Implementation of In-situ Resource Utilization for the Development of a Moon Village

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Skidmore, Owings & Merrill (SOM), in partnership with the European Space Agency (ESA) and faculty in the Department of Aeronautics and Astronautics at the Massachusetts Institute of Technology (MIT), has developed a design for a permanently inhabited Moon Village at the south polar region of the Moon. In-situ resource utilization (ISRU) is considered to be an essential element to enable the sustainability of long-term exploration missions. Sustainable construction, operation and maintenance of a permanent human settlement will require the use of local resources, to gradually reduce the dependence on shipments from Earth and the associated mission cost and complexity. In this paper, we propose a gradual strategy for the development of the ISRU capabilities through the stages of the settlement's evolution and describe the infrastructure required to support the volume of activities corresponding to the various development phases. The spatial layout of the ISRU elements is developed in coordination with the Moon Village masterplan that is documented in earlier publications. Aspects which can benefit from ISRU include oxygen and water production for propellant and life support, construction and hardware elements, electricity generation and energy storage, as well as re-use and recycling of materials brought from Earth. This proposed strategy highlights areas where technology development goals are identified which maximize opportunities for the implementation of ISRU.

I. Introduction

Plans to resume sustained exploration efforts on the lunar surface are firming up, with a number of robotic missions recently implemented or scheduled, as well as plans to send humans to these destinations in the near future[1,2]. These plans include the longer term objective of establishing a sustained human presence on the lunar surface, with the required infrastructure. The use of resources available at destination or in-situ resource utilization (ISRU) is considered essential to enable the sustainability of future long term exploration missions, as it would help to significantly reduce the dependence on shipments from Earth and the associated mission cost and complexity. ISRU could be applied to various aspects of exploration missions and ultimately to the construction, operation and

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maintenance of a permanent human settlement[3,4]. Potential uses of ISRU in this context include oxygen and water production for propellant and life support, infrastructure construction and manufacturing of hardware.

Skidmore, Owings & Merrill LLP (SOM), in partnership with the European Space Agency (ESA) and the faculty of Aerospace and Architecture at the Massachusetts Institute of Technology (MIT), have presented a concept for a permanent human settlement on the lunar surface[5,6]. While the master planning for the settlement has been reported in a previous publication[6], this article presents a gradual plan for the development of the ISRU capabilities through the successive stages of the settlement's evolution. After a review of previously reported approaches for ISRU application in lunar base concepts, the proposed phases for the settlement's evolution will be presented. For each phase, the various functions and associated activities required in the settlement will be discussed. The infrastructure required to apply ISRU to these activities will be described and the implications on the settlement layout will be derived. Such an assessment will allow to identify in the future areas where technology development is needed, in order to enable the implementation of ISRU in a lunar settlement context.

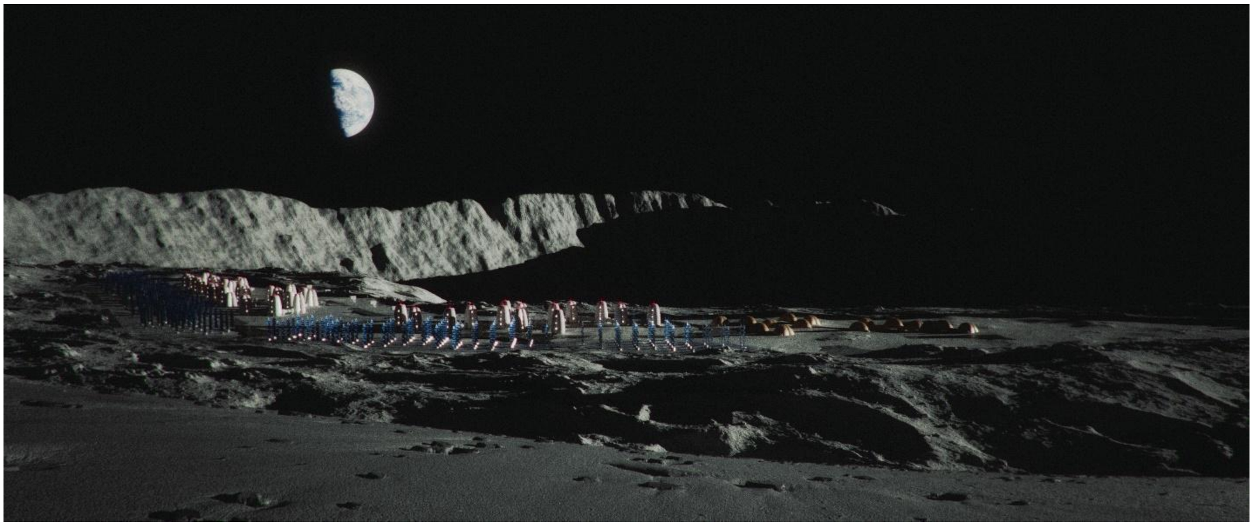

Figure 1: SOM/ESA MoonVillage concept on the rim of Shackleton Crater.

II. ISRU in Lunar Base Concepts

A number of concepts for lunar habitation and infrastructure, several of them including ISRU, have been suggested to date[9-16]. In this section, four diverse examples of lunar base concepts are discussed, with particular regards to ISRU approaches and methods. Analysis of the approaches proposed in those studies is relevant to the formulation of ISRU application scenarios in the present Moon Village concept.

