Future Space Architecture

Cross-Functional Multidisciplinary Design and Engineering

Daniel Inocente[1], Colin Koop[2] , and Georgi Petrov[3]
SOM, New York, NY,10005, United States

Piero Messina[4], Isabelle Duvaux-Bechon[5]
European Space Agency (ESA), Paris, 75007, France

Advenit Makaya[6], David Binns[7], David Brandao[8] and Robin Biesbroek[9]
ESA, European Space Research & Technology Centre (ESTEC), Keplerlaan, Noordwijk, 2200 AG, Netherlands

Skidmore, Owings & Merrill LLP (SOM), the European Space Agency (ESA), and faculty in the Department of Aeronautics and Astronautics and Medial Lab at the Massachusetts Institute of Technology (MIT), first established a partnership in 2018 to explore aspirations for a permanent lunar settlement through cross-industry collaboration to influence future thinking about sustainable exploration architectures. The idea for a "Moon Village" presented by the ESA Director General Johann-Dietrich Wörner, inspired this partnership to envision an open architecture based on global cooperation for the common objective of enabling long-term sustainable human exploration and development on the Moon. In 2019 the partnership unveiled the first glimpse into this multidisciplinary project revolving around principles of resiliency, self-sufficiency, and a next-generation integrated habitat architecture. In January of 2020, a Memorandum of Collaboration (MOC) was signed at ESA's headquarters and the cooperation was extended to advance habitat architecture with an emphasis on concurrent design and engineering of concepts for a multi-functional integrated habitat. The evolution of this collaboration initiated a study within ESA's Concurrent Design Facility (CDF), to conduct a cross-disciplinary study, encouraging design innovation and the application of alternative engineering methodologies. The partnership centered on the need for international cooperation to support innovative concepts and technology program capabilities that bring commercial and government closer together, fostering new ideas that align with reaching exploration goals toward the utilization of space resources and human access to planetary surfaces including the Moon and Mars.

I. Introduction

The partnership between ESA and SOM represents a paradigm shift in space research initiatives and offers insights that only cross-sector entities working together to envision humanity's future in space can achieve. This initiative is founded on the premise that research and development in space can benefit all of science, art, industry, technology, and society. Today, we see the increased participation and cooperation between international partnerships covering a wide range of space activities. It is also demonstrated in the transition of space activities going from being an exclusive domain to widespread participation from actors across nations, including private companies, industry, academia, and the public. The next era of space research and development will fundamentally transform the future of scientific cooperation and the global interactions between disciplines will play an important role. Out of this will emerge opportunities for advancing technologies and methodologies across disciplines in unpredictable ways, many of which will lead to the future success of human activities beyond Earth along with major advancements in terrestrial technologies.

The resulting concepts generated during the SOM and ESA partnership addressed the technology development needs of current and near-term technologies to make possible a next-generation surface habitat. The habitat was designed to integrate numerous research activities: emphasizing human and robotic exploration, anticipating ISRU development, and the testing of construction techniques with surface systems. The case study integrated functions required to confront extreme temperatures, exposure to ionizing radiation, and abrasive lunar dust among other requirements. The design addressed safety, efficiency, and human-centered systems – to support health, eating, sleeping, exercise, personal hygiene, waste management, and performance functions.

The CDF included a multidisciplinary team of experts to carry out a study that looked into the conceptual definition of a lunar habitat architecture as a precursor for a multi-partner human settlement named the “Moon Village” illustrated in **Figure 1**. An in-depth study of the architecture included mission concept design and systems engineering over a series of intense sessions conducted by the multidisciplinary team at the European Space Research & Technology Centre (ESTEC). The ESTEC team composition included expertise from (Systems, Mission Architecture, Structures, Thermal, Materials & Processes, Mechanisms, Radiation, Power, Life Support, Advanced Concepts, GNC, ISRU, Safety, and Architecture). The primary mission objectives included establishing a well-defined boundary condition for the habitat concept, identifying the requirements for the lunar environment including thermal, power, and environmental protection as well as others. The objectives also included defining a design reference mission, the concept of operations, analysis of operational costs, and trade space to launch, transfer, deliver, and deploy the habitat architecture. This paper summarizes many of the findings discovered during the CDF and the report generated from that effort.

