3.5 Phase 5: Lunar Settlement

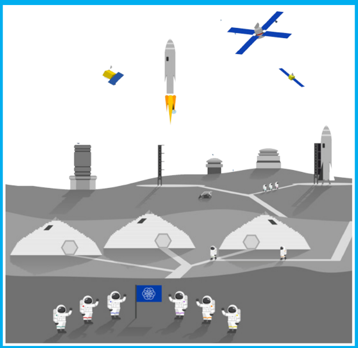
PHASE 5

LUNAR SETTLEMENT

2060 — The goal of the settlement extends beyond scientific work on the Moon and towards permanent habitation.

INDEFINITE

... — Increase in scale, and diversifcation of purpose and activities, while adhering to sustainability goals.



PURPOSE: To establish a **lunar community** whose focus/ethos extends to **prosperous living** on the moon.

- **Permanent** and established **community/society** on lunar surface.
- Lunar base and habitat become **self-sustaining**.
- **Function** of the base **expands** to incorporate a diverse range of space activities.

OPERATIONAL DETAILS

This phase is best characterized by shifting away from conducting lunar base missions and operations, and more towards the act of living and spending one's life on the Moon. This stage of the lunar base is distinguished from the past in having the capability of being completely self-sustaining. No support would be required from Earth, and all supply requirements of the base could be maintained through on-base production. This self-subsistence may not be achieved at the initiation of this phase, but will be a goal of the phase and will be achieved as the phase progresses.

Moreover, a political framework will be structured and preeminent principles will be erected to assure a prosperous and nonviolent life within the settlement. During this phase, the base will extend its activity beyond the scientific facilities developed in the previous phases. It will expand to include much more habitation, and the facilities required to sustain the increasing population, such as medical facilities and entertainment. As this phase progresses and human activity on the Moon increases, there could be the development of much larger markets, including tourism or other unforeseeable business ventures. This phase could also see the establishment structures for further exploration of the solar system, such as launching capabilities, or even advancements that could support activities on Earth.

During the Phase 5 time frame, the settlement will be expanding in situ resource utilization, to shelter a larger population and to incorporate facilities for advanced purposes. As in the previous phase, the technological aspects are pulled from Airbus Defense and Space and NASA's Lunar roadmap. The operational requirements for this stage of the lunar settlement are shown in Table 3.10.

Table 3.10. Overview of operational requirements for Phase 5

PHASE 5		
INFRASTRUCTURE	GOVERNANCE ASPECTS	HUMAN FACTORS
Architecture • Expanding the number of existing modules on station and their habitability to accommodate an increase in human population. • Potential construction of launch facilities. Power and Distribution • Scaling of solar array infrastructure and nuclear fission reactors to accommodate requirements of the settlement. • Potential to transition into ^{3}He based nuclear fusion, if technology is available. Communication/Navigation • Introduction of cellular network concept for communication among inhabitants. • Implementing a Lunar Positioning System which mimics Earth's GPS/GNSS capability and purpose. Transportation • Use of Lunar railways. In Situ Resources • Increased scale of operations to accommodate the growing need of resources and establishing a commercial fuel market.	• Level of governance required for activities could be a subset of an existing body on Earth, and an extension of existing bodies. • Potential for having a new entity on the Moon with greater transparency of activities. • Potential for the establishment of an equivalent to the United Nations Security Council for the Moon.	Life Support • Establishment of Closed-loop life support systems. Medical Capabilities • Medication for long permanence on the Moon. • Emergency operations assessment and development. • Establishment of in situ medical operations. Culture • Expansion based on Earth, with the inclusion of religion, new societies, and team models. • Development of a lunar societal culture

3.5.1 Phase 5 Infrastructure

This phase is driven mainly by the increase in scale of the infrastructure already developed in the previous phase. The goals are to increase the capabilities of power and distribution, communication, navigation, transportation, and habitation to ensure the demand requirements for this larger base are met.