A. The Robotic Lunar Surface Operations (RLSO) and RLSO2 studies

The original RLSO study[7] led by NASA and Boeing Aerospace and Electronics in 1990 had a strong focus on automated/robotic elements and ISRU. The envisioned location was a mid-latitude mare site. What makes the study stand out is its clearly defined, industrial purpose - the production of propellant from ilmenite - and its practical approach. The RLSO study generated several design recommendations which are equally relevant in the context of the Moon Village development:

- Factor in remote robotic and crew operational considerations
- Use a consistent, object-oriented model
- Minimize the in-situ effort required
- Design self-contained subsystems
- Provide non-cascading access/change-out paths
- Assure means for human activation of all tasks

- Exploit indigenous features
- Design components to be recycled

In an article introducing the more recent RLSO2 study[8], B. Sherwood, who participated in both the RLSO and RLSO2 studies, sums up and updates the findings of the original study. He suggests a set of principles as foundational design directions for a practical Moon base. The main ones are listed below:

- Most lunar base operations, most of the time, must be robotic
- Substantial base infrastructure can be constructed and base operations conducted, despite only a few short, intermittent crew visits
- Lander cargo capacity, configuration, and flight rate fundamentally affect base element design
- Autonomy and Robotics considerations are driving requirements for all base elements
- Paving routine traffic routes is the driving requirement for construction timelines
- A significant amount (~15%) of delivered mass is required for spares inventory
- Habitat systems and other complex components should not be buried directly with regolith
- Crew time is valuable; extravehicular activity (EVA) time is even more valuable. Shifting tasks from crew to robots has positive value
- Repair at the sub-component level is essential
- The number of different elements should be minimized
- The well-known challenges of lunar base concepts should be tackled directly: protecting base assets from lander jet debris, first-landing problem, regolith radiation shielding, dust control, night survival

B. The First Lunar Outpost (FLO) study

This study[9,10] conducted by NASA in 1993, outlines mission concepts to emplace the first base for permanent human presence on the Moon[9]. The study focuses on concept validation of the basic elements required for a permanent manned base, with much of the investigation dedicated to design development for the lunar habitat. The FLO was proposed to be launched in two mission stages: an unmanned first mission stage would launch and land a habitat module in a fully assembled, integrated state on the lunar surface. The second mission stage would bring a crew of four in a manned combined lander and ascent vehicle. The proposed site for the mission was an equatorial Mare region, and the mission profile intended for a crew stay of 45 days. The habitat was designed to remain situated and be reused for multiple missions, provided that all consumables were resupplied from Earth. The FLO study objectives were primarily demonstration and validation of concepts for human safety, productivity and activities in a lunar outpost. Other primary objectives included accommodating transport operation to/from the lunar surface, accommodating for scientific study throughout the mission, and exploiting in-situ resources.

The following considerations were highlighted in the FLO study:

- The FLO habitat module was to be emplaced in a fully integrated and assembled state, in acknowledgement of the needs for reduced installation complexity at the habitat site and for minimization of EVA for construction/installation activities.
- The FLO study assumed no previous surface infrastructure at the landing site, another driver for a pre-integrated habitat. This approach limits the mission site to within Mare regions; outside the Mare regions, ground surface conditions are presumed to be much less favorable for landing and transportation.
- Additionally, an unpressurised lunar rover was considered necessary to carry out EVAs, local exploration activities and transportation of cargo between habitat and the lander.
- Modularity and hardware adaptability were to be incorporated into the FLO design as much as possible, to enable reconfiguration and maintenance of the habitat/infrastructure. This was to promote longevity and flexibility of the habitat, and to allow for future expansion of the outpost once capabilities had increased.
- The problem of consumables waste was highlighted in the FLO study. In the FLO missions, all waste would be returned to Earth for processing/disposal with the returning crew.
- While ISRU is specifically mentioned as a primary objective of the mission, ISRU activities prescribed within the FLO missions were limited to technology demonstrations on the surface and in the laboratory. No consumables production or construction via ISRU was proposed.

C. Artemis/FLO

In 1992, McDonnell Douglas and Shimizu Corporation conducted a short study based on NASA's proposed Artemis automated lander and the FLO study[11], going into more detail concerning ISRU capability development. The base development is described over the course of 25 years and at the beginning comprises the same equipment and infrastructure as FLO. Starting in 1997, data would be collected, ISRU tests would be performed and Earth return samples collected with an automated lander. Two years later, humans would be sent to the lunar surface in crews of four for six-week stays in a regolith covered habitat. In 2003 the base would have grown to accommodate a crew of five astronauts, conducting astronomical studies and producing oxygen, hydrogen and helium-3. FLO's life support system would be able to recycle all water and recover oxygen from carbon dioxide. Six years later, FLO would already feature two lab modules and oxygen, hydrogen and helium-3 production plants, tended to by a crew of eight. In 2012, the base would be expanded with another two astronauts and three modules: a third lab and second habitat module, and a Mars test facility to practice and test systems and technologies or a future outpost on the red planet. The station would be solar powered. However, the ISRU facilities would be able to produce enough helium-3 nuclear fuel at that point to test a helium-3 fusion reactor. Another ten years later, the base would be an entirely closed loop system, with food production, waste recycling and a crew of 15. The Artemis/FLO study describes the slow growth of a base into a small settlement with a high level of self-sufficiency, using in-situ resources and a greenhouse to achieve that goal. While helium-3 is mined for power generation with a fusion reactor, oxygen and hydrogen are produced for fuel and the habitat's life support system. For the final phase of the Artemis/FLO plan it is envisioned that the crew of 15 can live and do research on the base with only a low frequency of cargo delivery.

D. Habot

The Habot concept[12-16], developed by Mankins and Cohen in 2000 – 2004, is a mobile habitat with the ability to land and move autonomously on the lunar surface, combining human and robotic lunar exploration capabilities. Over the duration of one to two years, several Habots would land on the Moon and gather at the base location, with the crew following after the first habitat is landed and verified. The concept's main advantages are the habitats' mobility and modularity. The mobility allows for more efficient exploration, richer science at the sites of interest and flexible site selection. The modularity provides greater systemic redundancy and economy of scale. However, the mobility comes with increased complexity and risk (i.e. modules not being able to return to the ascent vehicle or to connect), as well as the necessity for the modules to carry their radiation shielding with them. Given the modules' mobility, ISRU would likely have to be mobile and/or temporary, but is expected to be limited, in any case.