Figure 1: Moon Village Earth Rise Visualization

Source: Inocente et.al "Master Planning and Space Architecture for a Moon Village: 70th International Astronautical Congress, 2019.

II. Methodology

Traditional methods in aerospace engineering and design for entirely new and complex architecture systems involves step by step development processes. These traditional methods progress through a sequence of tasks, moving from one system expert to another without direct and real-time coordination between all team members. The Concurrent Design Facility offers an entirely new method for tackling complex aerospace challenges and provides a platform to exercise a uniquely integrated methodology involving all team members at the same time in a state of the art facility equipped with hardware, software, and communication technologies to create a multidisciplinary environment. [1]

The complexity of designing a surface habitat inspired the SOM-ESA partnership to utilize the capabilities of the CDF, enabling the entire specialist team across disciplines to work together in real-time and evolve an integrated lunar surface habitat architecture with all critical systems considered. The CDF team was led by Team Leader Robin Biesbroek and Study Manager, Advenit Makya over a series of six technical sessions together with participation by the SOM team. Additionally, interested European entities were invited as observers to join the sessions with multiple opportunities to share thoughts and engage with the group.

The primary and secondary objectives of this study are presented in **Table 1** and selected portions covered in more detail in this paper to provide an insight into the level of technical design and engineering required for a mission of this magnitude.

CDF Study Primary Objectives:
1. Review the boundary conditions of a habitat concept study
2. Identify requirements of the habitat module concerning the lunar environment:
a. Thermal
b. Power
c. Environment (including Radiation shielding/Micrometeoroid/Dust)
3. Define Habitat functional design features:
a. Power (solar, nuclear, energy storage)
b. Thermal
c. Material selection (safety aspects)
d. Interface between the inflatable shell and rigid structure
e. Deployment mechanisms: Inflatable Shell & Secondary floor structures
f. Airlocks including interface with shell
g. Radiation Protection Systems (Water, Composites, Multi-Layer)
h. Life Support
4. Define Habitat Interior design features:
a. Mobility
b. Safety
4. Standards/interfaces
CDF Study Secondary Objectives:
5. Define a rough Concept of Operation and ROM Running Costs for the Habitation Module
6. Propose a baseline for launch and delivery to the lunar surface:
a. Launcher selection (Mass & Volume Constraints)
b. Propulsion, GNC (trading off alternatives: integrated to the habitat vs additional vehicle)
c. Delivery to the lunar surface (trading off alternatives: directly vs Gateway, Transport Vehicle, Surface Manipulation System)
7. Assess ISRU (Optional)
a. Shell requirements: thickness, mechanical properties, porosity
b. Applicable manufacturing processes

Table 1: CDF Objectives

Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

III. Requirements and Design Drivers

The proposed lunar surface habitat is a hybridized class 2 type structure as defined by Cohen [2] [3] with an expandable environmental and protection shell system that interfaces with multiple rigid structural and non-structural elements. The hybridized solution presented multiple challenges and opportunities with regards to delivery, deployment, and survival during delivery and once in operation on the lunar environment. The functions of the habitat included a broad spectrum of programmatic uses enabled by the increased usable volume and surface area distributed throughout the multiple levels. The mission requirements and design drivers are taken from the detailed report and listed below [4]:

Habitat Features, Functionalities, and Design:

- Ability to accommodate a crew of 4 people and support Mission Duration up to 500 consecutive days for a given crew.
- When deployed on the lunar surface, the Habitat and respective support systems shall be able to provide functions for Crew Habitation as well as support to Science and Surface operations, including crew access to and from the lunar surface.
- Sufficient radiation protection to ensure exposure is within maximum allowable exposure levels for the crew over the mission duration, accounting for both periods of a nominal and solar event external radiation levels.
- A 10-year lifetime after deployment on the moon surface.
- The location is to provide access to resources, optimal illumination conditions, and scientific interest.