3.5.1.1 Architecture

Habitation Module

During Phase 5, the lunar base will continue to grow, and develop into a settlement. The settlement will be populated by employees, mission operatives, and resident who have potentially chosen the Moon as their home. Additionally, as this phase progresses, the possibility of children being born and raised on the Moon becomes an critical scenario to consider. This would require several considerations and studies about the effects of hypergravity on development, but must be investigated as humans shift towards permanent lunar settlement (NSS, 2018). The increased growth of the settlement population will increase the demand for habitable modules. Hence, technologies such as rigid modules, inflatable and deployable/expandable modules or regolith 3D printing (mentioned in Phases 2, 3, and 4) will be refined, improved, and duplicated to support a larger settlement, in keeping with sustainable goals (detailed in Section 4: Lunar Sustainability Goals).

Beyond the Moon

A well-established lunar settlement could be able to take advantage of the hypogravity environment on the Moon, allowing launches at lower costs and with higher performance than those from Earth; letting humans to travel further within the solar system and arrive faster. This could eventually lead to the possibility of settling other celestial bodies, specifically but certainly not limited to Mars. The orbital platform started in Phase 3 would acts as supporting infrastructure for additional missions to the lunar surface and beyond (ESA, 2017).

3.5.1.2 Power and Distribution

The growing rate of people, systems, and power dependent activities will determine the needed size of power production, distribution, and storage needs. Fusion can produce energy at a ratio of 100:1 (output:input) (Navratile, 2017). The theory is simple, but one needs to recreate the conditions of a star, and the confinement of the plasma requires a lot of energy, but should still require less than the energy output in order to be economically viable. Lockheed-Martin recently patented a Compact Fusion Reactor (CFR), which could be a promising technology for supporting this phase of the roadmap.

The abundance of Helium 3 on the Moon makes it an ideal source for nuclear fusion (Johnson, et al., 1999). Fusing Helium 3 atoms to Helium 4 is pollution-free. The expected massive amounts of Helium 3 on the Moon is viewed as a game-changer in energy supply (Dobransky, 2013). It is difficult to predict when Helium 3 can be used economically in a repeatable fusion process. Recent breakthroughs generate new hope that the timeline shifting problem will be solved soon.

3.5.1.3 Communications

Preserving stable communication between the lunar base and within the settlement itself is paramount for this phase to achieve the goals asserted; Moon ground stations shall be further developed at this stage, enabling a more comprehensive communications line of sight (Coutinho and Welch, 2018). In addition, a Moon network communication system similar to a cellular network concept shall be considered (Coutinho and Welch, 2018). Vodafone Germany and Nokia have proposed enabling a 4G network on the lunar surface. This would represent a milestone for providing a stable surface communication network and could help the operations during this stage of the lunar base (Vodafone Group, 2018).

As for Earth-Moon communications, the development and usage of Laser-Based Communication Systems could be beneficial at this stage, as the need for increased data transfer is likely to occur. In 2013 NASA accomplished, with the Lunar Laser Communication Demonstration (LLCD), a first two-way, high data rate laser communication from lunar orbit, which achieved significantly higher data rates than traditional RF systems (Kuroda, et al., 2014). This technology will undergo further testing in 2019 (Mohon, 2018).

3.5.1.4 Navigation

The navigation systems proposed in the previous phases would not be sufficient to guarantee connectivity conditions within daily life similar to those present on Earth to lunar society, and would need to be expanded. Therefore, the establishment of a proper Lunar Navigation Satellite System (LNSS), e.g., the lunar equivalent to a Global Navigation Satellite System, in orbit around the Moon could be necessary.

An alternative approach that could be implemented when Phase 5 begins is the Lunar Positioning System (Batista, et al., 2012). This includes a constellation of 16 CubeSats orbiting the Moon along two inclined circular orbits at an altitude of 33,400 km from the lunar surface, with an orbital period equal to that of one-fourth of a lunar day. Such an LNSS would provide good accuracy for position, velocity, time determination (PVT), considering that the minimum number of visible satellites to provide global coverage of the Moon at that altitude is only four. The choice of a non-lunar-synchronous orbit, which would reduce the relativistic errors and the number of required satellites, is justified by the fact that this orbit would be too high above the L1 Lagrangian point, causing the CubeSats to be pulled back by the strong Earth's gravitational field.