E. Comparison and conclusions drawn for the Moon Village

The principles proposed by Sherwood for the RLSO2 study are relevant to the Moon Village settlement concept. Especially the suggestion that most operations, particularly those which are physically challenging for humans, should be done robotically. Human and robotic assets should be used in the most effective way, based on which asset is more adapted to a given task. Paving firstly the landing pad, followed by all highly frequented mobility routes, is another essential principle which enhances safety and facility of operations. It is also important to consider standardization, modularity, repair and maintenance already at the system-level design, to significantly lower complexity and launch mass. The specificity of the Moon Village concept is that of an open architecture, flexible to various operational purposes. The proposed master plan and layout therefore need to keep a degree of adaptability.

The FLO approach of emplacing the habitat fully integrated and assembled has two large drawbacks: a launch mass far beyond the capabilities of currently existing launch vehicles and a heavy reliance on Earth resources. The Moon Village concept would aim to reduce these drawbacks by maximizing robotic in-situ resource utilization in the construction of habitats. Contrary to the FLO study, previous landing infrastructure is assumed when the first habitat arrives. For the present Moon Village concept with multiple separate habitats/modules, there is a similar necessity for multifunctional rovers as in the FLO study, both for local transport and exploration purposes. Applying ISRU for construction of roads, landing pads, berms and other basic infrastructure would enable landing and roving on less favorable terrain, such as the Highlands locations at the lunar South Pole. The importance of modularity and hardware adaptability is adopted in the present Moon Village concept, as it is considered vital for a long-term sustained lunar presence. The FLO approach of limiting ISRU activities to technology demonstrations is not sufficient for our concept of a self-sustaining Moon Village scenario. In addition, waste being returned to Earth for processing/disposal should be avoided in a self-sufficient Moon Village context – infrastructure should be put in place to recycle waste where possible, and safely store waste where not possible.

	RLSO	RLSO2	FLO	Artemis/ FLO	Habot	Moon Village
Importance of (remote) autonomous/ robotic operations	+	+				+
Landing pad/frequented route preparation essential		+	-			+
Lander capacity/configuration fundamental for base element design		+			+	+
Standardization, modularity, repair and maintenance consideration already at system-level design		+	+		+	+
Use of in-situ resources (e.g. fuel/power generation, construction, food production)	+	+	only tech. demos	+		+
Design of recyclable components	+		-	+		+
Adaptability, flexibility to various operational purposes and conditions			+		+	+
Minimization of EVA		+	+			+
Base development in stages				+		+
High level of self-sufficiency				+		+

Table 1: Comparison of design principles with regards to their relevance for the different lunar base concepts

Similar to Artemis/FLO, achieving a high level of self-sufficiency is a major goal of the Moon Village concept. Equally, ISRU plays a key role in achieving this objective. However, in the later phases of the development, the purpose of the present Moon Village goes significantly beyond a small research base. Apart from governmental space agencies, public and private research institutions, as well as private companies and individuals are expected to operate in the Moon Village. Therefore, the development of the base needs a high degree of flexibility and plans for the early phases need to incorporate growth capability.

Whilst the Habot provides great flexibility and adaptability to changing mission goals, in the context of the Moon Village the advantages of a stationary base outweigh the flexibility of a mobile habitat. Power supply, ISRU, radiators, landing pads and mobility paths on a stationary base can be permanent and hence more powerful. Habitats can be larger and inflatable, and regolith can be used for ISRU radiation and micrometeoroid and debris shielding. Planning for one terrain and location only and using modular habitat architecture also limits the complexity of the base. The penalty associated with a stationary base is that it requires moving all non-mobile assets from the landing pad to the base site with heavy equipment movers. In addition, pressurized rovers are necessary to perform excursions away from the base.

III. Phases of the Moon Village Settlement's Evolution

The development of the Moon Village settlement, from the preparation of the site to a full self-sufficient base is proposed to be staged in phases. For each phase, a set of functions need to be available for the installation and operation of the settlement and the support of the crew. Fulfilling those functions implies performing certain activities, for which infrastructure elements and hardware – developed on site or delivered from Earth – are required. The following sections describe the functions, associated supporting activities and required infrastructure, for each of the successive phases. In each phase, the contribution of ISRU to those activities and the implications on the layout of the ISRU areas in the settlement is discussed.

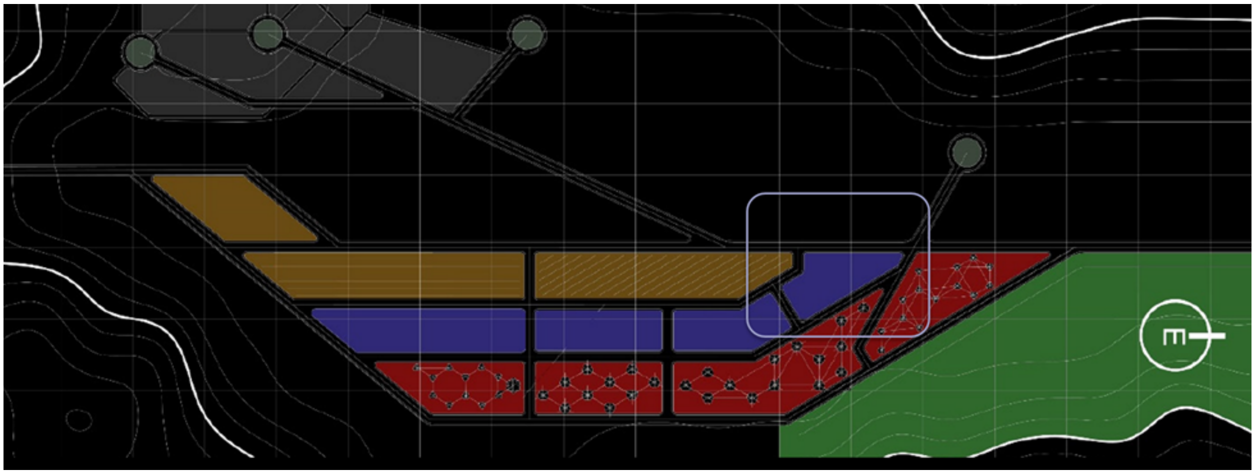

Figure 2: Master plan of the Moon Village composed of a series of linear bands of development. The ISRU plant described in this paper is located in the highlighted area.

