Lunar Base Construction Overview

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ABSTRACT

Previous lunar missions and campaigns have been restricted to using robotic landers and lunar orbiting satellites as well as sortie type of operations using astronaut crews (NASA Apollo program). Now, the next phase of lunar exploration has begun under NASA's Artemis program and there has been an international response where other nations such as China, Russia, India, Canada, Japan and the European Union of nations, have all expressed interest in either collaborating or competing with NASA on the Moon. This next phase has an over arching goal of achieving a permanent human presence on the Moon via sustainable methods.

A lunar base with human occupancy will require infrastructure to provide shelter, utilities, landing/launch pads, roads, communications, power and all the other necessities to sustain human life and protect equipment. Since human biology is not well suited for surviving in the lunar environment, there will be many forms of automated equipment, autonomy and robotic helpers that will minimize the amount of Extra-Vehicular Activity (EVA) required by the crew. This will mean that the radiation dosage received by the crew will stay within acceptable and safe career doses. Radiation shielding via the use of regolith can also mitigate radiation dangers.

The required infrastructure must be constructed, but the mass and logistics of bringing all the construction materials from Earth are prohibitive, which makes the necessary construction difficult to achieve. In-Situ Resource Utilization (ISRU) aims to solve this challenge by sourcing construction materials locally or "in-situ". This means that their transportation can be completely eliminated, resulting in large cost savings by avoiding the launch out of Earth's deep gravity well and subsequent trans lunar injection, lunar orbit capture and landing.

This paper will give an overview of the required construction tasks and related equipment that will be required to robotically build a lunar base using in-situ resources. It will also organize these tasks into logical groupings so that technology development and implementation can be pursued within a framework that can be referenced by all involved.

INTRODUCTION

Establishing a base on the Moon has been the subject of human speculation, planning, analysis, technology development and pre-cursor missions for over 156 years. In 1865, the French author Jules Verne wrote a novel: 'From the Earth to the Moon: A Direct Route in 97 Hours, 20 Minutes", which captured the popular imagination at the time. In 1901, "The First Men in the Moon" is a novel that was published a scientific romance by the English author H. G. Wells, originally serialized in "The Strand Magazine" from December 1900 to August 1901. These kinds of literary works of fiction inspired subsequent generations of scientists, engineers and explorers, and as technology evolved, the concept of a lunar base became more realistic and feasible.

In the 1950's, Dr. Wernher von Braun was recruited by the United States and he started a publicity campaign which laid out a vision for space exploration which included human tended space stations in orbit, a lunar base and an eventual human Mars landing (Bergaust, 2017).). The 14 May, 1950 headline of The Huntsville Times, "Dr. von Braun Says Rocket Flights Possible to Moon", might have marked the beginning of these efforts, which ultimately led to the Apollo program, which was driven by the "Cold War" with the Soviet Union, and resulted in an astounding and successful first landing of humans on the Moon on July 20, 1969 (Logsdon, 2010).

Since then, the high cost of space exploration and the lack of political drivers has prevented an actual lunar base from being constructed. The United States of America (USA) National Aeronautics & Space Administration (NASA) followed a plan to build a reusable "Space Shuttle" whose purpose was to build the "International Space Station (ISS)" in low Earth orbit which would then lead to expanded knowledge to enable human deep space voyages to the Moon and then Mars. As the Space Shuttle and ISS programs were stretched out by decades to accommodate national budget realities and political decisions, the vision and desire of many people to expand humanity's reach to the Moon and Mars became hostages to these expensive programs. In 2011, safety concerns and the completion of the ISS construction resulted in the end of the Space Shuttle program (Launius, 2008). By 2017, the ISS was aging, and NASA was faced with decisions on the strategic future of the United States (US) space program. In parallel, technology, skills and financing evolved to the point where commercial space endeavors by private companies and ventures led by billionaire entrepreneurs could also achieve space transportation. The commercial space efforts have proven to be more agile and cost effective than large bureaucratic government programs, as evidenced by the NASA Commercial Orbital Space Transportation System (COTS) program and the subsequent Commercial Crew Program (CCP) (reference). On December 11, 2017, US space policy evolved with the signing of Space Policy Directive 1 which provides for a US led integrated program with private sector partners for a human return to the Moon followed by missions to Mars and beyond. Notably, it directs NASA to pursue human expansion across the solar system (Hill, 2018). This resulted in the announcement of the Artemis program, also in 2017, as the result of reorganization and the continuation of successive efforts to revitalize the U.S. space program since 2009. Its stated goal is: " With Artemis missions, NASA will land the first woman and first person of color on the Moon, using innovative technologies to explore more of the lunar surface than ever before. We will collaborate with commercial and international partners and establish the first long-term presence on the Moon. Then, we will use what we learn on and around the Moon to take the next giant leap: sending the first astronauts to Mars." (NASA, 2022) The justification given is: "We're going back to the Moon for scientific discovery, economic benefits, and inspiration for a new generation of explorers: the Artemis Generation. While maintaining American leadership in exploration, we will build a global alliance and explore deep space for the benefit of all", (NASA, 2022). If in-situ resource utilization (ISRU) and advanced technology are used, then it is theoretically possible to "bootstrap" a self-sustaining, self-expanding industry at reasonably low cost. Simple modeling was developed to identify the main parameters of successful bootstrapping. This indicates that bootstrapping can be achieved with as little as 12 t mass landed on the Moon during a period of about 20 years (Metzger et al, 2013).