Moreover, although the cost associated with placing CubeSats into orbit is much lower than most normal-sized satellites, these small satellites require a much smaller atomic clock. Recently, there have been some technological advancements towards chip-scale atomic clocks (CSAC), and it is very likely that there would be further improvements until the beginning of Phase 5 (Batista, et al., 2012).

3.5.1.5 Transportation

With Phase 5 addressing the establishment of a lunar society, the focus of transportation shifts from an exploration purpose to a lifestyle and cost effective purpose. To accommodate the growing number of passengers traveling to and from the Moon, it is anticipated that large amounts of fuel production would be established on the Moon by this time. However, all examined roadmaps referenced in the Roadmap introduction failed to address establishing the capability of managing and storing large amounts of cryogenic fuel on the surface of the Moon for long periods. Furthermore, the need for advancement in rocket technology to utilize other alternative in situ resources as propellant is necessary to maintain the sustainability of lunar resources, in line with Goal 14: Sustainable ISRU.

Surface Transportation

Similar to previous phases, establishment of a community on the lunar surface would require methods of commuting from one location to another. As such, the settlement would require a more sophisticated surface transportation system than seen in previous phases to enable comfortable movements between the facilities.

The use of Lunar Roving Vehicles, briefly described in Phase 4, would not be sufficient for this purpose. However, the concept of an electrically powered bus, already described in Phase 4, could be adopted during this phase and scaled appropriately to accommodate more people. Additionally, if an electric grid is secured in the settlement, there would be the opportunity to implement a lunar railroad (Schrunk, et al., 2007). While wheeled-based transport has advantages of mobility, a railway system is more energy efficient (Bernold, 1994), but requires more initial investment in infrastructure. It is also a more versatile method of transportation since more compartments could simply be added to accommodate a larger number of people or cargo. A similar concept of a fixed destination transport includes lunar cable lifts (Bernold, 1994). This system includes the advantages of the railway concept, but without the engineering difficulties of accommodating the large thermal expansion of rails that would be experienced on the lunar surface and avoids dust storms caused by traveling close to or on the lunar surface. Overall, implementing any of the above methods of surface transportation would mitigate the use of lunar resources, assisting the sustainability of a settlement.

3.5.1.6 In Situ Resources

Phase 5 will progress the utilization of lunar resources in the same way as the basic operations phase. However, with the increasing number of base inhabitants, the lunar regolith mining efforts should be expanded to meet the architecture and life support material requirements. Furthermore, to procure more hydrogen for the anticipated commercial fuel market demand, lunar ice water mining could be enhanced. To address the transportation needs of this phase, resources could be used to construct landing pads, roads, and railways.

3.5.2 Phase 5 Governance

During Phase 5, the demands on governance go beyond global governance on Earth to communicating activities and basic local operational governance on the lunar surface. As the population on the Moon grows, and the durations of visits to the Moon progress from months, to years, to even permanent habitation, the system of governance required to manage an evolving settlement and society could far exceed the demands of anything beyond Earth.

The level of governance required for potential Phase 5 activities, which extend far beyond the basic operations supporting scientific endeavors in Phase 4, could be a subset of an existing body on Earth, and an extension of the bodies such as the United Nations General Assembly (UNGA) and UNOOSA. However, as the settlement grows and more actors venture to the Moon, an interesting question will arise as to whether the population on the Moon is viewed as a subset of the population of the Earth, or whether, over time, they become their own society of people. It might be that if / when the population on the Moon evolves to have its own cultures, activities, habits, and local laws inevitably, then an argument for having a new government entity on the Moon, with greater transparency of activities and customs, becomes compelling.

The self-proclaimed Kingdom of Asgardia, “home” to 280,000 citizens, offers an interesting example of the limitations in existing international legal frameworks for the Moon. The objective of Asgardia is to use the principles of international law to become the first space nation in history. Asgardia has even applied to become a member of the UN (Asgardia, 2017). In international law, a State is constituted of a population, a territory, and effective governance. Once these elements are identified, it only needs the recognition of other States (the UN is an organization of States) to become a fully independent actor of international law. The case of Asgardia is of interest when thinking of a lunar base as the settlers could have a similar approach to independence and appropriation of the Moon territory. Asgardia already has a population, and a form of effective governance. It plans to launch a space station that would then serve as its territory and allow it to complete the list of elements necessary to be recognized as an actual state (Asgardia, 2017).

