and GPS-like systems. These are also some of the main uses satellites have on Earth. Gateway is a planned international space station on the Moon, which will serve as a hub for lunar research and will possess facilities to hold people [2]. NASA has already launched several satellites like the Lunar Reconnaissance Orbiter to the Moon, which proves how necessary NASA sees lunar satellites [30].

Solar Sails and Momentum Exchange Tethers

Solar sails are a propulsion method that uses sunlight and momentum of massless photons in the relative vacuum of space to move the sail and its cargo to up to near-light speeds [18]. The IKAROS solar sail was launched by the Japanese Aerospace Exploration Agency(JAXA) that first demonstrated controlled solar sailing [30]. NASA, with their NanoSail-D spacecraft, has demonstrated this technology as well [31]. The Planetary Society's Lightsail 1 spacecraft is a notable private satellite that was launched [18]. NASA's Advanced Composite Solar Sail System (ACS3), a new demonstration of solar sail technology, launches in early 2023. The solar sails, if on satellites, may be used as an alternative to fuel for some uses such as changing orbital path or dodging space debris. As such, solar sails may contribute to previously mentioned uses for satellites. The technology readiness level (TRL) of solar sails is 9, because it is proven in several flights across different organizations successfully [32]. Some notable negatives of a solar sail include engineering difficulties. The solar sail, if to be used for surface landing modules, must be able to retract from the body to be able to land. Additionally, it is delicate to temperature depending on what material the solar sail is made from. For the framework of a lunar base, the Gateway space station will systematically assist in launching solar sails into lunar orbit to study the composition of the lunar surface, as well as general geography analysis for locations on the lunar surface that are difficult to reach with land rovers.

Momentum Exchange Tethers (MET) are cables used for propulsion and flight control through momentum exchange. This method of propulsion is significantly less expensive than traditionally fueled chemical engines in rockets, because there is no fuel requirement.

METs are TRL 5-7(Development to Demonstration Stage) and will most likely not be ready for use in early lunar missions. Tethers are not yet fully implemented in even Earth orbit missions and are not proven for long term or long range space launches. However, NASA seems to positively view this technology and is working on development.

Section 4: Exercise and Dinner With a Nice View

Introduction

The astronauts will face troubling conditions on the Moon.Appropriate nutrition and exercise is crucial to avoiding health deterioration from the harsh lunar conditions which may include cosmic radiation, low gravity, and asteroids. Detailed caloric needs and other nutrition requirements are laid out, along with possible candidates for direct agriculture on the lunar surface, which must have been proven to be either relatively superior in nutrition percentage or be cultivated to a harvestable degree in lunar regolith.

4-1: Caloric Requirements/Ratio of Carbohydrates, Protein and Fat

The caloric requirements for a person varies depending on gender, age, height, weight, and daily activity. To determine a value for an individual, the Harris-Benedict Calculator for daily energy expenditure can be utilized [4]. The basal metabolic rate (BMR), which is “equivalent to the amount of energy (in the form of calories) that your body needs to function if it were to rest for 24 hours,” is first calculated. This is done using one out of two formulas, chosen depending on gender, and includes variables of weight, height, and age. An activity factor (AF) depending on the degree of activity during the day is multiplied to get the final result of the total daily energy expenditure for one person, personalized to an appropriate degree. BMR is calculated in kcal/day. The formulas for BMR are as follows:

For men: BMR = 66.5 + (13.75 * weight in kg) + (5.003 * height in cm) - (6.75 * age)
For women: BMR = 655.1 + (9.563 * weight in kg) + (1.850 * height in cm) - (4.676 * age)
Total Daily Energy Expenditure (DEE) = BMR * AF

Activity factor varies depending on the following conditions:

Table I. This constructed table provides an overview of how activity level relates to the Activity Factor used in calculating the daily energy expenditure [4].

Activity Level	Sedentary (little or no exercise)	Lightly active (light exercise/sports 1-3 days/week)	Moderately active (moderate exercise/sports 3-5 days/week)
Activity Factor	1.2	1.375	1.55

Activity Level	Very active (hard exercise/sports 6-7 days a week)	Extra active (very hard exercise/sports & a physical job)	Astronauts(intense exercise for 2.5 hours every day)
Activity Factor	1.725	1.9	1.75

An activity factor will be estimated between 1.6 and 1.9 for astronauts that are constantly moving during missions, undergo stress, and exercise to counteract bone/muscle mass loss from low gravity conditions. To take an average, 1.75 will be chosen as an activity factor, thus daily caloric expenditure for each person on the moon becomes BMR * 1.75.

Caloric Requirement in kcal/day per person: BMR * 1.75

Regarding ratios of calorie intake between protein, carbohydrates, and fats, the International Space Station (ISS) menu provides ~50% of calories as carbohydrate, 17% as protein, and 31% as fat [6]. The ~50% will be considered as 52% for the sake of adding to 100% total.

