3.2 Phase 2: Infrastructure Preparation

PHASE 2

INFRASTRUCTURE PREPARATION

2025 — Infrastrcutre materials ship from Earth.

10 YEARS

2035 — Basic habitat structure/frame is complete.

PURPOSE: To establish/construct necessary **infrastructure** for **short-term missions.**

- Autonomous habitat setup, **robotic construction** of habitats via 3D sintering and moon regolith piling.
- **Cargo shipments** stocking supplies, tools, and necessary initial resources.
- Establish the volume of useful **resources** (e.g. water) that can be extracted in a sustainable manner.

The purpose of the robotic infrastructure preparation phase is to begin the establishment of habitats and demonstrate the technology necessary for future human missions, with an estimated duration of 10 years. The development of this phase will rely on robotic operations to establish the structural foundation for the lunar base, which will be further developed into a life-supporting habitat in Phase 3. This structural foundation will provide functional qualities of physical support, radiation protection, micrometeor protection, and dust exposure reduction, all of which are required for prolonged human habitation and to address the concerns highlighted within the scientific arguments against going to the Moon (Section 2.3.2). Some roadmaps, particularly from Airbus, ESA, and the Global Exploration Roadmap (ISECG), mention the investment of time and resources to pre-construct the foundation of a future lunar base.

The sections within this phase address the technical requirements, in terms of power, communications, navigation, and transportation as well as the governance aspects needed to conduct operations concerning infrastructure preparation on the Moon. An overview of these operational requirements is presented in Table 3.7, below.

Table 3.7. Overview of operational requirements for Phase 2

PHASE 2	
INFRASTRUCTURE	GOVERNANCE ASPECTS
Architecture • Implementing in situ manufacturing of habitats via 3D regolith printing and solar sintering. • Sending some rigid and expandable structures from Earth. Power and Distribution • Combination of solar arrays and compact nuclear fission reactors. Communication/Navigation • Use of both line-of sight and surface-based communications with high data transfer rate and ability to ensure precise operations. • Continuation of ground-based navigation for robots with the additional implementation of star trackers and sun sensors to increase location accuracy. Transportation • Use of heavy launch vehicles with a focus on reusability. • Implementation of a Lunar Space Tug, to provide constant ferrying of cargo and supplies. In Situ Resources • Small scale mining and processing of Lunar regolith to procure in situ habitat materials.	• Define the management of resource utilization. • Governance structures largely dependent on actors present on the Lunar surface.

3.2.1 Phase 2 Infrastructure

Upon selection of a habitation site (conducted in Phase 1), laying the infrastructure necessary for future human missions becomes the priority. The habitation styles presented below are variations that could be developed. The choice is largely dependent on the in situ resources available within the local outpost location selected. Furthermore, the infrastructure associated with supplying power, communicating to, and transporting the robots that will be constructing the proposed habitats is also presented.

3.2.1.1 Architecture

There are multiple ideas for how to construct the structural aspects of the lunar base infrastructure. Concepts differ depending on the chosen location, but regardless of the location, the dependence on ISRU is a common factor.

Rigid structure

The first structures that will be produced on the Moon will be manufactured shelters or hangars with the implementation of a Thermal Protection Systems (TPS). These shelters will prevent damage to robot components due to significant changes in temperature, radiation, micrometeorites, and dust, while they work to develop the larger structures that will be used later for human habitation (Hernandez, Sunder and Vestgaard, 1989).

Large structural elements could be brought from the Earth directly, similar to how space stations have been previously constructed, however, this would be extremely costly (ESA, 2019b). Also, the fuel and fairing capability required for soft landing these structures on the surface of the Moon presents technical challenges (Benaroya, et al., 2016). Therefore, ISRU is thought to be an essential first approach to lunar habitat development.

Regolith 3D Printing

One of the concepts, developed by ESA and Foster and Partners, is 3D-printing the external shell structure of habitats out of lunar regolith, as seen in Figure 3.3 below. This technique requires a single multi-purpose robot which has the ability to collect and distribute regolith, layer by layer, around an inflatable dome in order to create a protective shell. Implementing this technique would minimize the weight of structures and the amount of manufacturing material launched from Earth (Foster and Partners, 2013). It would also reduce the required amount of regolith, which is in line with the goal of "Sustainable ISRU."

