3.4 Phase 4: Basic Operations

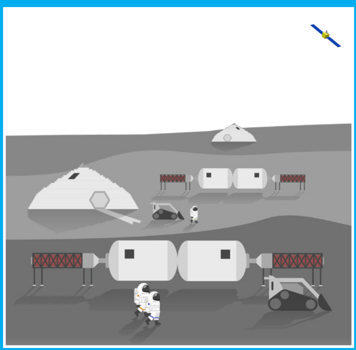
PHASE 4

BASIC OPERATIONS

2040 — First long-duration crewed mission leave from Earth.

20 YEARS

2060 — Basic habitat structure/frame can be expanded.



PURPOSE: To conduct **science based missions** (similar to astronauts on ISS) with focus on mission specifics.

- Presence of **permanent human habitation** (~6 to 10 astronauts).
- **Classic science** being conducted (lunar geology samples and analysis, far side of the Moon radio telescope, lunar mining, etc).
- Testing of **life support systems** and long-term technological aspects.
- Establish legal guidelines for Moon occupancy.

The concept of a 'Basic Operations' phase serves a variety of purposes in the overall evolution of a lunar settlement. The underlying intentions of its existence is to conduct science-based missions with a focus on key objectives initiated by governing agencies or corporations, thus fulfilling the scientific rationales in Section 2.3.1.1. It does so by utilizing existing infrastructure and habitation finalized in the previous phase. The secondary function of the phase is to test life support systems and further push technology developments for use in the later settlement phase, which support the exploration rationales in Section 2.3.1.2.

Published roadmaps from Airbus Space and Defense as well as the ISECG share phases with the previously mentioned focus. In a simpler sense, this phase is analogous to the current status of the ISS. However, rather than serving as a microgravity laboratory, the lunar base in this phase serves as a home for astronauts to live and conduct activities focused on the development of lunar geography, physics, and astronomy.

The harshness of the lunar site and the duration of lunar missions provides an adequate training ground and learning opportunities for human missions beyond our planetary system. This fourth phase also serves as a period during which long-term effects of hypogravity on the human body can be studied. From this, feasibility from a medical perspective can take place to assess whether prolonged hypogravity habitation is safe. Overall, with the end goal of developing a sustainable lunar settlement, this phase serves as a major test bed for potential settlers of the future. As such, for this phase to be considered successful, the life support technologies must be tested and science conducted as per the desire of the funding organization.

With the previous phase addressing the transition and interface among robotic exploration with humans, the operational requirements of this phase are different and focus more focus on long-term and continuous human inhabitation, which requires different technological aspects and human element considerations. The technological considerations and timeline elements are sourced from NASA's Lunar Roadmap and Airbus Defense and Space. Specifics of each will be identified accordingly. An overview of the operational requirements specific to this phase is provided in Table 3.9 below.

Table 3.9. Overview of operational requirements for Phase 4

PHASE 4		
INFRASTRUCTURE	GOVERNANCE ASPECTS	HUMAN FACTORS
Architecture • Use of existing habitat and mission specific structures. Power and Distribution • Scaling existing solar power infrastructure and implementing thermal concentrated solar power to address power needs during Lunar night. • Implementation of a power management system to regulate efficient use of energy. Communication/Navigation • Surface communication between astronauts and Lunar base. Transportation • Use of pressurized roving vehicles for distant surface exploration and transportation of raw in situ resources. In Situ Resources • Collection of in situ materials focused on obtaining resources required to sustain long-term human habitation. (ex. water ice, oxygen, and others).	• Ensure that the Moon can be used for new emerging activities. • Activities are following International Law on Earth. • Active governance detailing the agreed roles and responsibilities of all space actors and establishing a management structure to control and govern the activities.	Life Support • Use of partially closed-loop systems, similar to ISS. • Proactively addressing external stressors experienced during long-term missions to enhance crew productivity. Medical Capabilities • Extensive First Aid and medical training for crew, similar standard seen in ISS. • Access to more robust medical equipment and tools, similar to those aboard the ISS. Culture • Development of Lunar subculture and upholding cross-cultural understanding during mission training.