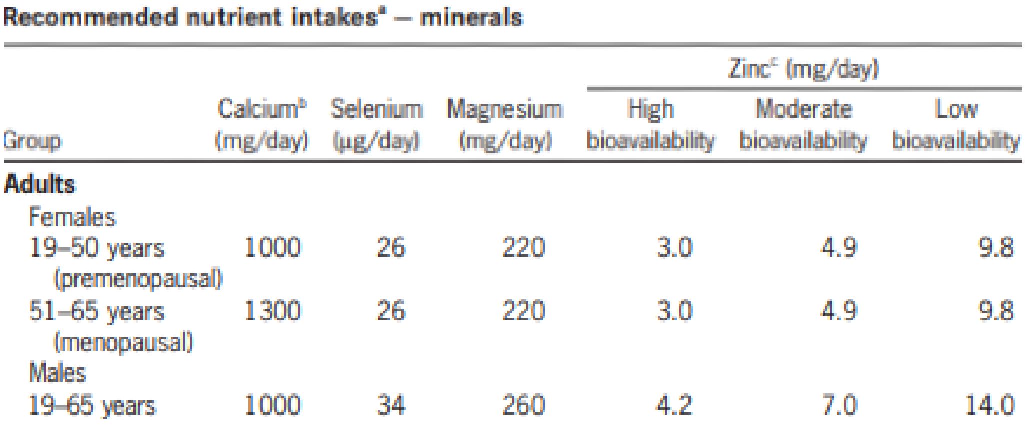
The average BMR is about 1409 kcal (5900 kJ) for a woman and about 1696 kcal (7100 kJ) for a man.[4] With this average value, the DEE is as follows:

Per male per day = 2968 kcal
Per female per day = 2465.75 kcal

The astronauts selected for the lunar mission will perform best if they are given individual DEE values and given distribution of meals accordingly.

4-2: Minerals/Vitamins Requirements/Sources

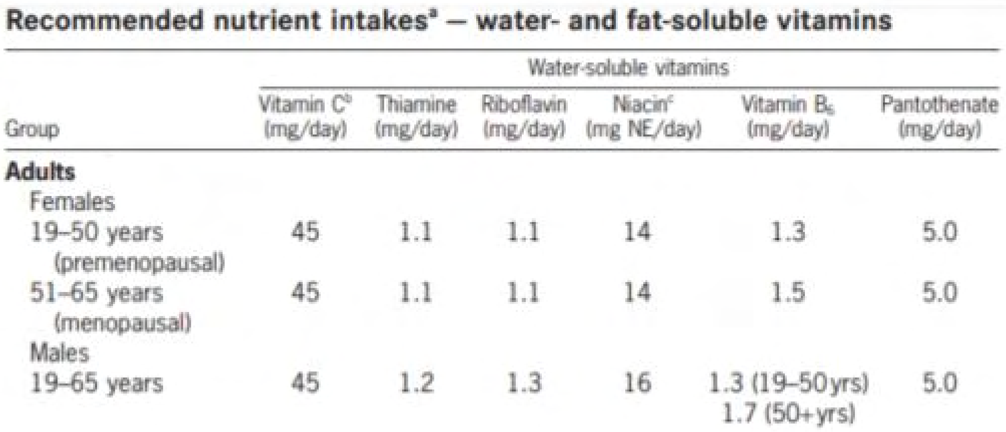
Vitamins, minerals and water do not contain calories. These have separate requirements. Each type of vitamin and mineral will be factored into the dietary plan for astronauts. The 100 people on the Moon base will be assumed to be over 19 years of age and healthy.Values are extracted from the WHO’s Vitamin and mineral requirements in human nutrition, 2nd edition [5].



Recommended nutrient intakes[a] — minerals

Group	Calcium[b] (mg/day)	Selenium (µg/day)	Magnesium (mg/day)	Zinc[c] (mg/day) High bioavailability	Zinc[c] (mg/day) Moderate bioavailability	Zinc[c] (mg/day) Low bioavailability
Adults						
Females						
19–50 years (premenopausal)	1000	26	220	3.0	4.9	9.8
51–65 years (menopausal)	1300	26	220	3.0	4.9	9.8
Males						
19–65 years	1000	34	260	4.2	7.0	14.0

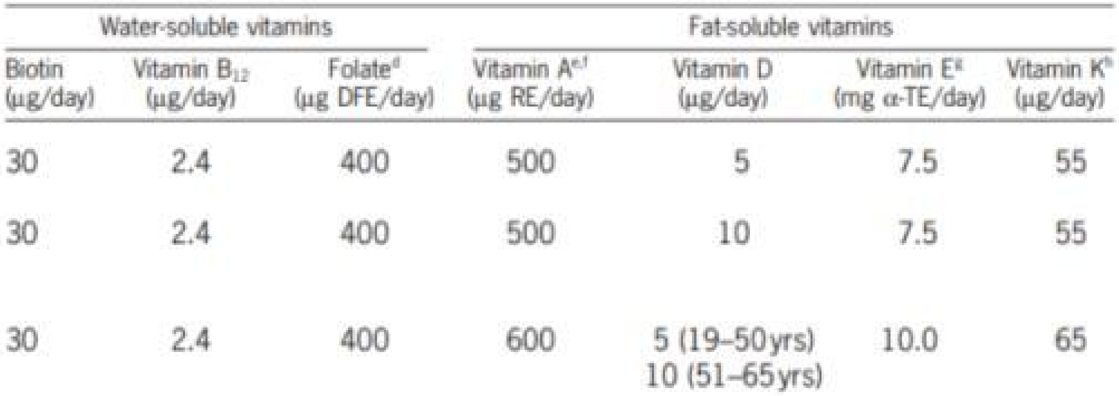
Figure V. The recommended nutrient intakes for minerals from calcium to magnesium, depending on bioavailability. Moderate bioavailability is assumed for astronauts [5].