A population on the Moon, whether it evolves to become a State of its own, such as the aims of Asgardia, or even more drastically, its own entity outside of international law altogether, could have some practical justifications. As of today, the liability for space objects and activity rests with the state of registration. This means that current breaches of international law land squarely at the states level. However, once activity becomes organic on the Moon, it may not be feasible, let alone suitable, to lay responsibility at states on Earth for activity organically created on the Moon.

One approach to govern the growing number of people and activities on the Moon and in Phase 5 could be to create a separate governance entity. This could be in the form of establishing an equivalent to the

United Nations Security Council, to bring control and order on the Moon, and to create policy and recommendations that members should abide by similarly to the function of the United Nations General Assembly on Earth today. It's worth noting that the Moon could also have dedicated local law enforcement agency.

3.5.3 Phase 5 Human Factors

To support the growing population of lunar residents, medical support would be provided widely, and combined with procedures to guarantee safety of human health. Here, LSSs and medical capabilities are addressed together with the cultural aspects that could evolve during the development of a settlement.

3.5.3.1 Life Support

Closed-Loop Life Support Systems

A critical requirement to sustain the population growth that will occur in this phase is establishing a Closed-Loop Life Support System (CLLSS) to provide the essentials for the human life without the help of any terrestrial input. This would become increasingly important as the lunar settlement population grows. Most of the examined roadmaps listed in Table 3.1 in the introduction to the Roadmap Section do not contain fully developed CLLSS. Airbus, the Global Exploration Roadmap, and the National Space Society specifically emphasize the importance of evolving a settlement to become self-sustaining.

A fully CLLSS will be required in order to continuously produce human life requirements, such as oxygen, food and water, while recycling waste products to be used as inputs in the production of these life supporting requirements. One example project in this field of CLLSS is the Micro-Ecological Life Support System Alternative (MELiSSA), shown in Figure 3.11.

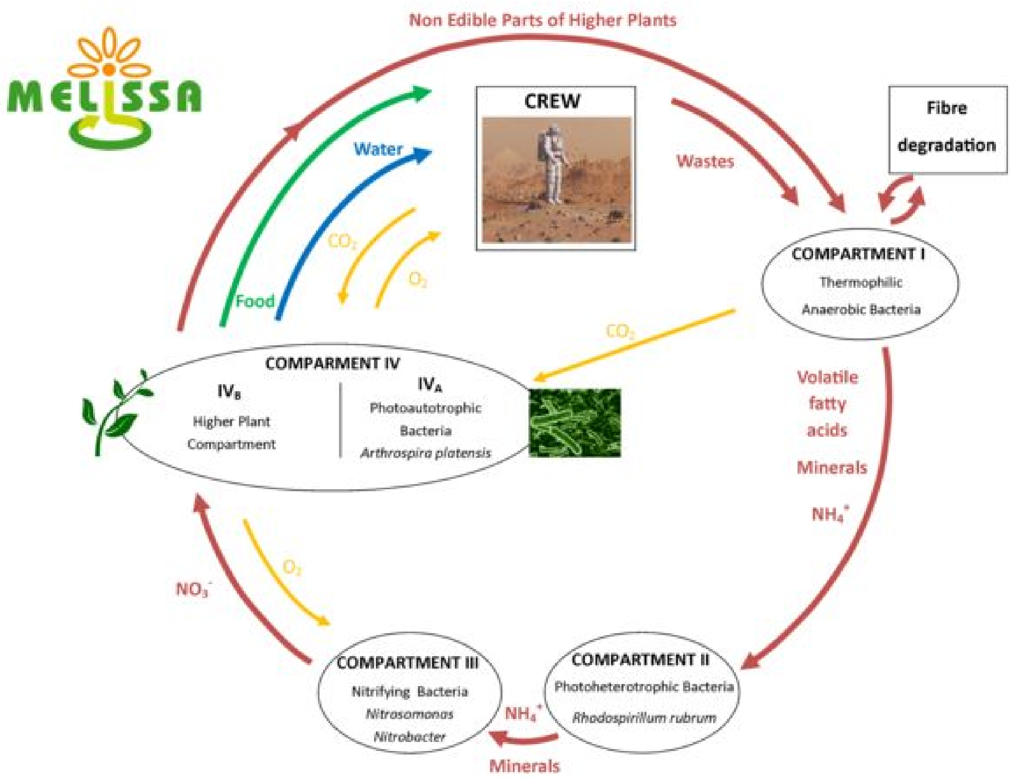


Figure 3.11. MeLISSA loop diagram (ESA, 2015)

