3.3 Phase 3: Habitat Development

PHASE 3

HABITAT DEVELOPMENT

2035 — The first crewed mission is sent from Earth to the surface of the Moon.

5 YEARS — Developing previously established infrastructure into life supporting human habitat.

2040 — Infrastructure on the Moon is cabale of continuously supporting 6-10 human inhabitants. Operations are ready to begin on a scale comparable to that of the present day ISS.

PURPOSE: Transition towards presence of **humans** in **low-lunar orbit** (orbital platform).

- Entails ~2 week **missions** by humans to the **lunar surface.**
- Progress **habitat development** via more detailed infrastructure, machinery, support systems, and hydroponics.
- Establish, based on resource prospection, how many people can inhabit the Moon so that it can be **sustainably occupied**.

In this phase humans will be sent to the surface of the Moon for the first time since the early 1970s, using a series of short duration crewed missions. These missions will be comparable to the Apollo missions in length, being anywhere from 1-2 weeks long (Loff, 2017). The purpose of these missions would be to build on the infrastructure developed robotically in Phase 2 so that the Moon is suitable for long duration crewed missions of 6-10 people. This would be achieved through cooperation between the new lunar crews conducting the missions and robots, which would already be present on the surface, along with new robotic technology that may be sent.

Robots and humans have unique complementary capabilities. Robots can handle tedious jobs very well, calculate very fast, lift heavy things, sense very well, and handle extreme environments.
However, humans are better at interdisciplinary tasks, creativity, and complex problem-solving. Since habitats need to consider both mechanical factors that require specific abilities that robots can offer, as well as creative input to make sure that habitats and infrastructures are liveable, humans and robots working together in this phase is critical to the establishment of a permanent habitat on the lunar surface.

Together, they can produce fully pressurized, completed habitats and a living environment comparable to that of the ISS. Human-robot interfacing will also protect lunar crews from dangerous EVA, which directly contributes to Goal 8: Health and Safety, as well as mitigating the concerns highlighted in

Section 2.3.2. During this phase, the foundation for larger operations can be established as well, not just habitation. The lunar crews can work to prepare and further develop the foundations for increased resource collection, refinement and utilization operations. This phase will be concluded when there is an infrastructure in place to sustain a permanent human presence on the Moon, with crew members rotating every six months per year (ISECG, 2018).

Like the previous sections, the operational requirements to successfully carry out the phase are summarized in Table 3.8 below, followed by a detailed discussion. New to this section is "Human Factors," which is defined in this report as the aspects that must be addressed during the operation of a phase due to a human presence. These factors include life support, medical capabilities, and culture, which will be further presented in Section 3.3.3.

Table 3.8. Overview of operational requirements for Phase 3

PHASE 3		
INFRASTRUCTURE	GOVERNANCE ASPECTS	HUMAN FACTORS
Architecture • Development of habitat similar to current operational standard of the ISS. Power and Distribution • Development of concentrated solar power via mirrors. • Use of fuel cells and/or batteries for portable power and storage. Communication/Navigation • Surface communication between astronauts and Lunar base. Transportation • Human rated Lunar landers. • Potential to use an orbital platform to facilitate transport to the surface. In Situ Resources • Development of larger scale in situ resource collection mechanisms. • Subsurface resource extraction via small scale mining operations.	• Ensure that the Moon can be used for new emerging activities. • Activities are following with International Law on Earth. • Local governance helping to ensure human safety, norms and rights with different activities.	Life Support • Use of open-loop life support systems. • Implementing Extra Vehicular Activity (EVA) suites for surface exploration missions. Medical Capabilities • Use of standard First Aid Medical accessories kit, similar to Apollo missions.