3.4.1 Phase 4 Infrastructure

The infrastructure requirements of the 'Basic Operations' phase are dictated more by the types of missions or operations the base will be conducting while also addressing the long-term inhabitation of humans. Furthermore, the architectural aspects discussed in Phases 2 and 3 lay the foundation of living quarters for this phase. Therefore, the necessary aspects of power and distribution, communications, navigation, and transportation will be presented instead.

3.4.1.1 Power and Distribution

In Phase 4 the need and capability to produce energy continuously is required due to the permanent inhabitation of the base. An increased number of solar energy collection facilities is necessary. However, a different approach must be taken to address the lack of sunlight during the Lunar night.

One approach is to extend the thermal Concentrated Solar Power (CSP) system built in Phase 3, with multiple CSP facilities, spaced circumferentially around the Moon at a specified latitude, to provide power continuously without the need for power storage. The use of multiple CSPs is most feasible near the poles since the distance between the CSPs as well as the duration of the lunar night is shorter than if the facilities are located closer to the equator.

The concept of a thermal CSP system is that energy concentrated from solar electromagnetic radiation is used to heat a working fluid to drive a dynamo, much like a typical turbine generates electricity (Iskander, et al., 2008). The Moon has craters and other sites that due to their position in eternal shade are never irradiated, resulting in low-temperature areas "cold bodies." The proximity of very cold bodies and very hot bodies generated by CSP makes the Moon a viable location for generating thermoelectric power (Paige, 2009 and Farrell, et al., 2010). Studies have shown that this process can be altered to create a closed loop system (Edmund, et al., 2013), allowing the habitat to become closer to independence from Earth and supporting Goal 12: Zero Waste. There are different versions of CSP, all of which have slight variances in efficiency depending on where each system is implemented on the lunar surface (Wagner, 2012).

On the Moon, there are no atmospheric conditions that require a solution to withstand wind gusts and rain (Williams, 2017). Plus, the gravity on the Moon is only ⅙ Earth's gravity, which results in needing less robust construction than on Earth, and means that the base of the CSP could be produced in situ (Williams, 2018b).

To compensate for the lack of solar energy during a lunar night, the medium heated by the CSP system, e.g., sodium or ceramic can be stored in hot sink storage for powering the thermoelectric installation and for directly heating the habitats, as shown in Figure 3.10. Directly heating the habitats can save 20-30% on primary energy consumption for heat production by omitting conversion to electricity (Snijders, 2008). During the Lunar day, the cold sink can be used to cool the habitats directly using a heat exchanger, making electrical power savings possible of 60-80%. The long-term energy storage can be achieved by using electrolysis and storing the produced hydrogen and oxygen in tanks and fuel cells.