LUNAR BASE MISSION ARCHITECTURE & CONSTRUCTION

There have been many studies attempting to map out a feasible space mission architecture for a long term lunar program, but none have been sustainable. However, the collective knowledge generated by these studies has raised the state of the art and continues to inform the decisions and strategies which are being planned for the Artemis program. It is important to leverage these studies to inform and accelerate lunar base construction efforts going forward. Table 1 shows a list of the various studies that have been performed by NASA since the late 1980's.

Table 1. NASA Lunar and Mars Space Mission Architecture Studies (Drake, 2005)

Office of Exploration (OExP) - 1988 Case Studies Human Expedition to Phobos Human Expedition to Mars Lunar Observatory Lunar Outpost to Early Mars Evolution **Office of Exploration (OExP) - 1989 Case Studies** Lunar Evolution Mars Evolution Mars Expedition	**First Lunar Outpost - 1993** **Early Lunar Resource Utilization - 1993** **Human Lunar Return - 1996** **Mars Exploration Missions** Design Reference Mission Version 1.0 - 1994 Design Reference Mission Version 3.0 - 1997 Design Reference Mission Version 4.0 - 1998 Mars Combo Lander (Johnson Space Center (JSC)) - 1999 Dual Landers – 1999
NASA 90-Day Study - 1989 Approach A - Moon as testbed for Mars missions Approach B - Moon as testbed for early Mars missions Approach C - Moon as testbed for Mars Outposts Approach D - Relaxed mission dates Approach E - Lunar outpost followed by Mars missions	**Decadal Planning Team (DPT)/NASA Exploration Team (NExT) - 2000–2002** Earth's Neighborhood Architecture Asteroid Missions Mars Short and Long Stay **Exploration Blueprint - 2002** **Space Architect - 2003**
America at the Threshold - "The Synthesis Group" - 1991 Mars Exploration Science Emphasis for the Moon and Mars The Moon to Stay and Mars Exploration Space Resource Utilization	**Exploration Systems Mission Directorate (ESMD) 2004–2005**

Most of these studies focused on the space transportation, landing and launch aspects of humans traveling to the Moon and Mars. Very little attention has been given to the surface operations and surface systems that will be required to survive and thrive on the surface for extended periods of time – initially months and then years of permanent presence. However – a key tenet of systems engineering is to start the design process with the fundamental needs and end state in mind, so a good systems architecture should be driven by the end state of a lunar base which involves daily surface operations by crew, robots, and equipment to explore, conduct science, gather resources, process resources, create economic value and improve the human condition.

Some notable exceptions to the lack of surface systems analysis are the Eagle Engineering inc. study reports, which were commissioned by NASA in 1988 (Phillips et al, 1988) to study actual infrastructure needs, construction methods and equipment, and the Mars surface architecture (Hoffman, 2001), which provided a series of vignettes that informs the likely concepts of operations on the Martian surface.

Surface infrastructure needs for a lunar base can be functionally categorized as follows (Table 2 and are shown schematically in Figure 1):

Table 2. Lunar Base Surface Infrastructure Functions

Landing / Launch	Radiation Protection
Lander servicing	Meteorite Shielding
Propellants management	Moonquake mitigation
Power	Science activity stations
Communication	Resource mining / utilization
Habitation	Regolith operations / hauling
Life Support & Consumables	Logistics management
Transportation	Excavation & Construction Services
Extreme Access	Dust management
Thermal management	Maintenance / Repair / De-commission
Extra-Vehicular Activity (EVA)	Waste management
Food Production	Crew Health

Databases to inform the design and development of appropriate infrastructure can be found in the following NASA references:

- 1988 Eagle Engineering Lunar Base Surface Systems (LBSS) studies
- 1991 Element/Systems Database (from 90 day study)
- 1993 First Lunar Outpost (Habitation, Surface Systems, Rover volumes)
- 1996 Human Lunar Return (Surface Systems volume)
- 2002 Earth's Neighborhood studies
- 2005 Exploration Systems Architecture Study (ESAS) – Constellation Program
- 2020 Artemis Program (Smith, M et al, 2020)

Artemis program surface systems studies have resulted in a comprehensive functional schematic for a sustainable lunar base, as shown in Figure 1.