Recommended nutrient intakes[a] — water- and fat-soluble vitamins

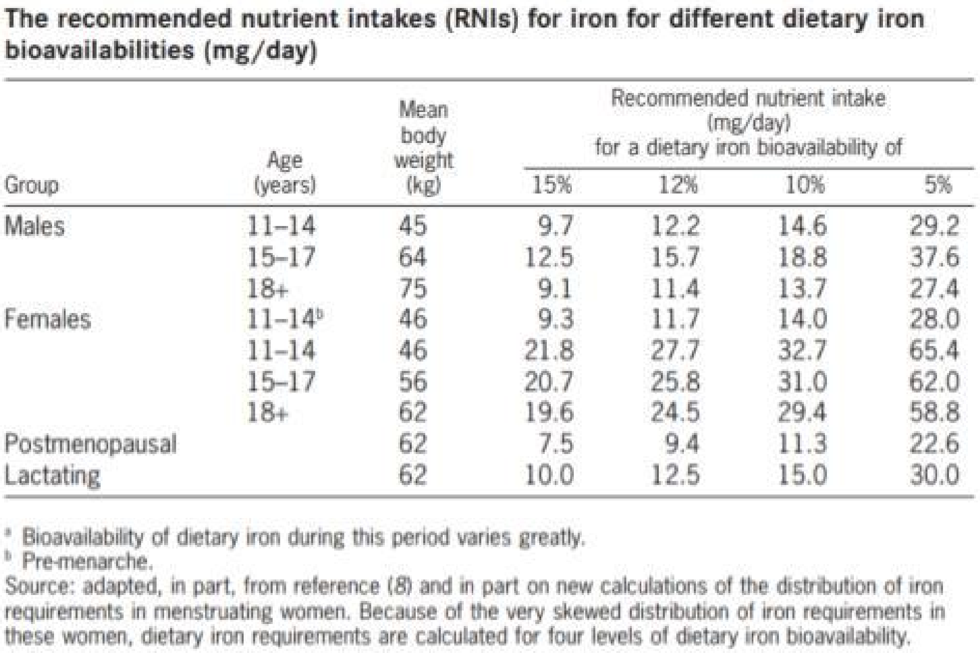
Group	Water-soluble vitamins Vitamin C[b] (mg/day)	Thiamine (mg/day)	Riboflavin (mg/day)	Niacin[c] (mg NE/day)	Vitamin B_6 (mg/day)	Pantothenate (mg/day)
Adults						
Females						
19–50 years (premenopausal)	45	1.1	1.1	14	1.3	5.0
51–65 years (menopausal)	45	1.1	1.1	14	1.5	5.0
Males						
19–65 years	45	1.2	1.3	16	1.3 (19–50 yrs) 1.7 (50+ yrs)	5.0

Figure VI. The recommended nutrient intakes for water-soluble vitamins [5].



Water-soluble vitamins			Fat-soluble vitamins			
Biotin (μg/day)	Vitamin B_{12} (μg/day)	Folate[d] (μg DFE/day)	Vitamin A[e,f] (μg RE/day)	Vitamin D (μg/day)	Vitamin E[g] (mg α-TE/day)	Vitamin K[h] (μg/day)
30	2.4	400	500	5	7.5	55
30	2.4	400	500	10	7.5	55
30	2.4	400	600	5 (19–50 yrs) 10 (51–65 yrs)	10.0	65

Figure VII. The recommended nutrient intakes for water-soluble vitamins Biotin to Folate, and Fat-Soluble vitamins from Vitamin D to Vitamin K [5].



The recommended nutrient intakes (RNIs) for iron for different dietary iron bioavailabilities (mg/day)

Group	Age (years)	Mean body weight (kg)	Recommended nutrient intake (mg/day) for a dietary iron bioavailability of			
			15%	12%	10%	5%
Males	11–14	45	9.7	12.2	14.6	29.2
	15–17	64	12.5	15.7	18.8	37.6
	18+	75	9.1	11.4	13.7	27.4
Females	11–14[b]	46	9.3	11.7	14.0	28.0
	11–14	46	21.8	27.7	32.7	65.4
	15–17	56	20.7	25.8	31.0	62.0
	18+	62	19.6	24.5	29.4	58.8
Postmenopausal		62	7.5	9.4	11.3	22.6
Lactating		62	10.0	12.5	15.0	30.0

[a] Bioavailability of dietary iron during this period varies greatly.

[b] Pre-menarche.