3.3.1 Phase 3 Infrastructure

The infrastructure laid out in prior phases provides the foundation for fundamental human operations. However, even the most sophisticated robots have their limitations. The infrastructure of Phase 3 addresses the expansion required for long-term operations, which requires human involvement. In this section, additional habitat structures tailored for human occupation are presented along with the power system needed to support them. Furthermore, the necessary communications and navigation systems for safe exploration are discussed along with the methods of transporting the astronauts. The section concludes with a brief discussion on the expansion of in situ resource collection.

3.3.1.1 Architecture

Habitable Modules

The goal of Phase 3 is to conclude with a fully pressurized habitation, capable of carrying out the same level of operations on the surface of the Moon as the ISS conducts in Earth orbit, or even more. Therefore, the size and functionality of the ISS can be taken as a bare minimum construction requirement for Phase 3. This minimum equates to a total of 916 cubic meters of pressurized volume including 388 cubic meters of habitable volume (Daines, 2014).

For mission and astronaut safety, only six people inhabit the ISS at the same time. This restriction exists due to the limited escape capability of only having two accessible Soyuz spacecraft, each capable of fitting three individuals, in the event of an emergency (NASA, 2018b). However, a structure the size of the ISS on the Moon could host up to 10 inhabitants. Overall, due to the preliminary capabilities of the infrastructure and crew during Phase 3, the number of crew would be primarily dictated by the safety precautions and evacuation capabilities in place, in keeping with the prioritization of Goal 8: Health and Safety.

Pressurized Structures

To prepare for a human presence on the pressurized structures to keep the right atmosphere, temperature, and other imperative conditions for supporting life is vital. At this phase, the pressurized modules can be carried from Earth, ensuring more reliability than in situ production for deployed on the lunar surface and to undergo preliminary qualitative tests.

The habitable modules can be either rigid, as are ISS modules, or deployable/expandable, like the Bigelow Expandable Activity Module (BEAM) as shown in Figure 3.7. In both cases, it is possible to ensure radiation protection, yet this will increase the mass and volume. Another alternative is to use thin-membrane inflatable modules, which are easier to transport from Earth than rigid modules, due to their compactness. In order to sustain harsh lunar conditions, habitats based on inflatable modules would require additional radiation and micrometeorite protection, which was described above in Section 3.2.1.1 (Howe and Sherwood, 2009).

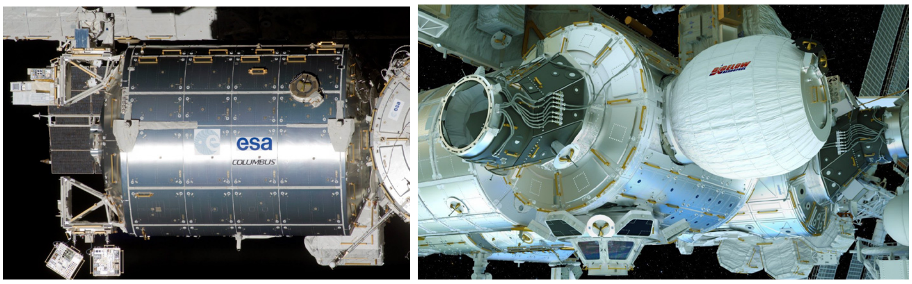

Figure 3.7. The Columbus Module on the ISS (left) (NASA, 2018c) and BEAM (right) (Bigelow Aerospace, 2016)

3.3.1.2 Power and Distribution

During Phase 3 ,the availability of energy needs to increase rapidly to support newly introduced robots, vehicles, habitats, and other facilities, and prepare for the following phases. To achieve this, using an alternative method for collecting solar energy shall be implemented. This would include the use of Concentrated Solar Power (CSP), which is based on mirrors redirecting sunlight to a solar energy collector (Barlev, 2011). Furthermore, CSPs have shown to have the highest power-to-weight ratio among non-nuclear solutions, however, the system requires precise alignment and the need for human involvement during setup.