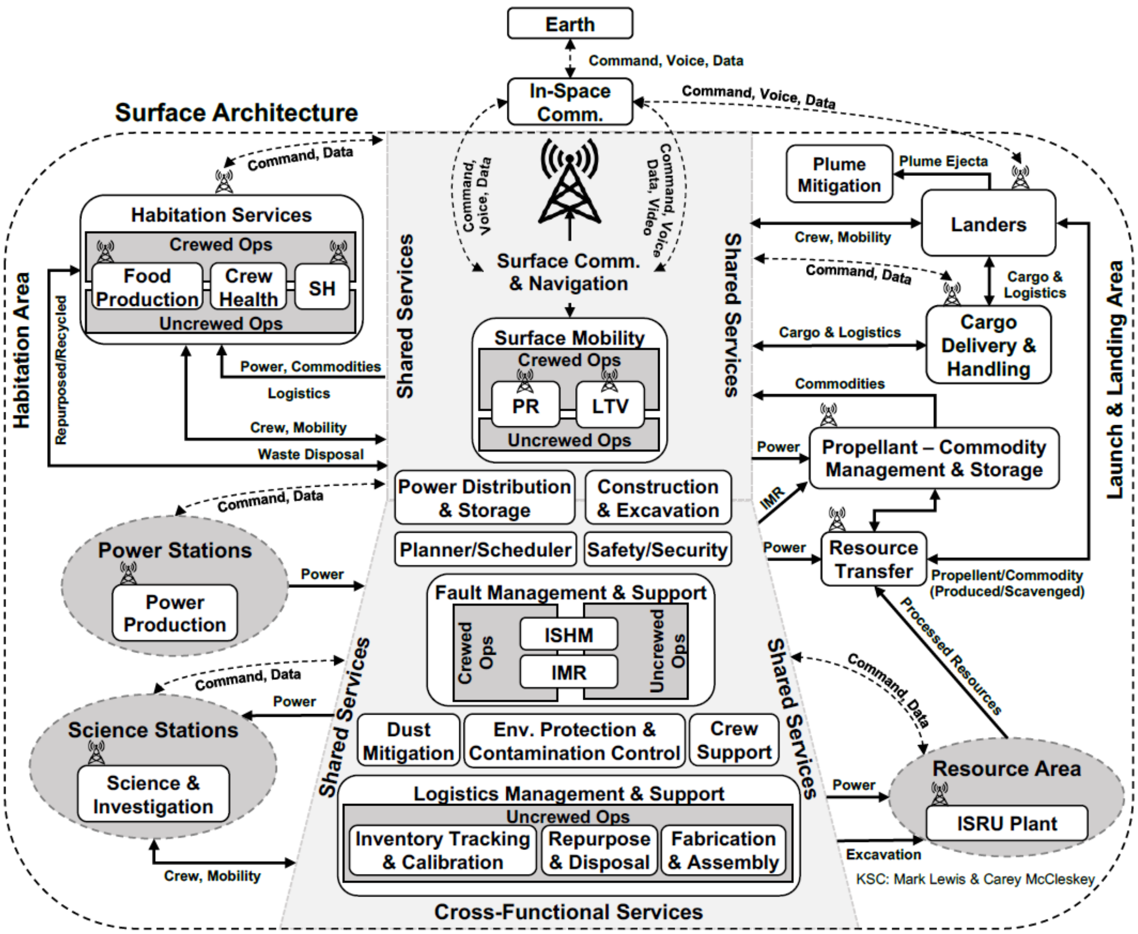


Figure 1. Schematic of Lunar Base Functional Needs
(NASA Kennedy Space Center (KSC), Lewis, M.E. & McCleskey, C.M., 2022)

The lunar base will be subjected to an extreme lunar environment with varying terrain, so all aspects of this environment and the interactions between functional elements are important considerations. During planning activities for the lunar base, the following interactions shown in Figure 2 must be considered.