Launch, Transfer, and Delivery:

- Compatibility with current state-of-the-art launcher capabilities.
- The Habitat and required support components shall be transferred into an appropriate Lunar Orbit, and then from lunar orbit to the moon surface.
- Surface transfer to the final location and deployment on the moon surface.

A. Concept of Operations

The habitat was designed to be manufactured, tested, and launched from Earth with either all or a significant amount of its internal equipment pre-integrated into the structure. The hybrid design includes several deployable systems such as exterior shell, floor system, and multi-purpose racks which would be configured and secured in a stowed condition during launch. During the transfer from Low Earth Orbit, a series of maneuvers were considered depending on the selected launcher capabilities and transfer strategy. Once the habitat and transfer vehicle reach Lunar Orbit, the habitat and required infrastructure are to be transferred to the selected site at the south pole near Shackleton Crater. The high mass lander element required would need a landing precision of 300 m 3-sigma with a minimum distance to the target site that minimizes the hazards of dust ejection and projectile to other vital equipment. Once on the surface, the habitat is to be transferred to the building site already prepared for full deployment and emplacement, securing the structure to the ground, performing any additional teleoperated site work necessary and initiating deployment, environmental systems, and atmospheric pressurization. Once fully deployed, remote testing of internal equipment for nominal performance is performed before initiating occupancy procedures. At this point, the crew arrives, performs any pending deployment activities, and occupies the habitat. The 1st crew will perform essential infrastructure priorities requiring numerous extra-vehicular surface activities for the duration of the mission with subsequent crew rotations to allow for continuous use of the habitat as a staging point on the lunar surface from which to conduct science, industrial and exploration objectives. The habitat is designed to remain flexible so that a wide range of mission scenarios can be accommodated requiring resupply of cargo and consumables. [4]

B. System Requirements

ESA's mission performance requirements during the CDF assessment were inspired by the utilization of the International Space Station to meet specific performance guidelines but the design under development is unique in regards to structure and volume to mass ratio. It is important to point out that the differences between deployable structures represented in this study and rigid space habitats similar to the ISS offer opportunities and challenges for the design. The benefits of an expandable shell technology is a lighter structure with opportunities to increase volumes. These expandable technologies also present unique challenges and will have a subset of special requirements. Due to the design of the habitat, the CDF applied a set of requirements to best highlight the associated challenges which are presented in **Table 2**.

	Mission Requirements	
Req. ID	**Statement**	**Rationale**
MIS-010	The Habitat shall be able to accommodate a crew of 4 people.	MPCV current crew capacity.
MIS-020	The Habitat shall support Mission Duration up to 500 consecutive days for a given crew.	Extended ISS expeditions and Radiation
MIS-030	The Habitat shall have a minimum 10-year lifetime (TBC) after deployed on the surface of the moon.	Multiple expeditions
MIS-040	The Habitat shall be deployed on a site combining easy access to resources, benign illumination conditions, and scientific interest.	Systems Section3.2.3.3 ISECG GER
MIS-050	The Habitat shall provide sufficient radiation protection to have an internal radiation environment compatible with maximum allowable exposure levels for the crew over the mission duration, accounting for both periods of nominal and solar event external radiation levels.	Radiation chapter
MIS-060	When deployed on the moon surface, the Habitat and respective support systems shall be able to provide functions for Crew Habitation (including, Life Support, Crew Quarters, Hygiene, Food preparation, storage), as well as support to Science and Surface operations.	Astronaut survival and operational capability.
MIS-070	The Habitat and required support components shall be launched in stowed condition from the earth.	Systems Section **Error! Reference source not found.**
MIS-080	The Habitat and required support components should be compatible with current state-of-the-art launcher capabilities.	Section 3.5 and 3.6
MIS-090	The Habitat and required support components shall be transferred into an appropriate Lunar Orbit.	Section 3.4**Error! Reference source not found.**
MIS-100	The Habitat and required support components shall be transferred from lunar orbit to the moon surface.	Section 3.4
MIS-110	Access of the crew to the interior of the Habitat from the moon surface (and vice-versa) shall be possible.	Section 3.2.3
MIS-120	The habitat and support components shall be transferred to the final location and deployed on the moon surface.	Section 3.4.1