To further improve the power-to-weight ratio of CSP systems for a lunar base, reusing parts of rockets, rocket stages, and tugs is a viable solution that has been developed. Current rocket technology permits the reuse of the first rocket stage and boosters; however, the second stage is often discarded beyond LEO. With extra fuel within the second stage, these combined rocket components could be transported to the Moon, reducing power infrastructure transportation costs significantly. As seen in Figure 3.8, components such as the nose cone, and rocket tank/stage can be pre-manufactured with reflective coatings, which can be set up to concentrate solar energy from the Sun. Moreover, the second stage propulsion tanks can be reused as on-site storage tanks for in situ production of hydrogen, oxygen, and water (Lafayette, 2002).

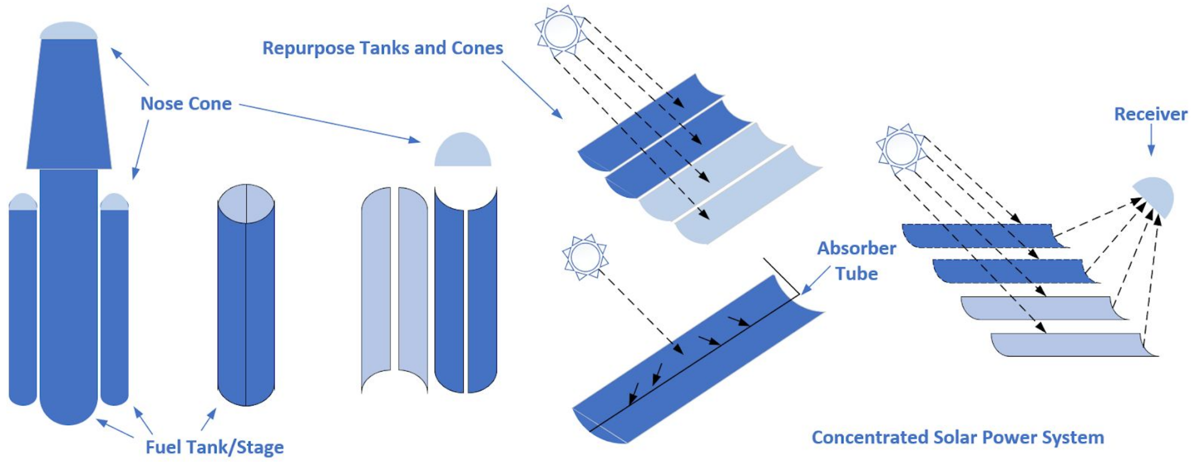

Figure 3.8. A CSP system constructed by reusing parts of fuel tanks and tugs

With anticipated surface expeditions occurring in Phase 3, the need for portable power supplies and storage is required. The use of lithium-ion batteries offers high specific energy with the capability of operating in a range of temperatures (Khan, et al., 2006). However, regenerative fuel cells have an even higher energy density with the ability to be refueled from in situ resources that can be extracted from the lunar regolith and ice water (NASA, 2015e). No matter the energy storage mechanism, a standardized method of refilling and extracting the energy from these is crucial for developing a robust power system needed for human exploration on the Moon.

3.3.1.3 Communications

Up until this point, the communications capabilities on the Moon will be limited to those of the specific robotic systems utilized in the missions of Phases 1 and 2. Similarly, the communication requirements during Phase 3 are specific to the individual crewed missions that will be conducted. However, Phase 3 will play a vital role in preparing for the later phases including the development of more robust communication platforms for the operations that will take place during Phase 4.

Surface Communication

This pillar mainly involves communication between the astronauts already on the surface of the Moon. The communication links could be astronaut-to-astronaut, astronaut-to-robot/rover, between lunar base and the Extravehicular Activity (EVA) crew, and facilities. For these purposes, the use of omni-directional Very High Frequency (VHF) antennas system could provide the necessary capabilities for these communication requirements. Relay satellites could be used for point-to-point lunar communications when there is no line of sight (Coutinho and Welch, 2018).