One of the first goals of Moon Village ISRU would be the use of the lunar environment's intrinsic resources: surface regolith that is abundantly available and rich in oxides, and water ice for the production of oxygen and water. This could be achieved through thermo-chemical reduction of lunar regolith. Furthermore, surface regolith could be used as is for radiation protection and processed for construction purposes (e.g. sintering for landing pad and road construction). The beneficiation of lunar regolith for space resource utilization is currently being investigated by the European Space Agency and many other research institutions worldwide as well as commercial entities.[17-19].

Due to the absence of direct observation measurements of resource quantities and lack of insights into resource accessibility, we base our assumptions on data from lunar surface probes (Apollo, Luna) and more recent lunar orbiters and impactors (Clementine, Lunar Prospector, LRO, Chandrayaan-1, LCROSS) and the SOFIA stratospheric observatory[20-25]. We make the assumption that a Moon Village base situated near those resources, particularly water ice resources that are possibly available in the Shackleton crater, could supposably excavate and beneficiate them in-situ to provide for base consumables, including propellants needed for round trips between the Moon Village and the Lunar Gateway. In addition, the near constant illumination at the crater rim of the South Polar region could provide large quantities of solar power that would be required for mining and processing activities.

Similar to RLSO2, and based on the Moon Village Concurrent Design Facility (CDF) study that was conducted in March 2020 at the ESTEC (NL) location of the European Space Agency, solar power constitutes a main pillar of the power infrastructure of the Moon Village. A nuclear fission power plant would provide a compact, efficient option to power mining activities (due to a lower sensitivity to dust and debris than PV panels exhibit) and as contingency power infrastructure[26]. At all development phases, the Moon Village photovoltaic infrastructure ought to provide arrays of PV panels and power transmission units, batteries for power storage and charging units, that facilitate robotic- and/or self-deployment.

IV. Phase 0

Phase 0 consists of the preparation of the settlement site before delivery of the habitat modules in Phase 1 and arrival of the crew in Phase 2. During the first, unmanned phases (0 and 1) availability and accessibility of local resources will be investigated and future development phases and missions will be adapted accordingly.

A. Functions, supporting activities and equipment

The functions required during this phase are:

- Solar power production on ground from photovoltaic panels
- Energy storage via regenerative fuel cells (RFC)
- Nuclear fission power production with a reactor (NFP)[27]
- Construction: landing pad and infrastructure, unpressurised dust mitigation shelter for equipment storage
- Oxygen/Water extraction from regolith for propellant production: in-situ propellant production is not conducted during Phase 0, but installation and testing of the process is considered important
- Communication

To fulfill these functions, the following supporting activities are required:

- Regolith excavation
- Regolith beneficiation for input in the oxygen/water extraction or construction processes: beneficiation involves sorting of particle size distribution or composition, depending on the process)
- Boulder removal

The equipment needed to perform those activities and achieve the identified functions includes:

- Photovoltaic panels
- Regenerative fuel cell (RFC)
- Nuclear fission power plant
- Communication towers
- Excavating rovers
- Beneficiation unit: sieves, electrostatic/magnetic beneficiation system
- Oxygen/water extraction unit
- Storage units (to be used in the future, but installed during Phase 0) for the products (oxygen, water, by-products from water extraction i.e. reduced metals)
- Landing pad construction unit: rover applying energy (e.g. microwave, laser or solar sintering)[28] or binder, boulder removal unit
- Berm and equipment storage shelter construction unit: additive manufacturing unit
- Redundancy: several items of construction units

It should be noted that delivery of the equipment required to perform the supporting activities is assumed and is not considered in the scope of this assessment.

B. ISRU layout implications in Phase 0

1. ISRU area

In Phase 0, no fuel will be produced yet. However, infrastructure will be set up, so production can start immediately at Phase 1. The area dedicated to ISRU in the Moon Village settlement needs to feature at least the following connections to the rest of the base's areas:

- Power transmission from the power production plant/area
- Transportation connection to the launch and landing site
- Transportation connection to the habitation area

During Phase 0, the ISRU area will feature two main activities: testing of oxygen and water extraction from regolith for propellant production (assessing availability and accessibility, testing and optimizing processes), and construction of infrastructure (i.e. landing pad, storage shelter). Both of the propellant production testing and the preparation of construction activities should be located between what will become the habitation area in the next phase and the launch and landing facilities. The propellant production area needs to be located closer to the refueling station and the construction facilities should be located closer to the habitation area. As the propellant production unit and the refueling station will be located close to the landing area, the equipment needs to be sheltered from potential debris. In addition to the tanks for cryogenic propellant storage, the ISRU area should also provide sufficient storage containers for the by-products from oxygen/water extraction, i.e. reduced metals for later production processes. It is important that at Phase 0, sufficient space is allocated for sequent developments. The first regolith beneficiation unit in Phase 0 is envisaged to be a pilot plant with not more than 500 kg of capacity[29]. In the later phases, fuel production is expected to become a major activity. While regolith excavation will likely move to adjacent areas over the following years, the area for the beneficiation facility should stay in place and have sufficient space to develop, in order to produce enough fuel for 4-8 round-trips to the Lunar Gateway per year in Phase 3. According to Elliott et al. this would require 160-320 t of fuel, and the processing of up to 90 000 t of regolith[30].