By adopting a waste recycling compartment and a plant compartment, the MeLISSA loop is aimed to convert organic waste into oxygen and nutritive biomass. This scheme represents an advanced life support system currently being worked on by ESA, with the potential of providing a solution for permanent human habitation on the Moon (Hendrickx, et al., 2006).

3.5.3.2 Medical Capabilities

Extended habitation in the lunar base could have implications for the human body, even if medical care and support is provided effectively. Preventative measures, inhabitant selection processes, and emerging advanced medical capabilities are mandatory for the existence and progression of a full scale and growing human settlement.

The rising population and longer on-site presence increases the likelihood of health issues during this phase, caused by lengthier exposure to the harsh elements of the lunar environment such as radiation and hypogravity conditions. The population growth will also lead to a mounting transmission of pathogens as well. Therefore, on site clinical and medical expertise is critical to avoid emergency flights to Earth, requiring valuable time and snowballing cost . Ground-based telemedicine and telesurgery are insufficient for this phase because of to communication latencies. Hence, on-site diagnostics, urgent treatment, preventative medicine, and a variety of pharmaceuticals must be available on the Moon during this phase and should include capabilities such as laboratory analysis, surgery, dentistry, sterilization, antibiotic treatment of infectious disease and mental health interventions, as well as simple clinical check-ups for inhabitants (Stewart, Trunkey and Rebagliati, 2007).

3.5.3.3 Cultural Aspects

During this phase, it is reasonable to expect that a unique lunar culture could be established, as has been the case with other isolated communities, such as Antarctica and the ISS. While lunar culture will be emerging during previous phases, including the Earth-bound culture of those working on lunar projects, or mission specific culture of various mission teams, this phase and beyond could contain new religious interpretations (Section 2.4.1.4), new social norms influenced by lunar environment enabled technology (Section 2.2.1.1), new teamwork models (Section 2.6.1.2), which is further expanded upon in Section 3.5.4, and new artistic pastimes (Section 2.4.1.2). As the lunar settler population grows, the importance of and market for lunar activities, such as entertainment, education, and tourism, could also increase as well (Section 2.1.1.2). As this phase progresses, it may also be important to consider the rights and liberties of the future inhabitants of the Moonbase, and what constitutes their rights to return to Earth (Denning, 2018). However, unlike the other phases and subjects in the Roadmap, both Phase 5 and "cultural evolution" are more difficult to define and quantify.

One example of a unique cultural evolution that could occur within the lunar settlement concerns cyber-physical, human-robotic systems. These mission enhancing systems, currently under development and rationalized in Section 2.2.1, could be well established during Phase 5 and could create new cultural norms. New norms, such as the increased cultural acceptance of robotic wearables on the lunar surface (similar to how ISS has unique cultural acceptance of the interactions between astronauts and its systems), could emerge from the substantial benefits achieved in improving the alignment between people, processes, and platforms on the Moon. This acceptance of long-term, cyber-physical, human-robotic interactions on the Moon could eventually create cultural change, or even a cultural divergence with Earth, in the same way as Industry 4.0 in Germany, Society 5.0 in Japan, and the Internet of Everything in the US (National Science Foundation, 2010; NASA, 2015d).

To address these cultural changes, several Lunar Sustainability Goals, specifically Open Access, Diversity and Opportunity, International Cooperation, and Standardization, are proposed and described in Section 4. Collectively, these goals work towards providing opportunities for a sustained international, intercultural presence on the Moon, in line with the vision of the Moon Village Association. It is imperative that the biases and prejudices present in Earth society do not translate to the lunar context, which would only be accomplished with active shaping of future lunar culture by space actors. This is what these goals hope to address. To achieve this requires ensuring access to the developing technologies and services that will shape the future lunar culture.