Source: adapted, in part, from reference (8) and in part on new calculations of the distribution of iron requirements in menstruating women. Because of the very skewed distribution of iron requirements in these women, dietary iron requirements are calculated for four levels of dietary iron bioavailability.

Figure VIII. The recommended nutrient intakes for iron, depending on bioavailability. Moderate bioavailability is assumed for astronauts [5].

4-3: Water Requirements/Sourcing

By NASA standards, 2.5 L/day for direct consummation and rehydration of food and an extra 0.24 L an hour for EVA operations is appropriate. The average water intake for astronauts on NASA missions has varied between 1.6 and 2.8 L/day, since Apollo [8]. 3 L/day will be employed for the Artemis III missions and beyond.

The source of the water will be ice on the Moon, as discovered by Hayen and Honniball, as stated in Section 3-1 [10]. Cold traps may be in total 40,000 km². The 60% of cold traps in the south equal 24000 km². If the astronauts were to just use the micro cold traps, there is around 6000 km² available.

Pessimistic Estimate

If 15% of the total cold trap area is micro cold traps,
Water trap area = 6000 km^2
If the cold traps are 1mm thick,
volume total = 0.006 km³ of ice = 0.00552 km^3 of water = $5.52 * 10^6 m^3$ of water.
250 ppm = 0.250 kg/m^3
$0.250 * 5.52 * 10^6 m^3 = 1.38 * 10^6$ kg of water 1 kg of water = 1 L of water.

For 100 people, 2.5L a day for each person, we need 250 L of water a day for consumption. If we were to put 100 years of drinking water aside, then we have $1.355 * 10^6$ Lof water left which may be used for other bodily needs such as the oxygen/nitrogen atmosphere that will constitute the lunar base requiring oxygen extracted via electrolysis from the ice water. See Section 3-1.

Optimistic Estimate

40,000 km^2 of cold traps that are 1 mm thick = 0.04 km^3 of ice = 0.0368 km^3 of water = $3.68 * 10^{10}$ kg of water = $3.68 * 10^{10}$ L of water.
For 100 people, 2.5L a day for each person, we need 250L of water a day for consumption. If we were to put 1000 years of drinking water aside,
=$3.68 * 10^{10}$ L of water left which may be used for other bodily needs such as the oxygen/nitrogen atmosphere that will constitute the lunar base requiring oxygen extracted via electrolysis from the ice water. See Section 3-1.

4-4: Diet Suggestions

The diet of the lunar human will consist of supplies from the Earth initially, which will be whatever the mission requires. The true path to sustainability lies in the ability to grow plants and harvest them in a speed and amount that will more than support the number of individuals involved in the colonization.

A group of researchers led by Wamelink studied plant growth in lunar regolith simulants [6]. Actual regoliths are not available for plant growth experiments, therefore NASA has developed regolith simulants. Ten different crops, garden cress, rocket, tomato, radish, rye, quinoa, spinach, chives, pea and leek were used in this experiment. Nine of the ten species grew well with the exception of spinach. It was possible to harvest edible parts for nine out of ten crops.

> “Three crop species from our earlier experiment (Wamelink et al. 2014) were used again, namely tomato, Solanum lyco-persicum L. … rye, Secale cereale L. … and garden cress, Lepidium sativum L. ... Crops new for this experiment were leek, Allium ampeloprasum L. … quinoa, Chenopodium quinoa Willd. … pea, Pisum sativum L. … radish, Raphanus raphanistrum subsp. Sativus… spinach ... and chives, Allium tuberosum Rottler ex Spreng. 1825 not Roxb. 182” [6].

Among the plants tested, the only vegetable that failed to grow well was spinach. The leek and chives grew at a slower pace than in Earth soil, while the quinoa failed to produce seeds. The cress, rye, radish, tomatoes and peas grew to a harvestable degree. As such, we recommend spinach, leek, and peas as they give protein and also crucial minerals like calcium and magnesium, especially in the spinach, as shown by the USDA Nutrient Database [13].

Additionally, meat has been grown in the ISS through 3D bioprinting, which is in the proof of concept stage of development [12]. If this is developed, it may give a refreshing alternative to the green vegetables astronauts may be forced to eat.

Section 5: Proposals

5-1: Summary of Proposals/Timeline

To the Moon

The Artemis mission III set in 2024 shall be the main point from which humanity starts lunar colonization [1]. The transportation technology used will include SLS and HLS. The Gateway space station serves as a hub for surface missions.

Atmosphere

The atmosphere composition of pressurized residence buildings or modules will be mostly a mixture of oxygen and nitrogen, with ratios similar to that of Earth. Nitrogen will be transported from Earth for the foreseeable future, and the price per unit of weight to transport to the Moon solely depends on the launch price of the rocket used to ship nitrogen because the price of generating nitrogen is negligible. Oxygen will be extracted from the ice traps on the south pole of the Moon [9]. Depending on the area of ice considered, the available amount for breathing varies from 240 years’ worth to 3.9 millions years’ worth of oxygen.