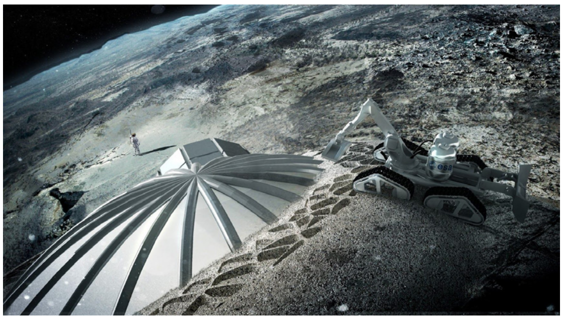
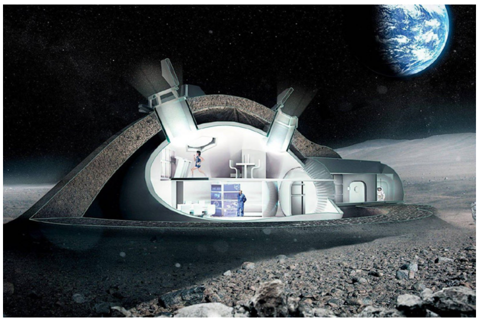

Figure 3.3. Lunar base made with 3D printing, section and overall view (Foster and Partners, 2013)

Solar Sintering

As a specialized form of 3D-printing, solar sintering concentrates sunlight in order to heat and shape lunar soil. This method could enable the production of habitat structures, landing pads, and dust protection walls, among others. Furthermore, it could also contribute to the construction of roads, which would decrease the amount of aerosolized dust that could travel into machines and habitats, causing technical issues. Solar sintering also provides the ability to contour craft, which creates entire solid structures (see Figure 3.4 below), and can join previously assembled bricks to one another for construction (Imhof, et al., 2017).

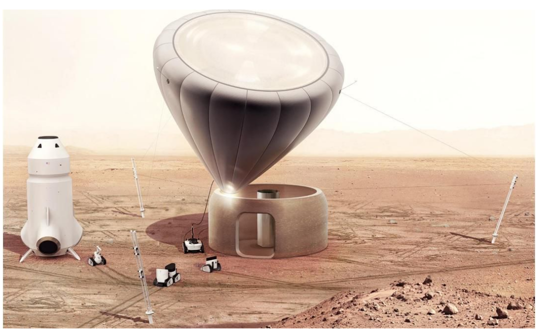
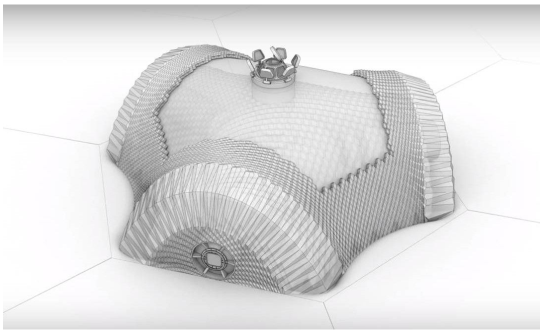

Figure 3.4. Solar crafting of the martian surface habitat (left) (Solar Crafting, 2015). Radiation and micrometeorite protection system based solar sintered regolith bricks (right) (RegoLight, 2017)

Implementing Ice

The concept of using ice to construct radiation protection shells for habitats was developed by SEArch+ for 3D Printing NASA Habitat Challenge Figure 3.5. While the concept was originally proposed as a martian base concept, it could be utilized on the lunar surface as well. Ice has good radiation protection capabilities and can be translucent, which allows for the introduction of the natural light to the structure a benefit for future occupants (Ciardullo, et al., 2016).