Table 2: Mission Requirements

Source: European Space Agency “CDF Study Report: CDF-202(A),” ESA, 2020.

C. Mission Systems

The habitat represents the primary element of the mission, enabling a crew of 4 to live, work and operate on the lunar surface once in operation. To achieve this the habitat requires multiple elements to support every phase of the habitat mission from construction on Earth to delivery on the lunar surface. These elements are all considered in the design of the habitat and integral to the success of the mission. The habitat in this study is also considered a typology of its own as a hybrid and capable of adapting to multiple uses which means that the design can be scaled parametrically to meet mission needs. Supporting elements are potentially reusable as part of the architecture to increase their utility and allow for an increase in crew size or delivery of additional habitats. These additional elements have been categorized as building blocks in previous work [5]. The supporting elements included in this study are presented below [4]:

Habitat Service Module

During the transfer phase, support functions to the Habitat may be required. These include:

- Power generation and supply to the Habitat to allow operating survival heaters to maintain required minimum non-operational temperatures within the allowable range for sensitive equipment (namely Environmental Control and Life Support Systems),
- Maneuver and Attitude Control Habitat in specific launch scenarios to allow for rendezvous and docking with other mission elements.

These tasks can be performed by a dedicated Service Module launched with the Habitat or by a tug (assumed for this study).

Airlock Module
The Habitat is currently assumed to not include an integrated Airlock in the design, depending on an additional module to enable ingress and egress of crews and equipment, as well as any Extra-Vehicular Activity when on the moon surface. This function is to be performed by an external additional Airlock Module that connects to one of the docking interfaces on the side of the Habitat.

Launchers
The capability of the launch segment is considered a driver for this mission. The following available launchers (current capability or in late stages of development) were considered for the study, depending on the Mission Category:

- Ariane 5, Ariane 6, Proton, Soyuz, SLS Block 2, HIIB, Long March 5, Falcon Heavy

New launcher developments were also considered (including new and early developments):

- SpaceX Starship
- SLS-like upgrade to performance requirement.

Nevertheless, SLS Block 2 performance was taken as the baseline for this study (assuming habitat mass optimization).

Lander
A purpose-built logistics lander is assumed to be required to transfer the Habitat and Cargo from lunar orbit to the lunar surface. Current developments both within the Agency (such as the Heracles EL3) but as well in commercial landers (PTS, SpaceIL, iSpace, Astrobotic, Blue Origin) target payload masses much lower than what is required for the studied mission. Reusability plays a big role in the sustainability of the operations on the moon surface, especially if propellants can be produced in-situ. The baseline is a single-use lander. It could be imagined a lander could also make use of local O2 from ISRU systems.

Tug
A purpose-built space tug is assumed to be required to transfer the Habitat, Lander, and Cargo from Lunar Transfer Orbit into Lunar Orbit. Current developments in very early stages of development include the multi-purpose Cis-Lunar Transfer Vehicle (CLTV),[6] but the capability is significantly below what is required for the Moon Village habitat and components.

Mobile Crane
A Mobile Crane system is assumed to be required to extract the Habitat from the Lander system, move the Habitat to the deployment site, and deploy the Habitat (and potentially other support systems) on site.