Infrastructure

The Shackleton Crater and the peak around it will be the location that is considered for this lunar base [33]. The 3 main infrastructure technologies will be the Habitable Mobility Platform for pressurized transportation, Lunar Terrain Vehicle for non-pressurized use, and the Foundational Surface Habitat for semi-permanent residence. The modules will be multiplied depending on the number of people on base. Agriculture will be based on hydroponics and aeroponics, which will reduce water usage and simplify the farming process. Solar sails shall be implemented as satellite technology, and the Gateway space station will serve as an intermediate between the Earth, lunar orbit, and the lunar surface.

Nutrient and Exercise

The required nutrients in calories per male per day is 2968 kcal, and per female per day is 2465.75 kcal. The mineral and vitamin requirements are as detailed in section 4-2. Ice is abundant on the Moon; therefore water is abundant as a drinking source. The filtration and electrolysis technologies required to convert ice to water will be transported from the Earth. Spinach, leek, and peas are recommended as crops for consumption due to their high amounts of vital nutrients such as protein.

5-2: Simple Schematics of Lunar Base

The following images are schematics designed to show how the lunar base may be visualized. One main schematic is followed by several others that detail further what features the fundamental technologies may end up possessing in the near future. All details are speculative suggestions due to a lack of detailed design drawings at this point and are not crucial to the proposals, except for the location setting and the greenhouse section of the diagrams. The diagrams are located in and around the Shackleton Crater, one of the 13 landing sites designated by NASA around the south pole of the Moon. The second image (Figure X) includes a scale added to an image that was produced by NASA which designates 13 landing sites near the south pole of the Moon. The third diagram (Figure XI) zooms in to the first image and shows where this lunar base will be situated. A visual transition between Figure X and Figure XI that shows the south pole of the Moon zoomed in starting from the whole Moon can be seen on NASA's Scientific Visualization Studio [38]. The fourth diagram (Figure XII) is an overview of all the technologies that we propose shall be implemented into Artemis III missions and beyond. The other diagrams detail specific speculations about how each technology may be designed, except for the Lunar Terrain Vehicle due to its unpressurized state and relative similarity to a doorless rover on Earth. The diagrams are not to scale, except for the second.

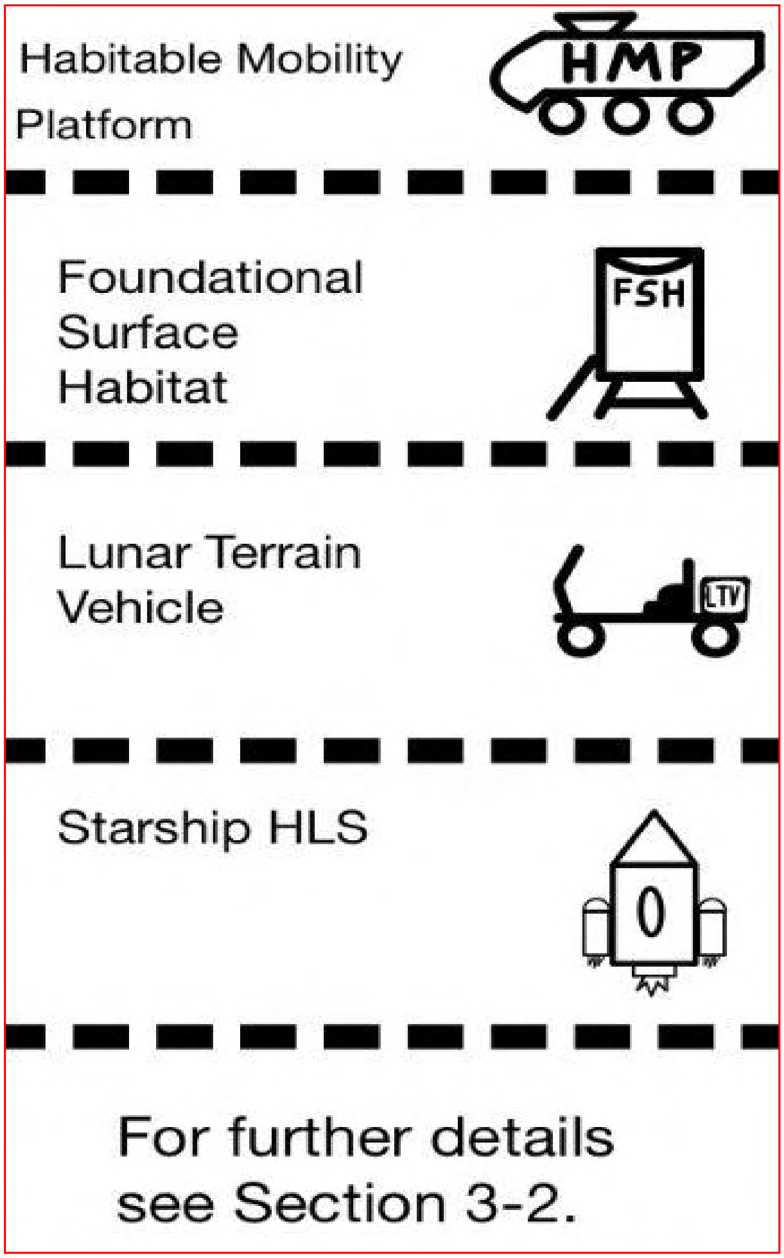


Figure IX. A key to the following schematics is shown above, with the names of the technologies labeled. They are further detailed in Section 3-2: Building Infrastructure.