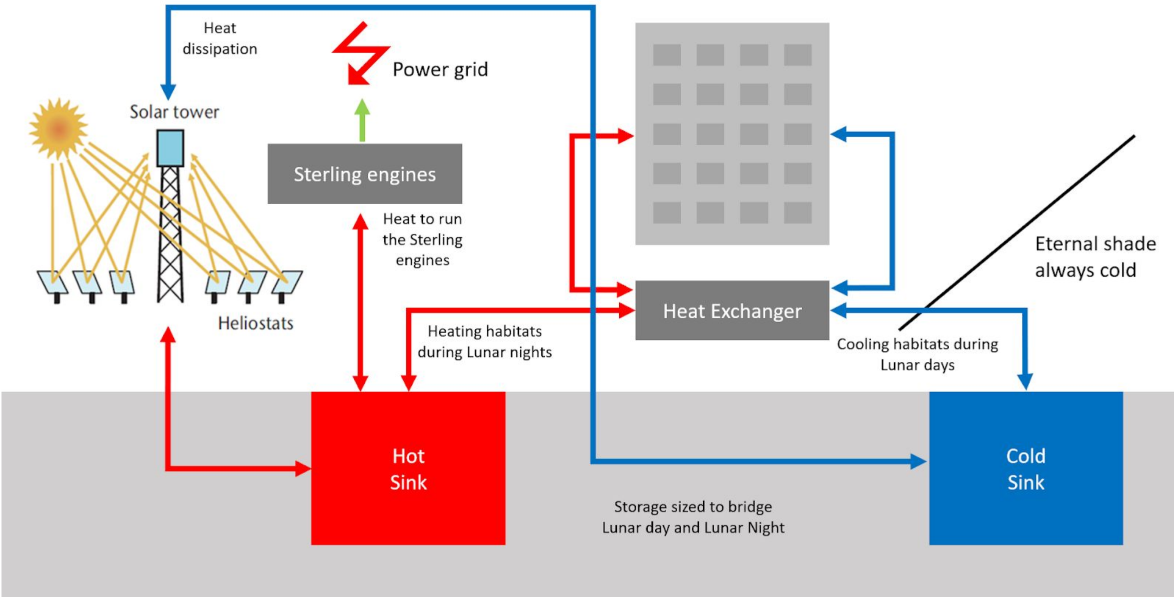


Figure 3.10. A CSP Tower system combined with heat and cold storage sinks

The increased complexity of the power grid would require an integrated power management system that is managed as part of an overall Moon base management solution. A light version for power (grid) management would already be needed in Phase 3.

The Power Management System (PMS) will manage and orchestrate the complete Power Ecosystem from source to consumption autonomously. Current Concepts of Operations (CONOPS) rely on ground control and are labor intensive and lacking automation. These concepts must be updated and include autonomy at every level. Explicitly named cross-cutting technologies are artificial intelligence, autonomous systems, sensors, and information technology (NASA, 2015d).

The PMS should be an integrated part of an end-to-end ecosystem management solution for the whole mission, providing triage information, monitoring for anomalies, predicting problems before they occur, and providing resolutions to solve issues or act autonomously when needed (e.g., when the staff is not able to respond).

3.4.1.2 Communication

In the context of long-term missions involving humans, the use of surface communications and Earth-based communications from the previous phase is vital. Looking forward, with the likelihood of scientific missions being conducted on the far side of the Moon, the need for a relay satellite becomes evident. Phase 1 addresses this with the presence of a single relay satellite placed in L2 Halo orbit. However, the need to scale the capability and number of relay satellites within low lunar orbit is a direct result of the increase in activity within the basic operations phase.

As for point-to-point lunar communications, initial development of Moon ground stations would take place in preparation for the future larger scaled settlements. This addition to the existing communications infrastructure would allow large amounts of continuous data transfer, even if the Earth is not in a direct line of sight, and would continue to expand the infrastructure for a future lunar society.

3.4.1.3 Navigation

Phase 4 includes crewed missions (6 to 10 astronauts) on the lunar surface to perform scientific experiments that should last no longer than 180 days. For this purpose, the expansion to the navigation system described in Phase 3 and the ground-based lunar navigation system mentioned in Phase 1 are sufficient to guarantee the accomplishment of both human and robotic activities on the Moon. The implications are that the cost associated with multiple satellite launches and station keeping of those satellites once in orbit would be high.

3.4.1.4 Transportation

Low Lunar Orbit Transportation

While a permanent human presence underlines this phase, the need to rotate crews and personnel is still required. Therefore, the transportation system for humans outlined in Phase 3 would still be in use during this basic operations phase. However, these modes of transportation require the vehicle to carry enough fuel to land and leave the surface. To make the process more sustainable, implementing in situ fuel generation is required (Zubrin, 1994), which relates directly to Goal 9: Sustainable Transportation and Goal 14: Sustainable ISRU. Propellant, in the form of hydrogen and oxygen, shall be synthesized from lunar polar ice caps to address this need.

Surface Transportation

With the presence of extended exploration missions, concepts of an electrically powered bus, with a pressurized operations cabin capable of accommodating up to two people, have been proposed. The bus is designed to have threaded wheels which handle the abrasive nature of the lunar dust and regolith (ASI, 2007). In addition, with mining operations being conducted to sustain the habitat in terms of water production and propellant, transportation of lunar resources from mining locations back to base is critical. Implementation of similar electrically powered buses with cargo bays for resources would meet the previously stated need.