2. Power generation area

During Phase 0 the base is to be prepared for the arrival of the first habitat. No human crew would be on site yet, but the preparation of the surface base (i.e. primarily the construction of the landing site and installation of the infrastructure) and ISRU testing activities will require a reliable power infrastructure. Robotic operations would comprise setting up the power and telecommunications infrastructure, unpressurized dust mitigation shelters for equipment and preparation of the landing pad via microwave sintering[28]. This would amount to an estimated 4 kW of power requirement for base operations and communications, another 10 kW for testing of water and oxygen extraction processes and 10-40 kW for construction work for landing site and infrastructure preparation during Phase 0. The power source for base operations, communications, and ISRU testing would be solar, with ~78 m^2 photovoltaic panels on ground. It is essential that the photovoltaic panels be as close as possible to the habitation, science and ISRU areas to avoid transmission losses. However, they should be as far from the launch and landing area and excavation zones as possible. This is to avoid that any activity on the base, which produces dust, inhibits solar power generation and reception. Energy storage units should be located as close to the consumer as possible to avoid transmission losses. To provide power for the landing site preparation and charging power for rovers that install the base infrastructure, one 40 kW nuclear fission power plant[27] (NFP) would be installed about 200 m from the dedicated landing site.

Phase 0 - Power requirements	
Power required	**54 kW**
Base operations, Communications	4 kW
ISRU testing	10 kW
Landing site preparation, infrastructure installation	10-40 kW
Power from nuclear fission plant (NFP)	40 kW
Power from PV panels required	~23.4 kW
PV panel area required	~78 m^2
Ground area required	NFP: ⌀ 50 m (>200 m from the landing site area) PV panels: ⌀ 30 m

Table 2: Estimated power requirements during Phase 0 of the Moon Village. Estimates for ground area requirements are based on Halbach et al.[31] and Mason and Poston[27]. Estimates of power requirements from PV panels, using RFCs for energy storage, are based on a solar power study for the Moon Village by the ESA Concurrent Design Facility (CDF)[26]. Assumptions: Darkness duration (max.) of 120 hours; Accumulated sunlight at settlement site of 80%; Power management and distribution (PMAD) overall efficiency of 90%; RFC round-trip efficiency of 55% (low efficiency of RFC chosen over battery due to substantially lower mass).

3. Launch and landing site

The launch and landing site most importantly will need to feature a launch and landing pad, a refueling depot and navigation equipment/beacons. Eckart et al[29] recommend the landing pad to be a couple hundred square meters large and that the location should be about 1-5 km away from the other areas, to protect them from blast debris. A pressurized rover and utility rovers will provide for transportation of crew and cargo from and to the landing and launch area. It is important to ensure that the habitation zone is not crossed over by take off and landing trajectories[29]. The same applies to the power generation zone, if a main power source is photovoltaic cells. To reduce blast debris and erosion of the site, the ground needs to be paved (e.g. via microwave sintering) or at least bermed to minimize maintenance and damage hazards. Roads to and from the landing site should be stabilized to ease transportation.

The refueling depot must provide refueling and storage equipment. The storage of the cryogenic propellants needs to be temperature controlled to avoid boil-off (e.g. by burying the tanks, keeping them in a shelter, or using heavy Kevlar tanks with multi-layer insulation (MLI)). The tanks and equipment must facilitate refueling and survive impacts of debris. Extension in further development steps of the base should be anticipated with sufficient space (e.g. for additional/larger refueling and storage equipment). During Phase 0 no significant amounts of fuel will be produced yet, however, the installation of the refueling depot will start.

V. Phase 1

In Phase 1, the first habitat module is delivered. The construction on the site continues – providing radiation shielding, mobility and equipment storage – as the volume of activities in the settlement expands.

A. Functions, supporting activities and equipment

The functions required during this phase are:

- Solar power production on ground from photovoltaic panels
- Energy storage via RFCs
- Nuclear fission power production with a reactor
- Oxygen/water extraction from regolith for propellant production for ascent/descent modules
- Water extraction from ice deposits in constantly shaded craters for propellant production
- Construction: radiation shielding, roads and pads, unpressurized equipment storage and shelter, berms
- Communication

To fulfill these functions, the following supporting activities are required:

- Testing additive manufacturing processes with regolith binder (e.g. lunar geopolymer[32-33], sorel cement[34])
- Regolith excavation
- Regolith beneficiation for input in the oxygen/water extraction or construction processes
- Boulder removal

The equipment needed to perform those activities and achieve the identified functions includes:

- PV Panels: delivery of more panels to the surface to match growing number of equipment
- Regenerative fuel cells to support the solar power plant
- Nuclear fission power plant
- Communication towers
- Excavating rovers
- Beneficiation unit: sieves, electrostatic/magnetic beneficiation system
- Oxygen/water extraction unit: additional units to start production of propellant and test the production of life support consumables
- Water extraction from ice deposits: rovers to collect ice or ice evaporation systems inside permanently shadowed craters and water transportation systems
- Storage unit for the products (oxygen, water, by-products from water extraction i.e. reduced metals)

- Landing pad construction unit: rover applying energy (e.g. microwave, laser, solar) or binder (e.g. lunar geopolymer, sorel cement), boulder removal unit
- Berm and equipment storage shelter construction unit: additive manufacturing unit applying energy or binder. Additional storage shelters are built to match increasing amount of equipment delivered to site
- Road construction: boulder removal, rover applying energy or binder, or construction using boulders
- Radiation shielding protection of habitat: additive manufacturing units (might be the same as storage shelter construction units, but more likely AM with binder
- Redundancy: several items of construction units

B. ISRU layout implications in Phase 1

In general, the experiences gained with ISRU production in the previous phase will be applied to larger scale activities in Phase 1. Therefore, the type and location of facilities will largely stay the same, yet their size and the number of equipment will increase.