Figure 3.5. The Mars Ice House robotic construction process and a section view (Ciardullo, et al., 2016)

Alternative in situ Manufacturing Methods

Other methods of constructing habitats for future missions based on in situ resources are outlined below:

- **Electron Beam Additive Manufacturing** - Uses a vacuum to create an electron beam that can be used to produce large metal parts (ESA, 2019c)
- **Fused filament fabrication** - Can create a wide range of materials and has already been tested in low gravity conditions (ESA, 2019c)
- **Lithography-based ceramic manufacturing** - Can use lunar soil to create ceramic items with very precise dimensions (ESA, 2019c)
- **Melting mare low-viscosity soil** - Potential to provide glass wool and glass fibers. This technique (which is thought to be solar-powered) has been proposed for structures composed of many small repeating units (ESA, 2019c)

3.2.1.2 Power and Distribution

During this phase, power infrastructure for robot operations shall be developed. The power infrastructure includes power generation, storage, and distribution. Since this infrastructure will be the foundation for future human missions, it is crucial to test its reliability before the first astronauts arrive. Furthermore, to achieve a high degree of self-sufficiency, ISRU would be the most practical option and would decrease the dependence on Earth resources. However, the ISRU must be conducted in a sustainable (Goal 14: Sustainable ISRU) manner that does not impede other space actors from utilizing similar resources (Goal 1: Open Access, Goal 4: International Cooperation).

With the above in mind, there are a few power sources that could be taken into consideration. The RGUs and RTGs technologies from Phase 1 do not provide enough energy to be useful in the current and subsequent phases. It is likely that solar power will be implemented as an energy source for robots and the future settlement. A number of solar arrays that are easy to install, maintain, and provide continuous energy would be ideal for this phase. However, this is also dependent on the outpost location, with polar sites seeing about 20% more sunlight than non-polar sites due to their latitude and a few exceptional areas experiencing 80% sunlight within a lunar day (NSS, 2018).

The complete absence of sunlight for solar power within permanently shadowed areas can be balanced due to the anticipated access of continuous sunlight nearby (NSS, 2018). However, in the event that solar arrays do not suffice, implementing an alternative power source would be required. Compact nuclear fission reactors would meet these needs. Specifically, NASA's KiloPower, capable of providing 10 kWh of electrical power via the decay of uranium-235 for a period of 10 years (Potter, 2018); and ESA's Lunar Surface Reactor, which implements radioisotope heat units with an expected power production of 100 kWh for a period of 10 years (Summerer, et al., 2015) are viable options. In later phases, these reactors could serve as backup sources to provide the minimum life support functions needed in case other sources fail since they will provide for at least 10-years of continuous power, which support Goal 8: Health and Safety. Furthermore, implementing a standardized method of power transfer during this phase would be beneficial, and support Goal 10: Standardization. It would allow instant access to power, regardless of the circuitry within the lunar equipment, robots, or future human settlement components while also promoting the involvement of international partners (Goal 4: International Cooperation) due to the standardized power system. This would also benefit habitat preparation, where no significant power infrastructure has been developed, yet.

Overall, these reactors would still need to be dismantled and disposed properly, in line with the sustainability goals, especially Goal 12: Zero Waste. In general, this phase serves as an opportunity to test the different energy generation, transformation, storage, and distribution technologies for future phases and to achieve Technology Readiness Level (TRL) 9 (flight proven system).

3.2.1.3 Communication

In addition to the need for Earth-Moon communication, this phase requires lunar communications between the orbiters (if available), autonomous robots, and rovers on the lunar surface. For this purpose, both line of sight communications, as well as non-line-of-sight alternatives similar to those discussed in Phase 1, should be implemented (Coutinho and Welch, 2018).

Telerobotic Operations Communication

During this phase, the use of telerobotics will enable Earth operators to "work on the Moon" every day with a real-time experience on the Moon surface (Cooper, et al., 2005). Nevertheless, telerobotic operations at remote distances, due to the time delay potentially will make human-in-the-loop commanding and monitoring of robots less effective. Radio signals take about three seconds to make a round-trip from the Earth to the Moon and back. If the delay is greater than five seconds, according to the Global Exploration Roadmap, it is recommended that robots are operated as autonomously as possible (through the implementation of automated subroutines), in order to ensure safety and efficiency (ISECG, 2018).