Power Station
Several options for Power supply to the Habitat and other mission components supporting the Habitat as well as surface operations were studied. Options include the use of nuclear fission generators or solar arrays combined with batteries or regenerative fuel cells for energy storage.

External Radiators
Due to the operational equipment and activities performed inside the Habitat, as well as the high variability in thermal conditions the Habitat has to sustain during its operational life, heat rejection needs drive the need for the use of a significant area of external radiators that have to be deployed on the lunar surface, in the vicinity of the Habitat.

D. System Assumptions and Trade-Offs

The habitat study took various assumptions as inputs to advance the CDF process which included some previously mentioned drivers such as a crew size of 4, a mission duration of up to 500 days, and available mission architecture capabilities to transfer, deliver and equip the habitat. A lander, tug, and launch scenarios were studied to determine the size of each system. The system assumptions are represented in **Table 3**.

System Assumptions	
1	Crew size: 4 pax.
2	Mission duration: 500 days
3	Cargo lander (E.g., EL3) with a payload capacity of 1700 kg (TBC), potentially refueled on the surface will be available.
4	Some scenarios (TBC) require rendezvous in lunar orbit with cargo lander (specification TBD)
5	Reduced Habitat mass or Habitat can be split into up to 2 parts (and 2 launches)
6	The gateway exists.
7	The involvement of humans will be assumed to be an available capability.
8	Early pre-cursor missions have demonstrated and implemented ISRU, hence Phase 2 of ISECG lunar exploration scenario is achieved.
9	The following surface capabilities exist at the time of the first habitat launch:
9.1	Existing class 1 habitats already present, e.g. service habitat, astronauts module(s) (Columbus like…) to act as initial support to the crew to 'un-pack' class II habitats
9.2	Limited stay of up to two weeks during construction class II habitats, with the crew able to return to the gateway.
9.3	Rovers
9.4	Robotics/telepresence from the gateway.

Table 3: System Assumptions
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

E. Lander Sizing

The lander is a critical element in the success of the mission. At the time of writing, there exists no such capability that can deliver a habitat of this scale. Additionally, for future missions such as this to be sustainable, landers will need to be reusable and an ISRU propellant capability will need to be developed. The sizing of the lander took considerations illustrated in **Table 4** into consideration as part of selecting the lander system.

Assumptions	
1	Lander is launched from Earth without payload but fully fueled (fuel and oxidizer)
2	Lander scenario, as opposed to an alternative Sky-Crane scenario (no losses assumed for canted thrusters as would be the case for the alternative)
3	Proximity operations, Attitude Control, and Hovering delta-V not taken into account at this stage (although margins are considered appropriate to cover for these)
4	Descent/ Ascent from/to a 100x100 km LLO
5	Delta-V for descent from LLO to the lunar surface taken as 1880 m/s.
6	Delta-V for ascent from the lunar surface to LLO taken as 1865 m/s. **Error! Reference source not found.**
7	ISP of the Cryogenic Propulsion system was assumed to be 450 s
8	ISP of the Bi-Propellant Propulsion system was assumed to be 320 s
9	For the calculation of the partial refuel of propellant in the surface (in the applicable usage scenarios), the LOX/(LOX+LH2) mass ratio was taken as 6/7ths (approximately 0.86)

Table 4: System Assumptions
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

Propulsion technologies considered for the lander included two types, Cryogenic: LOX/LH2 and Bi-Propellant.

The three use case scenarios for sizing the lander included:

1. A full refuel from launch to orbit, where the lander contains the propellant needed to deliver the habitat to the lunar surface and return without payload to LLO.
2. Full refuel in orbit and partial refuel (LOX) on the lunar surface requiring ISRU capabilities.
3. Full refuel both in orbit and full refuel on the lunar surface.

The mass of the lander was divided into 3 parts, the propellant mass, the structural support mass, and the propulsion system dry mass.