As described in Section 2.1, the space sector is transforming into a field with significant participation from both government agencies and commercial new space startups (Diamandis, Richards and Pelton, 2018). Jones (1985) postulates that whoever develops a lunar base, be it scientists from a government agency or other actors, must plan accordingly to smooth the transition from a purely scientific outpost to a self-governing body, to reduce the risk of repeating historical mistakes with the transfer of governance that have occurred on Earth. The establishment of a new lunar culture, which is based in services, human-robot interactions, and reinterpretations of cultural systems on Earth, would require a uniquely adapted governance system, as was discussed in Section 3.5.2.

3.5.4 Phase 5 Summary

The Settlement phase represents the completion of the whole lunar Roadmap. It symbolizes the ending of the evolution of lunar settlement, as depicted in this paper, with the population on the Moon capable of leading comfortable lives as we know today on Earth within the limitations of the Moon's environment.

The essence of this stage of the settlement is to extend the boundaries of the settlement, both in terms of the territorial borders and, in terms of the technical capabilities.

Habitable modules increase in quantity to host a larger population. Likewise, power will be supplied in greater quantities. Communication systems will be enforced and an efficient transportation system will provide access with ease to all facilities. The implementation of a Lunar Positioning System (LPS) provides the extended coverage necessary for far-side lunar exploration missions as well as set the foundation for positioning system of the lunar settlement.

On the other hand, this phase entails the possibility of exploring technologies that have never been applied. The LOPG will provide the opportunity to expanding humanity throughout the solar system and beyond, while also supporting the ferrying of humans to the lunar surface or to the Earth.

Life support represents a crucial section of this phase. The feasibility of closed-loop systems is a milestone for the Roadmap, since it would provide the opportunity to humans to live without resupply from Earth. In addition, sustaining the lunar population with health and safety requires medical capabilities, to avoid emergency returns to Earth and operate on-site. Furthermore, at this stage, lunar culture could expand to include new religion, new team models, and new societal norms that evolve around the interaction between people and the lunar settlement systems, which could be influenced by cyber-physical, human-robotic interfaces will likely influence these.

Finally, the internationality of this settlement invites interested organizations to collaborate for the sustainability of the mission. Cross-cultural mitigation could play a critical role for the diverse lunar population, while global partnerships would be recommended for effective economic sustainability. Governance of activities within the lunar settlement could become a branch of an existing body on Earth. Moreover, there could be potential to synthesize new entities to ensure greater transparency of activities, unique to the Moon, based on the actors present. Since the Moon would be largely independent by this phase, development of a Security Council, like the United Nations, could be established to create and enforce its policies and lunar laws.

3.6 Conclusion

After assessing the various lunar-centric roadmaps that have been published by various parties, a consolidated version has been created. This consolidated roadmap consists of five phases, namely: robotic surveillance, infrastructure preparation, habitat development, basic operations, and lunar settlement. The fundamental purpose of each phase has been presented with their predicted timelines and durations derived from existing, publicly available roadmaps. Operational details stipulating the technical aspects required for successful completion of each phase have been presented. These include prerequisites concerning: infrastructure, human factors, and governance aspects. The relevance of various prerequisites to each phase are outlined in the timeline shown in Figure 3.12 below. This timeline illustrates the activities present within each phase, and is inspired by the existing roadmaps presented in the introduction to this section. From this figure, it is clear when exploration stages phase out, and the settlement aspect phase in, and more operational requirements are necessary.

In conclusion, multiple companies, agencies, and organizations are developing long term plans for lunar settlement for scientific, commercial, and explorational rationale. UN COPUOS and the Secure World Foundation (SWF) have established a set of goals for long term sustainability of outer space activities. The guidelines are voluntary and serve as a framework which nations can incorporate into their national legislation. However, as highlighted in this consolidated roadmap, improved specificity for developing lunar sustainability should be considered. Therefore, the following section outlines Lunar Sustainability Goals which have been developed that can overlay onto existing roadmaps and serve as a supplemental framework towards guiding lunar activities for private companies, space agencies, and organizations with long term plans to visit the lunar surface.