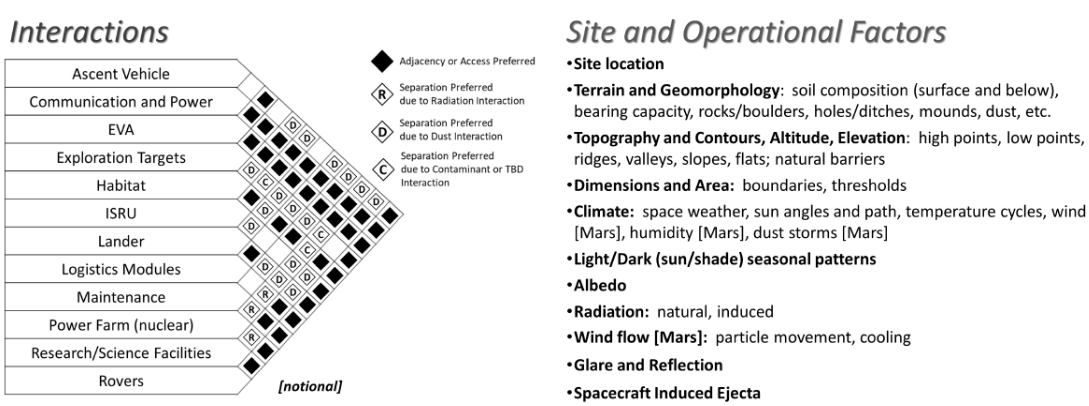
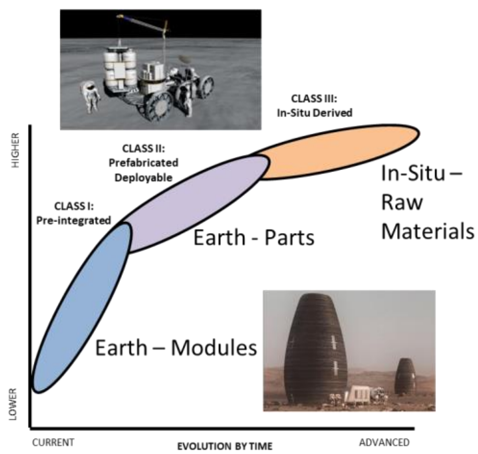


Figure 2. Lunar Base Site Planning Considerations (Lewis, R. et al, 2019)

The feasibility of construction is critical to the deployment of a lunar base. Initially the state of technology and knowledge associated with assembly and construction will be limited. In order to mitigate the inherent risk of attempting something new in an extreme environment, a phased construction approach has been defined (Kennedy, 2002) for habitats and modified here for general assembly, construction and outfitting. The infrastructure will initially be brought from Earth as pre-integrated modules with common interfaces (Class I). As the state of technology and expertise in lunar operations evolves then pre-fabricated parts can be brought from Earth and assembled or deployed (Class II). However, this implies substantial logistics and transportation costs, so the eventual goal is to become Earth independent through the use of in-situ resource utilization (ISRU), where in-situ raw materials and solar energy will be used to create a sustainable lunar production capability and all parts are in-situ derived (Class III).



Infrastructure Classification	Key Characteristics
CLASS I **Pre-integrated**	• Earth Manufactured • Pre-Integrated & Tested prior to Launch • Space Delivered with Immediate Habitation Capability • Launch Shroud Constrained • Limited to Launch Vehicle Payload Size & Mass Capability
CLASS II **Prefabricated, Surface Deployed & Assembled**	• Earth Manufactured • Requires surface Deployment, Assembly & Outfitting • Partial Integration of Subsystems • Critical Subsystems are Earth Based and Tested prior to Launch • Requires Assembly & Checkout prior to Human Occupancy • Larger Volumes Capable • Not Restricted to Launch Vehicle Shroud Size • Restricted to Launch Mass. Deliver on multiple vehicles • Can include ISRU-derived parts
CLASS III **In-Situ Derived and Constructed**	• Manufactured In-Situ, Derived from local Resources (Lunar or Mars) • In-Space Constructed • Requires Robotic Manufacturing Capability & Infrastructure • Requires Robotic and Human Labor During Construction • Requires Integration of Subsystems • Critical Subsystems are Earth Based and Tested prior to Launch • Larger Volumes Capable • Not Restricted to Launch Vehicle Size • Not Restricted to Launch Mass

Figure 3. Infrastructure Construction Classification

MASTER PLANNING & CONSTRUCTION MANAGEMENT OF A LUNAR BASE

Before site preparation and construction can start, it is necessary to do a thorough site analysis, master planning with subsequent design activities. The site analysis will establish the geotechnical properties of the regolith in the construction site. It is also important to understand and assess the sub-surface characteristics in a geological context so that solid foundations can be built for subsequent use in constructing infrastructure.