1. The propellant mass was calculated using the Tsiolkovsky equation.

$$\Delta V = I_{sp}\, g_0 \ln\left(m_0/m_f\right)$$

2. The structural support mass, which is the component of dry mass that is dependent on payload mass, was derived from historical data and reference to other landers **Error! Reference source not found.**. The parametric model philosophy used in this study was originally developed for.

$$m\_struc = 0.1534\ m\_pay + 317.6\ \text{kg}$$

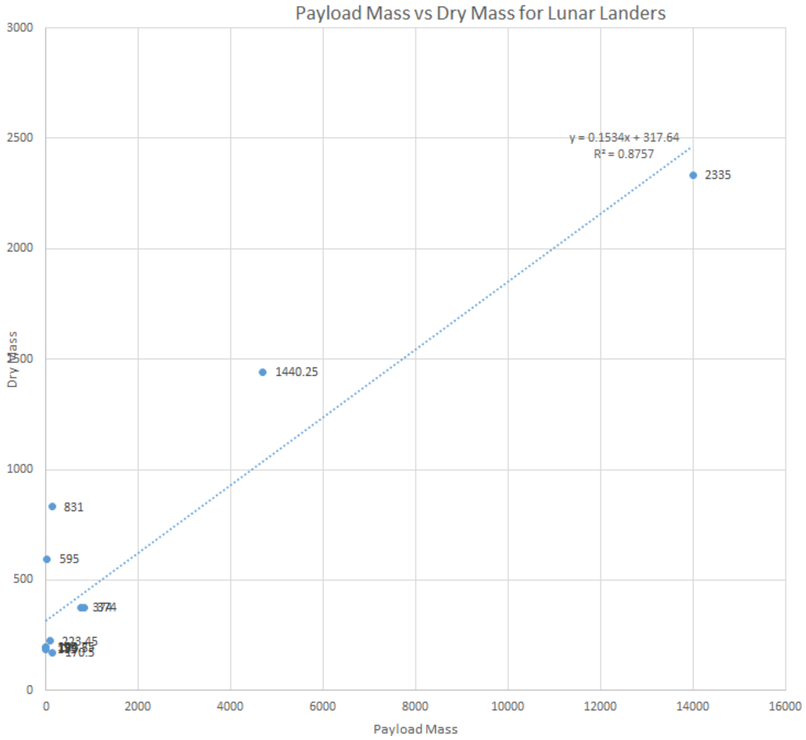


Figure 2: Structural Support Mass vs. Payload Mass for several currently proposed Lander designs and fitting used in the model

Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

3. Propulsion system dry mass: component of dry mass that is proportional to propellant mass.

$$m\_propdry = 0.15\ m\_propellant$$

Thus, the dry mass and wet masses of the Lander were calculated as (respectively),

$$m\_\text{dry} = m\_struc + m\_propdry$$
$$m\_\text{wet} = m\_dry + m\_\ propellant$$

The Wet Mass of the Lander was calculated for all scenarios across a range of masses compatible with the mission. It can be seen that among all usage scenarios, the Bi-Propellant solutions are the worst-performing options. As expected, the wet mass was also higher for the cases in which the lander is to carry the propellant (or part of it) for the ascent during the descent shown in **Figure 3**.