Different robotic types of missions have been executed in the past. Missions involving the deployment of humans were all under near real-time communication conditions. Robot-only missions took place under near real-time, as well as under delayed communication conditions. Near real-time robot-missions could make use of lower levels of autonomy (e.g., tele-operation) than missions with delayed communication situations (NASA, 2015d).

Earth-Based Communications

During this operational phase, the amount of scientific data transfer to be required for the missions will increase. Schedules need constant updating and live-feed video surveillance of the crew is likely desirable for mission safety as well as public outreach, which supports Goal 5: Education and Outreach. The increased amounts of data transfer would still be carried out by traditional RF communication systems, with the support of the relay satellite systems.

3.3.1.4 Navigation

Navigation capabilities would need to be expanded due to crewed missions and human exploration of the lunar surface. While the rudimentary positioning system used to coordinate robotic activity in Phases 1 and 2 could be relied upon as a basis, refining the localization capabilities of the system would be paramount to the safety of the lunar crews and their efficacy in accomplishing their missions.

3.3.1.5 Transportation

The arrival of humans to the Moon would require far more reliable systems of transportation, compared to those presented in earlier phases. There are a few launchers that have proven the capability of transporting humans into space; however, the only example of landing humans safely on the surface of the Moon was demonstrated by the Apollo missions (ESA, 2011; Jones, 1995). Soft landings conducted in previous phases for cargo drops would be analogous to the method of transportation for humans to the lunar surface in this phase. However, safely landing humans on the Moon is a feat that was achieved nearly 50 years ago, and has yet to be replicated since.

Surface-to-Low Lunar Orbit (LLO) Transport

While direct transfer to the lunar surface is feasible, it is possible that during Phase 3 there could be other technological developments for transference of humans to and from the lunar surface. Roadmaps produced by NASA and ESA have referenced the use of an in-orbit platform to facilitate the transportation of humans to and from the lunar surface. One example of this is NASA’s LOPG (Wall, 2018b). To test the reliability of the human landing systems and overall safety, a series of operational steps should occur (Bridenstine and Gerstenmaier, 2019), as outlined below. Overall, implementing a reusable system for human transport leads to lower costs, higher access frequency, and increased reliability of lunar surface transport, and directly supports Goal 9: Sustainable Transportation.

Step 1: Descent Element Testing

- Send uncrewed descent element through low lunar orbit and then deploy to the surface of the Moon.

Step 2: Full-Scale Testing

- Test multiple systems for the human landing system:
  - a) Lunar ascent element
  - b) Transfer vehicle element
  - c) Another lunar descent element.
- Aggregating all three components at the orbital platform, then transfer to 100 km staging orbit.
- Ascent/descent duo deploy to the lunar surface, transfer vehicle returns to orbiting platform.
- After a soft landing, ascent element transfers back to the orbital platform to provide a full end-to-end human-class test.

Step 3: Human Crew Deployment

- Astronauts shipped to an orbiting platform via a chemical propulsion system.
- Three commercial launchers provide another lunar descent element and two refueling elements for the transfer vehicle and ascent element, respectively.
- The same three-element infrastructure used to deploy a four-person crew to the lunar surface in the same fashion as seen in Step 2.

Surface Transportation

For missions which focus on the scientific rationale mentioned in Section 2.3, a method of long-range surface transportation for astronauts would be required. Using the Apollo missions as an analog, the use of unpressurized Lunar Roving Vehicles (LRV) allowed access to the surrounding terrain from the lunar module of up to 7.6 km during Apollo 17. Similar technology would be used for surface exploration involving lunar-geology missions or long distance mining operations. The LRVs developed during the Apollo era operated using an electrical power source (batteries). However, the past 50 years have provided ample progress in battery technology, meaning the rover's maximum range could exceed 120 km, greatly surpassing the capabilities of the LRVs seen in the 1970s (Baratta, 2019).