Once the site topography has been mapped and characterized to an accuracy of 1 centimeter or better, then a master planning process can begin, where all stakeholders are consulted, and goals and objectives are established. A digital Geographic Information System (GIS) can be populated with the topographical data which allows further layers of data and meta data to be added to provide context. Subsequently the site can be divided into various zones with functional allocations. For example, the lunar base can have a spaceport zone for landing and launch operations, including ISRU re-fueling of the vehicles, which implies having cryogenic storage propellant farms close by as part of the lunar spaceport. Other zones may include an industrial zone for manufacturing and maintenance activities, a research zone for laboratories and science activities, a mining zone where resources are acquired, an ISRU zone where useful products are extracted from regolith resources (e.g. oxygen), an equipment storage and maintenance zone, a habitation zone for human crews, a life support zone where breathing air is created, water is recycled and trash and human waste are processed, a rest and recreation zone for human social activities, and farming zones where food is produced and processed. (Mueller, 2022)

A notional site plan for an early version of a Lunar Base is shown in Figure 4 (Mueller et al, 2008). It shows a surface architecture that evolves and builds from the site where the first lander touches down. The first landing site becomes a hub for the base where roads radiate outward to link the various zone such as Power production with Solar Power Units (SPU), regenerative fuel cell Mobile Power Units (MPU), ISRU, Logistics, Habitation and two or more redundant launch landing pads for a spaceport function, where landings are alternated between the two pads. If one pad is undergoing maintenance or is occupied by another lander, then the second pad allows spaceport operations to continue. Berms or walls surround the pads to stop any ejecta caused by launches and landings or from an anomalous blast in the event of an accident, so that the base itself would not be damaged. Shade walls surrounding the propellant farms could provide a cold environment to minimize cryogenic propellant boil off losses. Trenches along the side of the roads will provide utility corridors for buried power cables, communications cables and possibly even piping for propellant transfer.

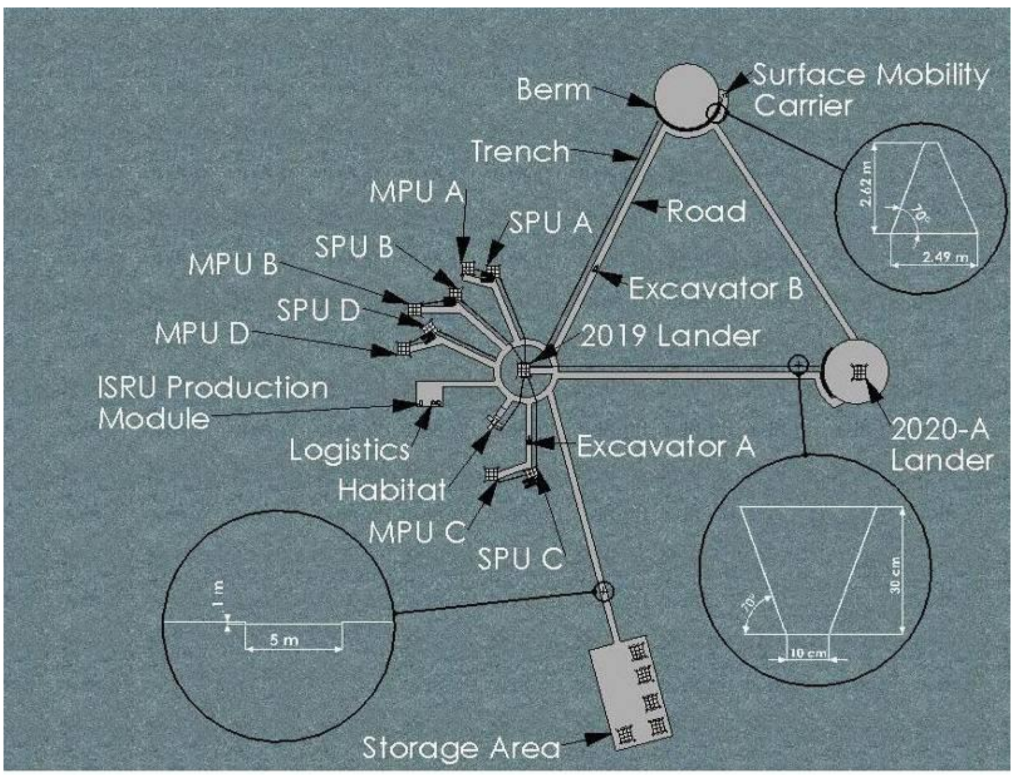


Figure 4. Example of a Notional Lunar Base Site Plan (Mueller et al, 2008)

After the planning and architectural studies have been completed then all the necessary functions will have been identified so that a systems engineering functional decomposition can occur with a resulting set of design requirements. Many of the technologies needed to satisfy the expected design requirements require more development as most lunar surface technologies are only at a TRL of 4-6 at this time. This means that substantial technology development work is required in laboratories and analog test sites here on Earth.