3.4.1.5 In Situ Resources

With the entirety of the infrastructure already setup, the use of lunar resources during this basic operations phase primarily serves the purpose of sustaining a permanent human presence with a secondary commercial focus.

The primary focus includes the extraction of water from lunar craters. Other means of obtaining water beyond the mining of water ice while on the Moon include extraction from the lunar regolith (Arregoitia, et al., 2007). Methods of extraction involve heating the regolith to force the water to evaporate and then condense back into the liquid state. Processing of lunar materials for the previously mentioned purposes shall occur in the vicinity of the habitat to allow optimal access to liquid water and provide refueling capabilities to transportation systems.

3.4.2 Phase 4 Governance

From Phase 4, the activities on the Moon expand beyond habitation development and pivot towards sustained activities over longer durations of time. Global governance would be required to ensure these new activities, carried out by groups of people, are, where appropriate, following International Law on Earth; including ensuring that the Moon is used exclusively for peaceful purposes (including non-weaponization, a ban on military installations, as per the Moon Agreement, and ensuring actions of a non-aggressive nature).

The ISS serves as a good analog for the scale of operations on the lunar surface in Phase 4, with 6-10 people working across a range of activities, including lunar geology sampling and analysis, radio astronomy on the far side of the Moon, lunar mining, and other activities. With the analogy of the ISS being a recurring theme for this phase, its governance methods could also be adopted. Here, the signing of an Intergovernmental Agreement (IGA) in 1998 by the fifteen governments laid the foundation of how decisions would be made. The agreement stipulates that ISS partners may extend their national jurisdiction onto their respective elements of the station (ESA, 2019d). In essence, whatever elements are registered to the state, are controlled by the state. Locations and areas of overlap that exist are decided upon jointly by the members involved. A similar approach and ideology would extend to a multinational lunar base. However, the inclusion of private companies, who technically fall under the jurisdiction of their registered state, would require a unique approach to this government level agreement.

Active governance involves describing in detail the agreed roles and responsibilities of all space actors and establishing a management structure to control and govern the activity, while continued global governance helps uphold policies aimed at guiding best practices in the sustainable use of the Moon and cislunar space.

3.4.3 Phase 4 Human Factors

With the current phase revolving around the extended presence of people on the lunar surface, and considering the harsh environment of the lunar surface, the human element becomes a crucial operational aspect. This section addresses the necessary changes in life support systems, medical procedures, and physical training required for successful completion of the phase.

3.4.3.1 Life Support

Partially Closed-Loop Life Support Systems

Unlike the short-term duration missions conducted during Phase 3, which carried enough food, water, and oxygen to conduct the mission, the basic operational phase would require a transition from this open-loop life support system to a semi-closed-loop-life-support system (SCLLSS). Here the goal is to replicate the life support standards seen aboard the ISS today. The ISS nearly has a 95% closed-loop capability for certain necessities by implementing a variety of methods of recycling waste products of one process back into another (Damann, 2018a).

The capability of surviving in pressurized modules started in Phase 3. Unlike the Phase 3 astronauts who were confined inside their lander modules. EVA suits and vehicles with the Portable Life Support System (PLSS) will be largely used for outpost activities.

As an analog, the ISS uses ESA's Advanced Closed Loop System (ACLS), a two-meter tall rack, that traps carbon dioxide from the breathable air and processes it in a Sabatier reactor to create methane and water. Phase 4 would rely on this technology to permit the survivability of the crew during the mission. The system is only a èartially Closed-Loop Life Support System, and it is not capable of providing nutrition, but it represents the way forward for the next phase of the Roadmap (ESA, 2018).

External Stressors

There are a number of overlapping stressors which are important to consider for long-duration living in space environments, particularly the Moon (Benaroya, 2018). These include

1. **Physiological**: Radiation, lack of natural time parameters, impacts to circadian rhythms, limited exposure to sunlight based on the lunar orbital period, ⅙ gravity.

2. **Psychological**: Isolation, mission demands, limited hygiene, interpersonal tensions, social conflicts.
3. **Mission Factors**: High workload, limited resources and communication, food limitations.
4. **Habitability**: Limited privacy, constant noise/vibration.

For individuals staying for long periods, the above aspects are crucial to addressing in order to maximize crew productivity and overall mental well-being.