3.3.1.6 In Situ Resources

This phase provides an opportunity to develop the larger infrastructure required for an in situ resource collection operation, in parallel with the development of the human habitation. While some in situ resources would be utilized up until this point, the majority of the past activities would consist of using regolith and other easy to access surface resources. In this phase, the required machinery could be brought to the Moon to begin something similar to a small-scale mining operation, where below surface resources could be extracted and refined for other uses. The resources include water, semiconducting compounds and other heavy metals that have been referred to both in Phase 1 of this roadmap and the economic rationale (Section 2.1) for going to the Moon. This phase is only preparatory in terms of bringing the required equipment and developing the extraction site or sites. All larger scale resource collection, refinement and utilization would take place as part of the operations of Phase 4.

3.3.2 Phase 3 Governance

With Phase 3 signifying the first-time humans have returned to the Moon since 1972, the level of governance required expands beyond global governance on Earth, to local (operational) governance on the Moon. Operational governance is essential to ensure human health and safety, and create an environment that allows for management of the various activities as the function of the base extends beyond the infrastructure preparation of Phase 2.

Governance in Phase 3 must ensure that the Moon could be used for different activities, in line with sustainability Target 1.3 for Open Access (Goal 1). Local governance could help ensure transparency of activities, which builds trust between lunar actors and helps foster cooperation between organizations.

The local governance required to maintain control over different emerging space activities with the arrival of the first wave of humans to the Moon could build upon existing international agreements such as the Antarctic Treaty, which uses a consensus-based approach to ensure appropriate uses and broad activities (e.g., science, tourism, maritime, etc.). The local governance is a form of public-private partnership which divides duties between stakeholders. (Launius, 2014; Ehrenfreund, Race, and Labdon, 2013; International Moon Village Workshop Final Report, 2017).

Over time, as activities develop and areas such as lunar ISRU become fledging operations, the operational governance on the Moon may shift to represent something similar to the high seas. The United Nations Convention of the Law of the Sea could be a useful analog in that it serves to manage the ocean and protect its resources while allowing for commercial activities and resource extraction. For the Moon, information from all possible stakeholders regarding development plans would be needed to design an inclusive operational management system that provides benefits for all stakeholders (Launius, 2014; Ehrenfreund, Race and Labdon, 2013; International Moon Village Workshop Final Report, 2017).

3.3.3 Phase 3 Human Factors

This phase is the first to include human factors, as this is the phase when humans arrive on the lunar surface. This section includes some details in regards to the increased need for life support systems, medical capabilities, safety precautions, and organizational frameworks. Most of the life support and medical specifics within this phase depend substantially on the specific requirements of the crewed missions to the Moon that will take place throughout the phase. However, it is essential that a foundation is established in all of these factors as early as possible, such that they are developed adequately and potentially support a growing, permanent human presence on the Moon.

3.3.3.1 Life Support

Open-Loop Life Support Systems

Oxygen, water, and nutrition in this phase are not provided by the current state of developed lunar infrastructure. Robotic mission initiatives would have already begin extracting lunar resources to produce water and oxygen for use in Life Support Systems (LSSs); however, this phase would rely on supplies carried from Earth. It is vital that this stage prepares LSSs to consistently and continuously sustain human life on the Moon for the following phases in a sustainable manner.

On the ISS, there is a partially closed-loop LSS that is able to recycle water and oxygen, but still heavily relies on resupply from Earth. Due to the distance circumstances, resupplying the Moon will be more complex and require higher costs than resupplying the ISS and therefore, establishing the basis of larger scale food production, hydroponics and other means of capturing and repurposing waste material will be essential to transitioning to later phases (Damann, 2018a).