Terrestrial Mega-Projects (> $10 Billion) are common and the methods for successfully implementing them are well known and proven If these are combined with NASA systems engineering to account for the extreme space environment, then we can use these methods as a framework for how to proceed with the construction of a lunar base. (Mueller et al, 2021).

Due to the protracted timeframe as well as technical and human complexity of megaprojects, enormous planning and change management is required. Successful project delivery is realized by using a phased approach, focused on development of client expectations, technical requirements and cost estimates. In the terrestrial construction industry, the phases of project development include: Concept (Initial Studies), Pre-Feasibility (Evaluate), Front End Engineering and Design FEED (Feasibility), Execute (Engineering, Procurement, Construction, Commissioning), Operate, and Closure. In the NASA systems engineering process this is equivalent to Concept (Pre-Phase A), Pre-Feasibility (Phase A), Front End Engineering and Design FEED (Phase B), Execute (Phase C-D), Operate (Phase E), and Closure (Phase F). During each stage of terrestrial development, the following aspects of project delivery are addressed: (Carrato et al, 2018)

Concept of Operations
Project Development Approach
Project Delivery Approach
Project Management
Ownership and Legal
Stakeholders and External Relations
Health and Safety
Fuel and Energy for Project Delivery
Logistics
Remote Construction
Power Storage and Distribution
Remote Commissioning
Remote Operation and Maintenance
New Technology and Technology Readiness Levels (TRL)
Capital/Operating Costs
Revenue
Risk
Intellectual Property Management
Financial Analysis
Funding
Requirements and Status of Studies

In the aerospace industry, it is customary to follow the NASA systems engineering methods. In order to be successful in engaging industry, it is important that industry should be able to translate between aerospace acronyms, conventions and processes and prevailing industrial practices, which are similar between aerospace and terrestrial construction, but require some translation and explanation (Mueller et al, 2021).

NASA ARTEMIS LUNAR PROGRAM

Phase 1 of the Artemis program makes use of the existing plans for SLS and Orion previously known as Exploration Missions-1, -2, and -3. These missions have been renamed Artemis I, II, and III, and will consist of an un-crewed flight around the Moon (Artemis I), a crewed flight around the Moon (Artemis II), and a landing at the lunar south pole, with potential crew operations aboard the lunar orbiting “Gateway” (Artemis III). After successfully returning humans to the lunar surface in 2024, Artemis will evolve to Phase 2. This phase will focus on building up a sustainable human presence in cislunar space and on the surface. NASA will continue to utilize the Space Launch System (SLS) and Orion for further numbered Artemis missions and begin to expand the Gateway into a more capable science and exploration platform using additional elements provided by a mix of commercial and international partners. An additional goal during this phase is to conduct technology trials and scientific experiments to prepare for crewed missions to Mars beginning in the 2030s.

In Phase 1, the “Artemis III” initial crewed mission will be during lunar daylight with two crewmembers landing on the surface, for a surface stay duration: 6.5 days (~156 hr) with 2 –5 surface EVAs, and exploration excursions of up to a 2 km radius away from the lander.