3.4.3.2 Medical Capabilities

Due to the isolated nature of an operational lunar base, having robust medical capabilities is important for the successful development of this phase. With a comparison to the modern-day ISS, ⅓ of the crew goes through 34 hours of medical training (Zhang, 2016). Familiarity with: Cardiopulmonary Resuscitation (CPR), vascular access, and intravenous (IV) fluid infusion is required. Similar standards shall be employed for the crews during this phase. Furthermore, gravity is known to affect the presentation, diagnosis, and treatment of illness that may arise (Grenon, et al., 2012). Therefore, anticipating the effect of hypogravity on any potential diagnosis and treatment is essential.

Updating the medical tools and procedures is not enough to sustain a long-term healthy crew. The prolonged exposure to the hypogravity environment of the Moon brings similar concerns to those that are seen on the ISS. As such, incorporating regular exercise into the work of astronauts helps them combat the potential of bone loss and muscle atrophy. However, with the Moon providing around ⅙ the gravity of Earth, the long-term effects seen will be less severe as those seen in the microgravity environment of the ISS (Damann, 2018b).

3.4.3.3 Cultural Aspects

Workplace Expectations

Unlike the previous phase, where astronauts were spending limited time on the Moon for exploration purposes, this phase involves long-term habitation. As such, when one lives and works in space, in a consistent environment, factors of culture and work expectations emerge. Implementing a schedule becomes crucial to balance the work expected of the crew and their daily lives which contribute to their mental health and ability to perform tasks. The mentality of staging the working period to best fit the capabilities of the crew, as is currently done on the ISS, and the needs of the mission is of greater importance than finishing the mission on schedule (Damann, 2019).

Cultural Challenges

During this phase, the initial crews may be able to overcome cultural barriers, as the priority in professional teams would likely be "getting the job done." Extra steps may be taken that focus on the individual, such as cultural competence workshops and selecting astronauts by their amiability and lack of ethnocentrism (Burke and Feitosa, 2015). However, there are no current practices in place that would guarantee that all space-faring nations would adhere to the same selection protocols (Landon, et al., 2016). Therefore, new tools being explored, which could create frameworks to ease cross-cultural teamwork (Heimbüchen, 2008). Although these have not yet been implemented in isolated environments which simulate spaceflight, it has been shown that people are unable to act agreeably for long periods in isolation. Therefore, additional measures in selection and training may be important considerations for smooth intercultural interactions (Rai and Kaur, 2012).

3.4.4 Phase 4 Summary

The Basic Operations phase focuses on conducting scientific missions and long-term testing of life support systems for a future human society. The use of previously established habitats plays a crucial role along with the existing power infrastructure, such as solar photovoltaic cells. The extension of this to include thermal concentrated solar power addresses the power needs that were previously not met during the lunar night. Existing frameworks of communication provide the link to successful mission operations on the lunar surface and for relays back to Earth. Continued use of the existing navigation system for astronaut surface navigation will meet the needs of extended missions.

In orbit transportation will utilize the existing lunar ascent element, while the inclusion of alternative surface transportations such as rovers and electrically powered buses provides direct access to the crew of remote areas. Finally, mass mining of polar ice and the collection of lunar regolith to produce elements such as liquid water and oxygen for habitat sustainability underly the entire basic operations phase.

With a major focus on life support testing and technology development, the transition to partially Closed-Loop Life Support Systems and the inclusion of advanced medical training and equipment is essential for long-duration crews. An approach of detailed scheduling, frequent exercise, and balancing work with personal life provides a smooth transition to the next phase, which focuses entirely on sustainable settlement and living.

The presence of different nations conducting long-duration lunar missions with individual focuses opens the need for legislation addressing the allocation of lunar space and resources. With this in mind, collaboration among space-faring nations would allow cultural and technological growth for future multicultural settlements. Furthermore, the operational framework to be implemented can mirror a variety of existing structures (e.g., the ISS, Antarctic Treaty, or public-private consortiums). Future settlements would likely expand upon these concepts and, in general scale, most operational aspects of this phase would be able to accommodate a growing population.