1. ISRU area

During Phase 1 of the Moon Village development, the construction facilities will be to a large extent mobile. The increased productivity and more complex construction works in the habitat area will require more, (and more sophisticated) equipment, utility and pressurized rovers. For this reason, new facilities to store, protect, maintain and repair this equipment and rovers will be built in the ISRU area. Due to the large increase in the volume of ISRU activities for extraction of oxygen, water and construction materials, a sharp rise in regolith excavation activity is to be expected. Mining areas should generally be as close to production facilities as possible. However, the excavation area cannot be located in close proximity to the solar power plant due to the hazard of dust affecting the photovoltaic cells. Thus it will obtain its power supply from a nuclear fission power plant.

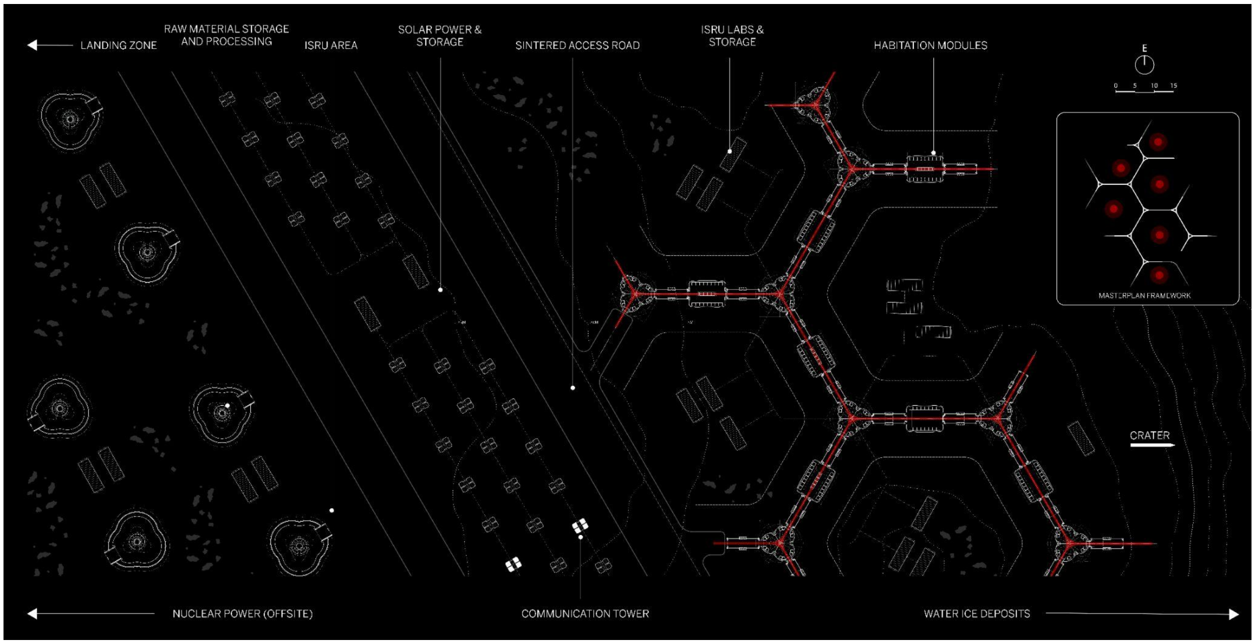

Figure 3: Detail of the Moon Village masterplan showing spatial relationship between various ISRU components.

2. Power generation area

During Phase 1 no crew is on site yet. This step in the development is used to set up the surface base and more infrastructure, prepare it for human occupation and use, and extend ISRU research and operations. Part of this effort will be to produce and store 40 tons of LH_2 and LOx as fuel (to support crew transport to and from the Lunar Gateway). Another 7.5 tons of water should be produced for the first habitat's LSS in preparation of the crewed missions. Taking the recommendations of Polit-Casillas et al.[35] of the RLSO2 study as a basis, we estimate that the power requirements for ISRU operations (fuel and LSS water production of 47.5 tons) will be around 152 kW. Base operations and communication are estimated to take another 3 kW, robotic construction and infrastructure installation will require 10 kW. Overall, we estimate that during Phase 1 the power supply infrastructure of the Moon Village should provide 165 kW.

Phase 1 - Power requirements	
Power required Base operations, Communications ISRU operations Robotic construction, infrastructure installation	**165 kW** 3 kW 152 kW 10 kW
Power from NFP	40 kW
Power from PV panels required	~209 kW
PV panel area required	~697 m^2
Ground area required	NFP: ⌀ 50 m (>200 m from the habitation area) PV Panels: ⌀ 75 m

Table 3: Estimated power requirements during Phase 1 of the Moon Village. Estimates for ground area requirements are based on Halbach et al.[31], and Mason and Poston[27]. Estimates of power requirements from PV panels, using RFCs for energy storage, are based on a solar power study for the Moon Village by the ESA Concurrent Design Facility (CDF)[26]. Assumptions: Darkness duration (max.) of 120 hours; Accumulated sunlight at settlement site of 80%; Power management and distribution (PMAD) overall efficiency of 90%; RFC round-trip efficiency of 55% (low efficiency of RFC chosen over battery due to substantially lower mass).

3. *Water extraction area*

As described in section A above, an important new activity will be the extraction of ice deposits from the permanently shadowed crater. The water extraction facility will be located in the crater area which is closest to the ISRU area zone. Laser power beaming will power mobile excavators/beneficiators when mining in a constantly shaded crater. Besides the facilities for water extraction, it is important to provide suitable (temperature controlled to avoid boil-off) and sufficient containers for storing the water (e.g. underground or sheltered tanks, heavy Kevlar tanks with multi-layer insulation).