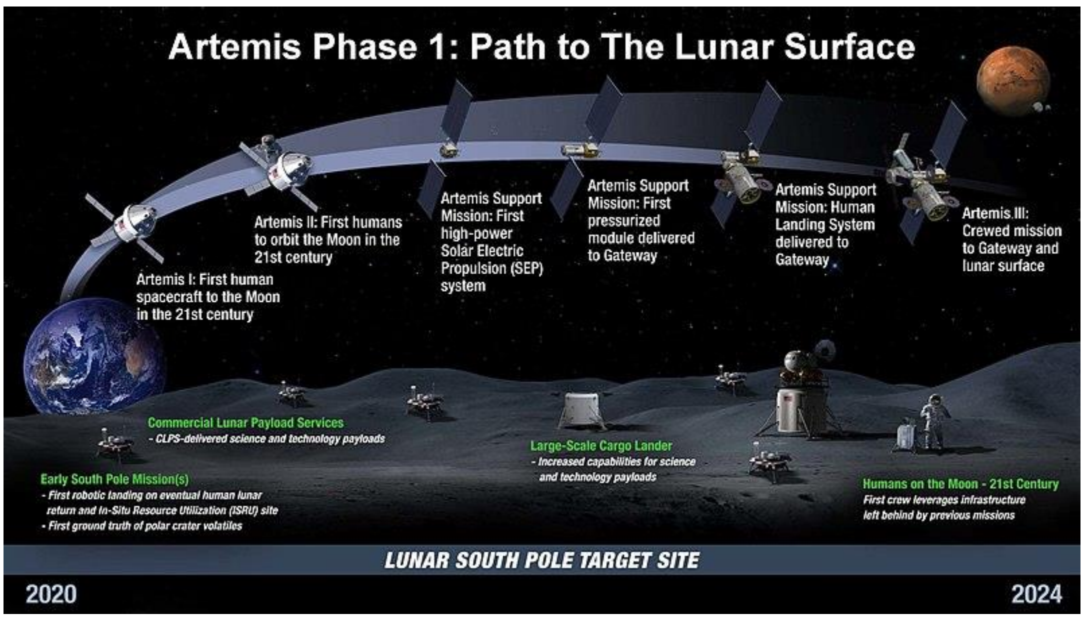


Figure 5. NASA Artemis Program Phase 1

Artemis Phase 2 Includes both longer lunar daylight missions and mission extending through lunar night, with four (or more) crew landing on the surface. Longer extended missions during lunar daylight (~14 Earth days) and sustainable long duration missions during lunar day & night (~42 Earth days to 6+ months). Exploration excursion distances from lander/habitat will be increased with use of unpressurized rovers and eventually pressurized rovers.

CONSTRUCTION OF INFRASTRUCTURE

During Artemis Phase 1, the emphasis will be on proving the systems that are necessary for transportation to the Moon and an initial operating capability. Since most of the technology readiness levels (TRL) of the needed surface systems technologies required for construction of infrastructure are still relatively low (TRL 3-4), this time period provides an opportunity to increase the TRL via development and terrestrial testing. A work breakdown structure (WBS) (Moses et al, 2021), has been proposed (Figure 6) that shows the activities that will need to be addressed to create supporting infrastructure in Artemis Phase 2.