In order to achieve robotic based infrastructure preparation, efficient communication between multi-robot teams is required. According to the Consultative Committee for Space Data Systems (CCSDS), at present, telerobotic operations concepts do not scale well beyond one robot operation (CCSDS, 2017), thus, such technology development is crucial for this phase. Robots building infrastructure should ideally have the capacity to achieve their goals while operating independently from external control. This autonomy can be achieved through a pre-planned set of instructions or by the introduction of Artificial Intelligence (AI) that will enable the system to reason and act rationally in different situations, ensuring the success of the mission (NASA, 2015d).

3.2.1.4 Navigation

To construct habitats remotely on the lunar surface using robots, precise navigation is required. Since the pathways of the robots will likely repeat, implementing the same ground-based lunar navigation system of Phase 1 would provide an initial identification of direction. However, as mentioned in previous sections, this method often has low accuracy. To overcome this accuracy issue, a celestial based navigation system could be incorporated and would include adding star trackers and sun sensors, making it independent of ground facilities (Ning and Fang, 2009). Designs of other sensors of this nature have shown to handle changes in the Sun's position and accommodate for rover attitude (Trebi-Ollennu, et al., 2001). Such technology would prove beneficial for autonomous robots involved in infrastructure preparation.

3.2.1.5 Transportation

Setting up the necessary infrastructure during Phase 2 relies heavily on in situ resources. However, many materials, equipment, and robots will still need to be sent from Earth to carry out the construction. With further advancements in rocket technology, the ability to transfer larger amounts of payload to the lunar surface should be achieved. As seen in Figure 3.6 below, a combination of national agencies and commercial companies are pursuing the ability to launch payloads on the order of 50 metric tons to the Moon. Any payload mass below that level is assumed as an expendable launch vehicle, meaning it does not return to Earth (Musk, 2017).

Commercial companies, SpaceX and Blue Origin, have focused development on reusable launch vehicles to decrease the overall production cost. This approach also decreases the likelihood of producing space debris and waste on the Moon from expendable launch vehicles, which supports Goal 9: Sustainable Transportation and Goal 11: Space Debris Mitigation. However, doing so also decreases the overall payload mass that can be carried in a single launch to the lunar surface.

Launch Vehicle	SLS Block 1B Cargo	SLS Block 2 Cargo	Falcon Heavy	Big Falcon Rocket	New Glenn 2
Operator	NASA	NASA	SpaceX	SpaceX	Blue Origin
Payload to Moon	37-40 t	> 45 t	23-25 t	+100 t	~10 t

Figure 3.6. Comparison of heavy launch vehicle capabilities (Amos, 2016)

Alternative transportation architectures have been proposed. The "Lunar Space Tug" (LST) is meant to provide a transportation system from Earth to cislunar space. Unlike the previously discussed transportation systems, the LST operates on solar electric propulsion, allowing it to be reusable by having a periodic rendezvous between LEO and LLO (Mammarella, et al., 2018).

Regardless of the methods used to traverse cislunar space, performing a soft landing with high payload mass is critical to the success of the phase. Guidance systems using landmark recognition to touch down softly will enable the cargo to be delivered intact (European Lunar Lander, 2012), while also avoiding the chances of inadvertently landing in undesirable areas, such as international heritage sites which should be protected per Goal 7: Heritage Protection. Overall, sending stock supplies of cargo containing spare parts, tools, and initial food and life support resources will also be critical prerequisite for the next phase.

3.2.1.6 In Situ Resources

In the context of Phase 2, the use of in situ resources plays a critical role in the successful completion of the phase. Lunar regolith has been identified as the main resource for base structures. Useable amounts of metals and composites would be implemented for construction, so the collection of in situ resources (e.g., lunar regolith) for constructing habitats would be the primary focus. This would involve small scale mining via on-site robotics, which would establish the foundation of resource collection that can later be scaled in future phases.