VI. Phase 2

In Phase 2, the first crew (4 persons) arrives at the settlement, landing pad capability is extended, new habitat modules (intended for science activities, technology development, commercial activities) with associated power capability (solar and nuclear fission) and pressurized rovers for crew mobility are delivered. The construction of the site continues, radiation shielding infrastructure, mobility and equipment storage is extended. ISRU-based regenerative power capability is assessed to determine further possibilities for sustainable power sources. First experiments on in-situ food production are conducted and refined manufacturing processes are developed.

A. Functions, supporting activities and equipment

The functions required during this phase are:

- Solar power production on ground from photovoltaic panels
- Energy storage via RFCs (assessment of H and O from harvested/extracted water)
- Nuclear fission power production

- Oxygen/water extraction from regolith for: propellant production for ascent/descent modules, life support, and food and biomaterial production experiments
- Water extraction from ice deposits for: propellant production, life support, and food and biomaterial production experiments
- Construction: radiation shielding, roads and pads, unpressurized equipment storage and shelter, berms
- Communication
- Non-recyclable waste storage
- Recycling of recyclable waste for hardware manufacturing and construction

To fulfill these functions, the following supporting activities are required:

- Regolith excavation
- Regolith beneficiation: testing/performing refined beneficiation processes for more complex hardware manufacturing (e.g. solar cells, electronics, resins)
- Boulder removal

The equipment needed to perform those activities and achieve the identified functions includes:

- PV Panels: delivery of more panels to the surface to match growing number of equipment
- Nuclear fission power plants: delivery of 2-3 new reactors
- RFCs to support solar power plant
- Communication towers
- Excavating rovers
- Beneficiation units: sieves, electrostatic/magnetic beneficiation system
- Oxygen/water extraction unit: additional units to sustain production of propellant and life support consumables and start experiments on water for food/biomaterial production
- Water extraction from ice deposits: additional units to sustain production of propellant and life support consumables and start experiments on water for food/biomaterial production
- Storage unit for the products: oxygen, water, by-products from water extraction (i.e. reduced metals)
- Construction unit: rover applying energy (e.g. microwave) or binder (e.g. geopolymer); boulder removal unit
- Berm and equipment storage shelter construction unit: additive manufacturing unit (same as for landing pad construction or separate). Additional storage shelters to match increasing amount of equipment delivered to site with the new habitat modules and new activities
- Road construction: boulder removal, rover applying energy (e.g. microwave, laser, solar) or binder, or construction using boulders. More roads are needed to connect the newly delivered modules
- Radiation shielding protection of habitat: additive manufacturing (AM) units (same as storage shelter construction units). More shielding required for additional habitat units
- Non-recyclable waste storage: storage units
- Recycling of recyclable waste for hardware manufacturing and construction: processing units
- Redundancy: several items of construction and manufacturing units

B. ISRU layout implications in Phase 2

Phase 2 sees the further extension and sophistication of the ISRU facilities in the Moon Village development.

1. ISRU area

One interesting new aspect will be the setting up of recycling facilities and waste storage for non-recyclable items. The recycling facilities will be located in the ISRU area, in part because the facility will require similar equipment and a similarly trained workforce, but also for logistic purposes, as a large part of the recyclable material will originate in the ISRU area.

Furthermore, an increasing amount of extracted products and by-products will require more sophisticated storage facilities and increased logistic activity. This will require construction and/or excavation work to build facilities that can store materials with increasingly strict storage requirements (e. g. temperature controlled, radiation protected).

Due to an increase in logistic and construction activity, more stabilized roads will be needed to make mobility safer, faster, and minimize maintenance work. The majority of those roads will connect the habitat area to all other areas of the Moon Village. In addition, the road connection between the ISRU area and the launch and landing site with the propellant storage and refueling facilities will be extended and improved.

2. Power generation area

The Moon Village activities concerning ISRU and base operations during Phase 2 are similar to the ones in the RSLO2 study and our preliminary estimations are based on the calculated power requirements of the RSLO2 study. However, for the Moon Village study we assume that the base, once it is occupied by humans, will be constantly inhabited and crewed mission durations will last between 300 and 500 days.

Based on a study conducted at the Concurrent Design Facility (CDF) of the European Space Agency (ESA) in March 2020, the Moon Village during its first phase of human occupation (one habitat, crew of four) would have a continuous power requirement of 59 kW for the habitat alone. We estimate that base operations would require another 6 kW and ISRU production of 80 tons of fuel (1 launch/round trip to Lunar Gateway for the exchange of crew and 1 contingency launch) would, with calculations based on the RSLO2 study, require 256 kW.

Phase 2 - Power requirements	
Option 1 - Solar power (67%) and NFPs (33%)	
Power required	**363 kW**
Habitat	59 kW
Base operations, Communications	6 kW
ISRU operations	256 kW
Robotic construction, infrastructure installation	42 kW
Power from 3 NFPs	120 kW
Power from PV panels required	~406 kW
PV panel area required	~1353 m^2
Ground area required	NFPs: 3 x ∅ 50 m (>200 m from the habitation area) Solar Panels: ∅ 100 m
Option 2 - Solar power (56%) and NFPs (44%)	
Power required	**363 kW**
Habitat	59 kW
Base operations, Communications	6 kW
ISRU operations	256 kW
Robotic construction, infrastructure installation	42 kW
Power from 4 NFPs	160 kW
Power from PV panels required	~339 kW
PV panel area required	~1132 m^2
Ground area required	NFPs: 4 x ∅ 50 m (>200 m from the habitation area) PV Panels: ∅ 80 m

Table 4: Estimated power requirements during Phase 2 of the Moon Village. Estimates for ground area requirements are based on Halbach et al.[31]*, and Mason and Poston*[27]*. Estimates of power requirements from PV panels, using RFCs for energy storage, are based on a solar power study for the Moon Village by the ESA Concurrent Design Facility (CDF)*[26]*. Assumptions: Darkness duration (max.) of 120 hours; Accumulated sunlight at settlement site of 80%; Power management and distribution (PMAD) overall efficiency of 90%; RFC round-trip efficiency of 55% (low efficiency of RFC chosen over battery due to substantially lower mass).*

VII. Phase 3

During Phase 3, advanced scientific equipment is installed on site, in-situ food production is developed, a food production module is delivered to the surface, additional crew members arrive on site, and waste management technologies are fully implemented.