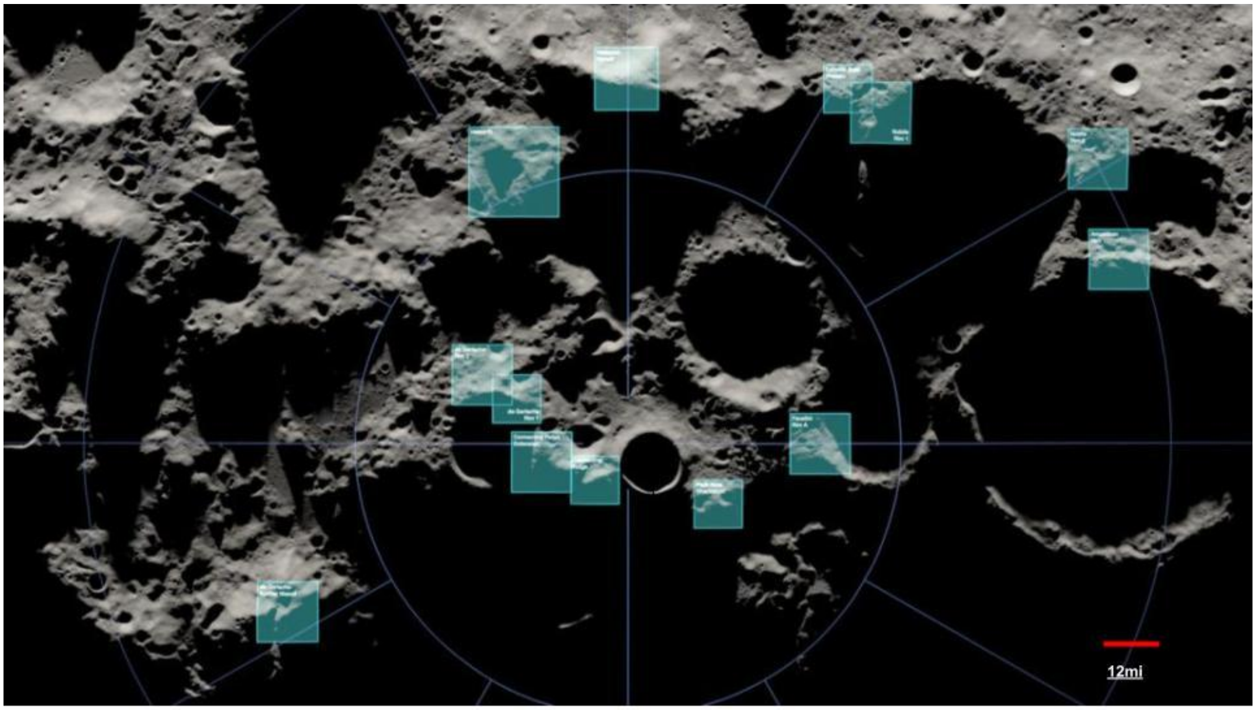


Figure X. The 13 landing sites designated by NASA, located on the south polar region of the Moon. The thinly lined cross marker shows the radius of the area where the 13 sites are generally located. The Shackleton Crater, located on the center of the gray cross, has a landing site nearest to it, namely the Peak Near Shackleton landing site. [37].

Figure XI. One of the 13 sites, the Peak Near Shackleton, is now zoomed in and labeled with lunar base technologies [34].