Outside of the lander modules, due to the harsh lunar environment described in Section 2.3.2.1 and Section 2.3.2.2, the crew would require Extravehicular Activity space suits. The primary function of an EVA space suit is to protect the astronauts for up to eight hours during EVA (Buffington and Mary, 2015). The space suit includes a Portable Life Support System (PLSS), a Pressure Garment System (PGS), and a Power, Communication, Avionics, and Informatics (PCAI) system. The functions provided by the space suits, apart from protecting the astronaut from the lunar environment, include maintaining pressure and temperature, dispensing oxygen, facilitating mobility, waste management, tracking astronaut biomedical data (Conger, et al., 2010). The involvement of the Portable Life Support System assists metabolic rate, critical life support and astronaut comfort (Watts and Vogel, 2016; Conger, et al., 2010).

3.3.3.2 Medical Capabilities

Due to the short duration of the crew's mission on the lunar surface, it is not necessary to have the complex medical capabilities that would be required by larger populations that would be on the Moon for longer durations in later phases. Missions would require medical accessory kits such as the one on the Apollo 11 Command Module, shown in Figure 3.9.

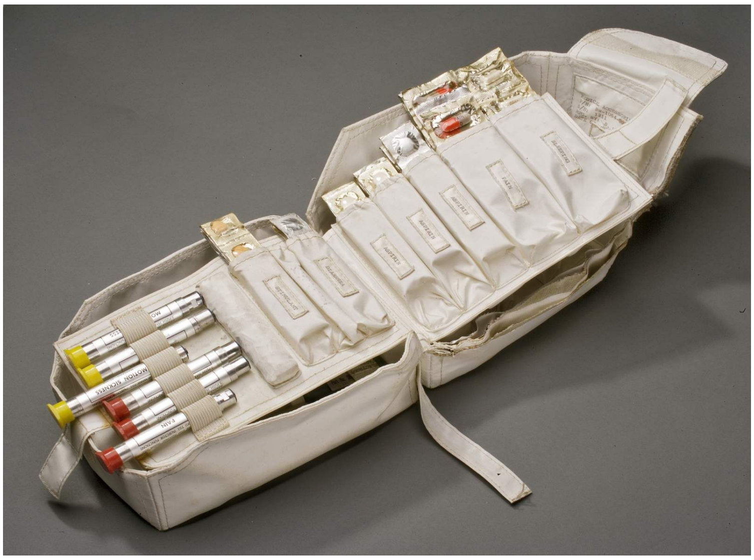

Figure 3.9. Apollo 11 medical kit (Smithsonian, 2019). The kit contains motion sickness injectors, pain-killers, eye drops, nasal sprays, bandages, an oral thermometer, spare crew biomedical harnesses, and pills against nausea, diarrhea, and other issues that may arise during short duration missions (Smithsonian, 2019).

3.3.4 Phase 3 Summary

Phase 3 represents the transition between exploration and habitation. At the beginning of the phase, the first crewed missions will be sent to the Moon, to support the increase of production and construction capabilities of the robots that are already there. Together, the robots will work with a series of crews to construct a habitat to sustain human life continuously, such that at the end of the phase, the infrastructure is sufficient to house 6-10 people, for six months to a year.

The use of concentrated solar power to sustain the energy requirements of the human-based missions has been discussed along with the use of batteries and fuel cells to provide a portable source of power during surface explorations. Details of surface communications and methods of improving navigation for astronauts during surface expeditions have been addressed by further developing the systems that have already been put in place. Furthermore, utilizing an orbital platform to facilitate transportation to the surface via lunar landers has been discussed accompanied by the expansion of in situ resources.

With initial missions being conducted by humans, the use of open-loop life support systems and EVA suits have shown to be essential during this phase. A standard first aid medical kit is incorporated to account for any medical emergency seen during the two-week missions.This phase has also emphasized the basis of ensuring the Moon is used for new emerging activities, which are following international law on Earth. Local governance structures shall be established based on the actors present on the surface to help ensuring human safety.

The accomplishments of this phase can be seen as analogous to the difference between Space Shuttle missions and missions of the ISS. This phase represents a significant amount of the preparatory infrastructural work in sustaining small scale operations, with the intention of upscaling in the future.