A. Functions, supporting activities and equipment

The functions required during this phase are:

- Solar power production on ground from photovoltaic panels
- Energy storage via RFCs (potentially H and O from harvested/extracted water)
- Nuclear fission power production
- Oxygen/water extraction from regolith for: propellant production for ascent/descent modules, life support, food and biomaterial production
- Water extraction from ice deposits for: propellant production, life support, food/biomaterial production
- Construction: radiation shielding, roads and pads, unpressurized equipment storage and shelter, berms
- Communication
- Non-recyclable waste storage
- Recycling of recyclable waste for hardware manufacturing and construction
- Material processing for complex manufacturing: by-products from oxygen extraction i.e. metals, silicon extraction, fibres drawing, ceramic and glass material production
- Investigation into availability and extraction of helium-3 and feasibility of nuclear fusion on site

To fulfill these functions, the following supporting activities are required:

- Regolith excavation
- Regolith beneficiation: refined beneficiation processes for complex hardware manufacturing
- Boulder removal

The equipment needed to perform those activities and achieve the identified functions includes:

- PV Panels: delivery of more panels to the surface to match growing number of equipment
- Nuclear fission power plants: delivery of more reactors to match growing number of equipment
- RFCs to support solar power plant
- Communication towers
- Excavating rovers
- Beneficiation unit: sieves, electrostatic/magnetic beneficiation system
- Oxygen/water extraction unit: additional units to sustain production of propellant and life support consumables and start production of water for food/biomaterial production
- Water extraction from ice deposits: additional units to sustain production of propellant and life support consumables and start production of water for food/biomaterial production
- Storage unit for the products (oxygen, water, by-products from water extraction i.e. reduced metals)
- Landing pad construction unit: rover applying energy (e.g. solar, microwave, laser) or binder (e.g. geopolymer or sorel cement), boulder removal unit
- Berm and equipment storage shelter construction unit: additive manufacturing unit (same as for landing pad construction or separate). Additional storage shelters to match increasing amount of equipment delivered to site with the new habitat modules and new activities
- Road construction: boulder removal, rover applying energy (e.g. microwave, laser, solar) or binder, or construction using boulders. More roads are needed to connect the newly delivered modules
- Radiation shielding protection of habitat: additive manufacturing units (same as storage shelter construction units). More shielding required for additional habitat units
- Non-recyclable waste storage: storage units
- Recycling of recyclable waste for hardware manufacturing and construction: processing units
- Redundancy: several items of construction and manufacturing units

B. ISRU layout implications in Phase 3

Besides the advancement and extension of technologies and infrastructure which are already in place, Phase 3 of the Moon Village development sees the introduction of material processing facilities for complex manufacturing (e.g. from by-products of oxygen production). Those facilities should have easy access to storage facilities of the raw materials, and will likely have very similar requirements than other production facilities already in place. A more significant step will be an investigation into helium-3 availability and extraction, its viability for export to Earth, but also for the introduction of a lunar fusion reactor. Due to the Moon's exposure to large quantities of helium-3 by solar wind, the suggestion that this isotope could provide safer nuclear energy in a fusion reactor — since it is not radioactive and would not produce dangerous waste products — has been made by some experts[36-38]. However, so far no helium-3 fusion reaction with a net power output has been demonstrated, nor have significant quantities of helium-3 been detected on the lunar surface.

If, in the coming decades, it can be successfully demonstrated that helium-3 fusion reactors can provide safe and efficient nuclear energy, this option should be investigated as possible power provision for the Moon Village. If suitable helium-3 mining grounds can be found within ca. 50 km of the Moon Village area, the area should be connected via new roads to the launch and landing area as well as to a lunar fusion reactor demonstrator sent from Earth. The demonstrator facility should be close to the mining grounds to minimize logistic effort and in a safe distance (>10 km) from the habitat area to increase safety for the Moon Village settlement, while still in the testing phase.

During Phases 0-2, many new insights into operational experience, availability of resources, technological developments and effects of environmental conditions will be gained. This means that later missions will be adapted (according to) the new conditions and circumstances. Due to the many unknown factors at Phase 3 of the Moon Village we only give a very rough estimates for power requirements:

Phase 3 - Power requirements	
Power required	>500 kW
Ground area required	>20 000 m^2

Table 5: Rough estimates for power requirements during Phase 3 of the Moon Village. Estimates for ground area requirements are based on Halbach et al.[31], and Mason and Poston[27].

VIII. Conclusion

In this paper we present a proposal for the implementation of in-situ resource utilization in the context of a Moon Village settlement. Previously proposed lunar base concepts were reviewed regarding their approach and guidelines to the application of ISRU. The concepts were compared and conclusions for the presented Moon Village ISRU proposal were drawn. A gradual plan for developing ISRU capabilities, the functions, supporting activities and necessary equipment were identified through successive development stages of the lunar surface base. The evolution of the settlements infrastructure/facilities required to apply ISRU were described and the implications on the settlement layout were derived.

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