Before using the raw materials, methods of chemically processing the regolith to extract useful resources is required. Fluorine has been identified as possible catalyzer. This process involves heating the regolith in the presence of fluorine, which binds to silicon and titanium components within the regolith, while displacing oxygen (Landis, 2007). The remaining by-products can be re-condensed, allowing extraction of the fluorine, making the process repeatable and sustainable per Goal 14: Sustainable ISRU. Once valuable components are collected, techniques to stabilize the regolith must also be designed to ensure that the infrastructure established in Phase 2 does not fail while in use during later phases.

3.2.2 Phase 2 Governance Aspects

After the first phase of robotic exploration and scientific discovery, the focus for governance shifts to defining the right approach to managing new lunar activities, particularly in the area of resource utilization. The second phase of development aims to establish the basis for the habitat. Here the need for operational boundaries is important, but the extent of the governance required will depend upon the composition of the actors on the lunar surface (e.g., one country or several countries, public and private organizations).

UN COPUOS has been governing uses of outer space since the launch of Sputnik. COPUOS is guided by a set of fundamental principles created by the UN General Assembly with the adoption of five major treaties, and serves as a good forum for furthering efforts to manage space on an international scale.

Existing law about resource collection and utilization is somewhat open to interpretation, as mentioned above in Section 2.6.2. The Moon Agreement, one of the five aforementioned fundamental principles, specifies in Article XI that the Moon and its natural resources are the common heritage of humankind. It further provides that once the exploitation of these resources is technically feasible, the parties to the Moon Agreement would create an *ad hoc* international regime to govern exploitation. This governance system would allow an orderly and safe development of the resources, their rational management, the development of opportunities in their use and especially an equitable sharing of the benefits derived from the resources (Jakhu, et al., 2018). However, this project was never executed and the parties that ratified the Moon Agreement are too few that it would have a limited impact on tackling the exploitation of resources, which is why the current legal framework regarding the exploitation and appropriation of lunar resources is considered outdated.

Some scholars believe that resources separable from the ground of a celestial body would have a different legal status than the lunar ground itself, which could be a way of allowing ownership of extracted resources (International Academy of Astronautics, 2015). This approach would be a new challenge for outer space activities, and forming an international consensus would be essential for a lunar base with resource extraction activities (Rao, et al., 2017).

United Nations Office for Outer Space Affairs (UNOOSA) and COPUOS can help define the best approaches for resource utilization. Soft-law can help guide activity outside and beyond international treaties, such as the ill-supported Moon Agreement, and can incentivize space actors to adopt good behaviors. However, it is important to note that many of these soft-laws are created in parallel with each other, creating duplication, and often at odds with one another, allowing for select picking of space nations to follow policies that best suit their aims and activities (Secure World Foundation, 2017). Therefore, having a consolidated set of policies that are agreed upon, similar to the UN SDGs for Earth, is necessary.

3.2.3 Phase 2 Summary

With outpost sites identified and a preliminary assessment of localized resources during Phase 1, initial infrastructure preparation and technology demonstrations for future human missions can commence. This phase has presented the use of rigid and expandable structures for habitats. These approaches utilize in situ manufacturing via 3D-regolith printing and use of autonomous robots for construction. Use of PV solar arrays is anticipated to power the robotic systems. Furthermore, the addition of nuclear fission, in the form of compact reactors, shows promise for alternative power production within this and future phases.

High data rate transfer rates and low latency is required, for both line-of-sight communications and surface communication, for handling the vast amount of data to command and control the robotic systems. To extend capabilities, the use of telecommunications provides instant access to operators back on Earth.

Specialized commercial launchers, who have focused on reusability, will provide a means of transportation for materials and robots from Earth to the Moon. Furthermore, constant ferrying of supplies via a lunar space tug is also possible. To enable in situ manufacturing of habitats, small scale mining and processing of lunar regolith shall begin in this phase.

With the previously discussed infrastructure preparation underway, defining the correct approach to managing resource utilization is required. Although existing legislation addresses the use of lunar materials, it is considered highly outdated and open to interpretation. Furthermore, the governance structure during this phase will depend mainly on the actors present on the lunar surface.

Completion of this phase would permit arrival of the first astronauts to the lunar surface for short durations, where continued development of the site into an operational base would commence, as will be discussed in the next phase.