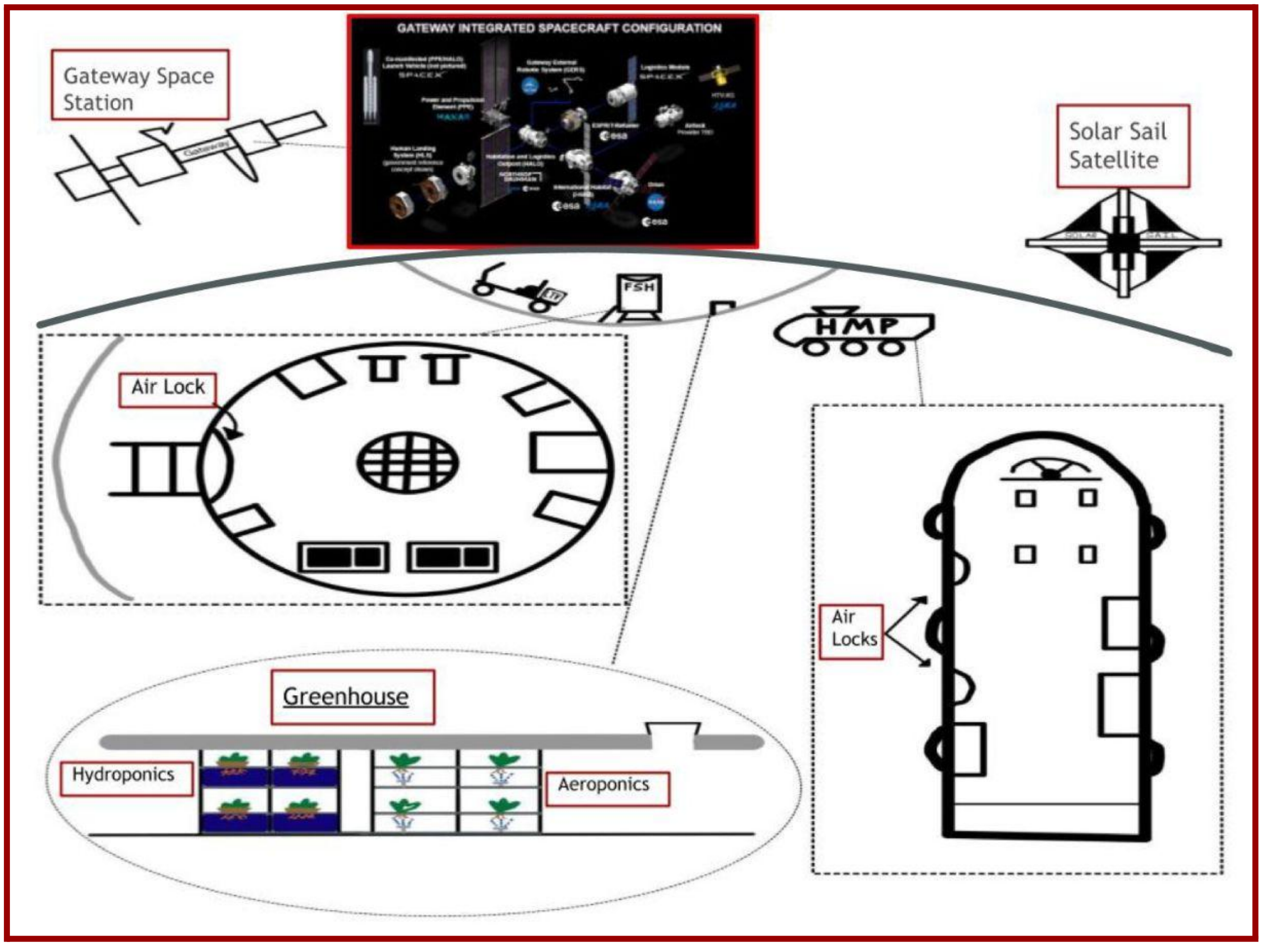


Figure XII. Main schematic outlining the technologies used. A zoomed version of Gateway space station's detailed diagram is available below [35].

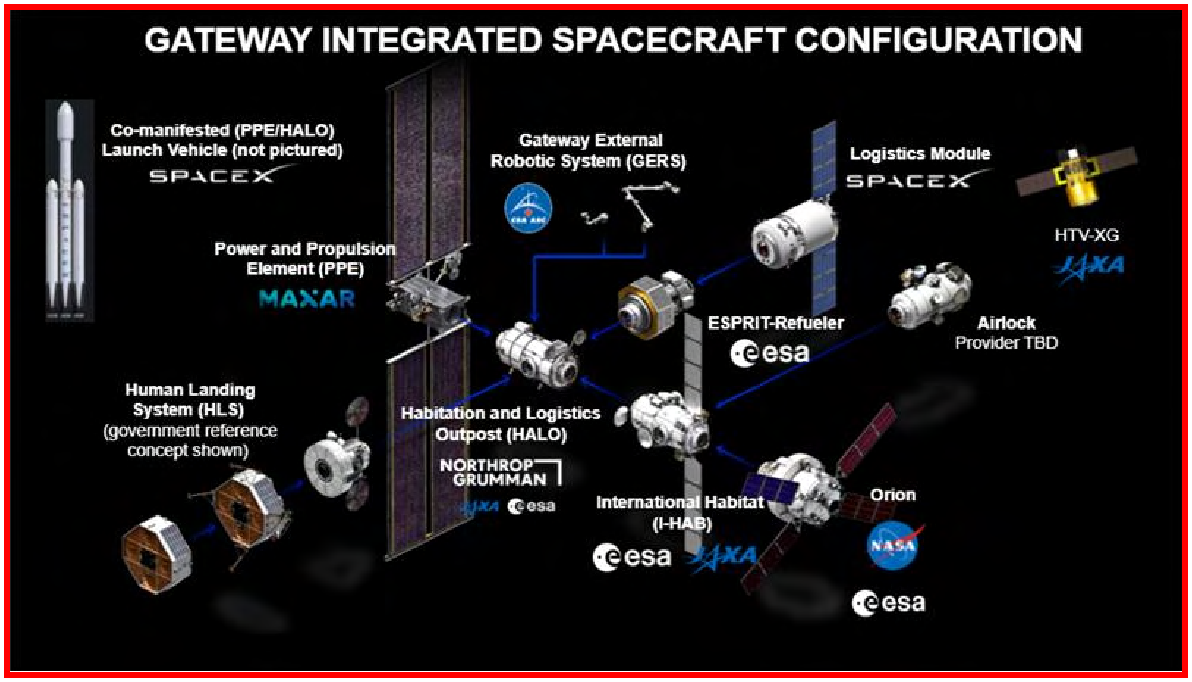


Figure XIII. The Gateway space station's integrated spacecraft configuration, in collaboration with international space agencies, displays the cooperative effort that space exploration requires [35].