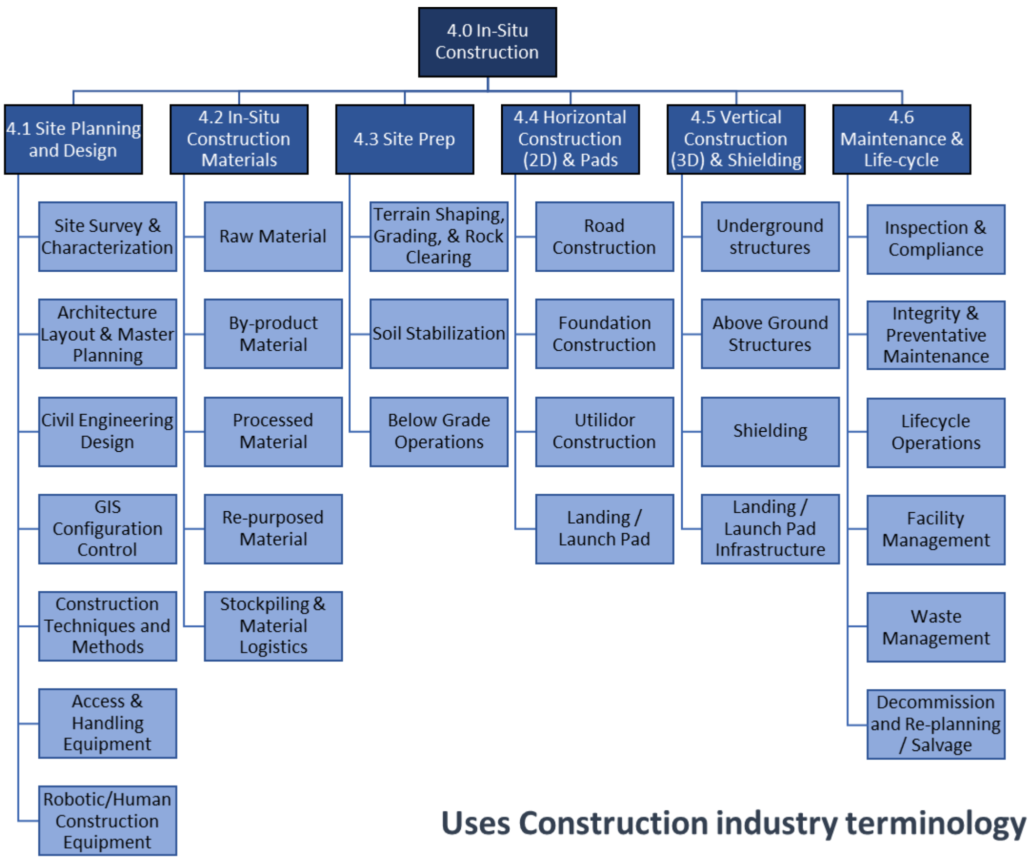


Figure 6. Work Breakdown Structure for Infrastructure Construction Activities

It is anticipated that the activities under 4.1 Site Planning and Design will need to be addressed first. This activity will inform the requirements for equipment and products that will be needed. Mission capabilities will also dictate how much mass and volume can be delivered to the lunar surface and how much electrical and thermal power will be available for construction activities. After materials have been acquired and site preparation has been completed, then horizontal and vertical construction can proceed. It is important to plan and invest with a complete life cycle approach so that operational costs do not become prohibitive, due to inadequate capabilities.

CONSTRUCTION TASKS AND RELATED EQUIPMENT

The required lunar base requirements will be assessed in a functional definition to provide a physical definition so that the required products can be designed and validated in a typical systems engineering process. The products will consist of robotic equipment and actual infrastructure. Table 3 shows examples of infrastructure that will have associated construction tasks and also associated equipment that could construct it. Since the requirements are not known yet, these examples serve to show how robotic equipment must be efficiently designed so that there can be multiple uses with a high level of versatility. For example, one mobility platform could have multiple implements attached to it which are swapped out for various different tasks. Lifetime and maintenance needs are also important considerations due to the extreme lunar operating environment.

Table 3. Infrastructure and Associated Construction Equipment

Notional Infrastructure	Robotic Construction Equipment
Landing / Launch Pads	Cut/Fill Excavator, Grader, Compactor, Paver
Blast Shields / Berms	Robotic Assemblers, Bulldozers, Loaders
Propellant Farms	Crane, Robotic assemblers, Grader
Roads / Pathways	Cut/Fill Excavator, Grader, Compactor, Paver
Dust Free Zones	Cut/Fill Excavator, Grader, Compactor, Paver
Utility Trenches	Cut/Fill Excavator
Nuclear Power Plant Shielding	Cut/Fill Excavator, Loader, Compactor
Space Radiation Shielding	Cut/Fill Excavator, Loader, Compactor
Meteorite Shielding	Cut/Fill Excavator, Loader, Compactor
Foundations / Seismic Mitigation	Cut/Fill Excavator, Grader, Compactor, Paver
Dust Free Zones / Plazas / Storage Areas	Cut/Fill Excavator, Grader, Compactor, Paver
Communication / Power Towers	Grader, Compactor, Vertical Constructor
Un-Pressurized Hangars	Grader, Compactor, Vertical Constructor
Pressurized Habitats	Grader, Compactor, Vertical Constructor
Consumables Logistics Tanks	Crane, Robotic assemblers, Compactor, Grader
Resource Mines / ISRU Zone	Cut/Fill Excavator, Hauler
Thermal Wadis	Cut/Fill Excavator, Grader, Compactor, Paver
Waste Disposal / Recycling Facility	Cut/Fill Excavator, Loader, Compactor

Table 3 shows that there is construction equipment commonality between the infrastructure tasks. Manipulation of regolith is the primary function, and a secondary function is assembling components with a crane and robotics. It can be seen that regolith excavation, compaction and hauling have significant importance in most of the construction tasks. The method to be used for paving the regolith surface is not known yet, although there are candidate materials stabilization technologies being developed. Likewise, vertical construction methods and materials are also still in development.

CONCLUSIONS

This paper has provided background data about NASA space mission architecture studies since the late 1980's, which have informed and evolved into the current NASA Artemis lunar program of record. A functional analysis of a lunar base was presented with interactions and construction classifications defined. Master planning and construction management criteria were discussed, and an explanation of Phase 1 and Phase 2 of the Artemis program was given.

In order to achieve the sustainable "infrastructure to stay" goals of the Artemis program which relies on ISRU and advanced technologies to be successful, a referenced work breakdown structure was suggested as a framework for future work organization and technology development efforts. Finally, notional infrastructure required for a lunar base was examined in terms of the construction tasks with associated equipment categories suggested. This analysis is at a very high and conceptual level to allow for future definition according to the evolved requirements, but it shows that there is significant functional overlap between various construction tasks.

It is hoped that organizing these tasks into logical groupings (as shown in the WBS) can be beneficial, so that technology development and lunar base construction implementation can be pursued within a common framework that can be referenced by all involved,

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