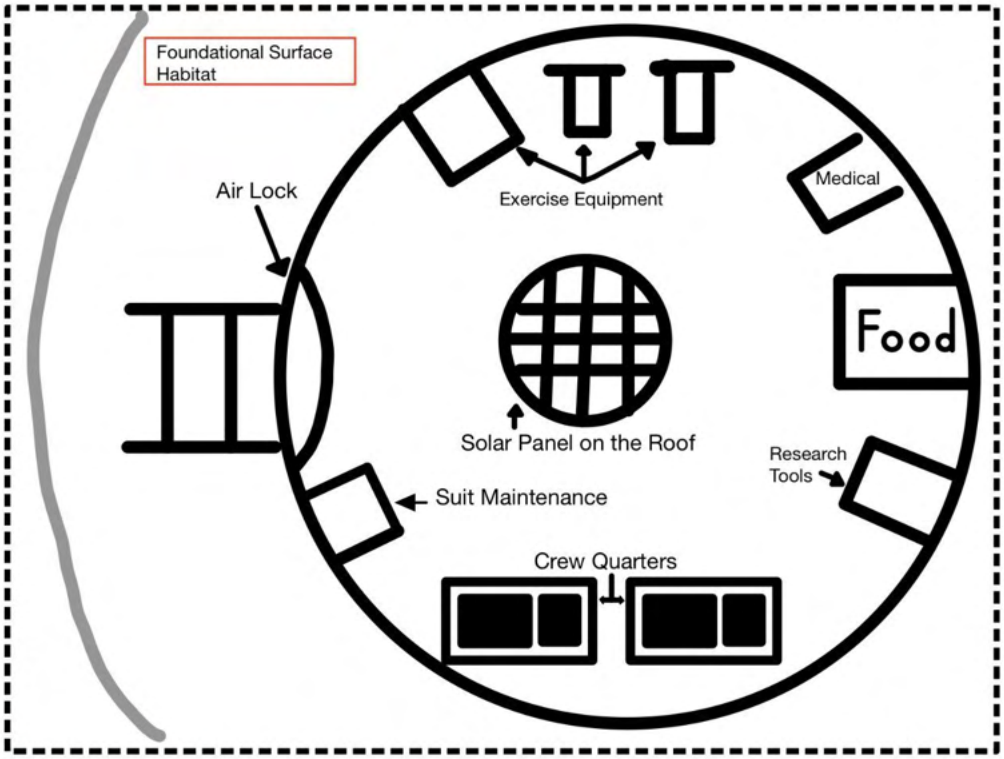


Figure XIV. Schematic detailing of how the FSH may be configured [3].

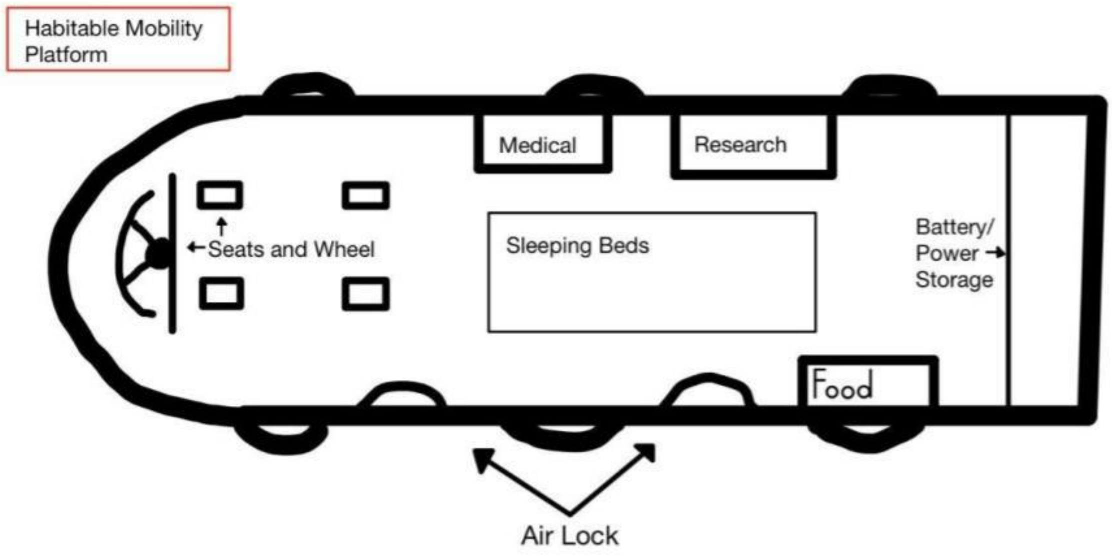


Figure XV. Schematic detailing of how the HMP may be configured [3].

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