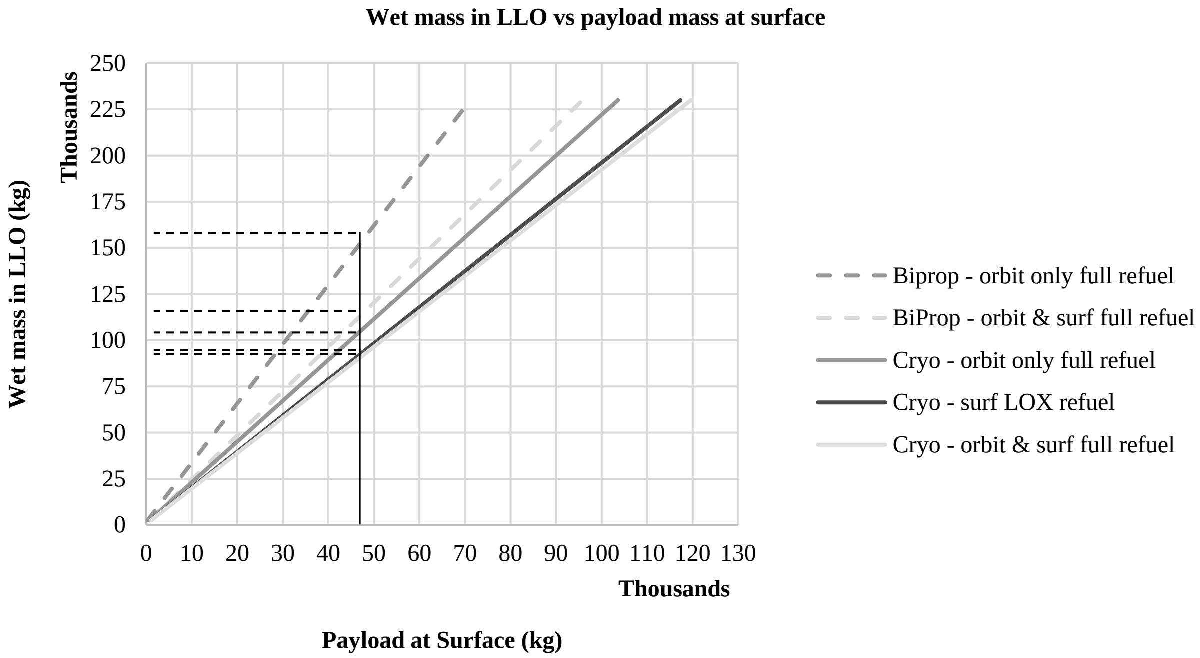


Figure 3: Wet Mass of a the Lander + Payload in LLO prior to descent to the surface vs. Payload Mass for the different usage scenarios assumed

Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

Extracting the results for the approx. 48 metric ton initial Habitat mass delivery to the moon surface from LLO, the wet mass for the Lander (including payload) and its respective launch mass from Earth (including propellant but excluding payload, as it is assumed rendezvous with the habitat occurs on-orbit/during transfer) are as follows [4]:

- Full refuel in orbit:

Cryogenic: LOX/LH2

Wet mass LLO (w/ payload): ~105 ton
Launch mass Lander (fueled): ~58 ton

Bi-propellant

Wet mass LLO (w/ payload): ~153 ton
Launch mass Lander (fueled): ~105 ton

- Full refuel in orbit + partial refuel (LOX) on the moon surface

Cryogenic: LOX/LH2

Wet mass LLO (w/ payload): ~93 ton
Launch mass Lander (fueled): ~46 ton

- Full refuel both in orbit + full refuel on the moon surface (or single-use lander if not refueled on the moon surface)

Cryogenic: LOX/LH2

Wet mass LLO (w/ payload): ~90 ton

Launch mass Lander (fueled): ~44 ton

Bi-propellant

Wet mass LLO (w/ payload): ~123 ton
Launch mass Lander (fueled): ~75 ton

F. Tug Sizing

The tug is also a critical element of the mission. It allows all of the primary mission elements (crewed vehicle, lander, and habitat to be transported from Low Earth Orbit along a path toward lunar orbit. As we discovered with the lander that its wet mass at launch could be larger than the habitat, the assumptions for the tug consider a tugged payload within a mass range.

Tug Assumptions	
1	The Tug is launched from Earth without payload but fully fueled (fuel and oxidizer)
2	Proximity operations and Attitude Control on delta-V not taken into account at this stage
3	The Tug is launched directly into Lunar Transfer Orbit (LTO)
4	Delta-V taken as 974.4 m/s, assumes insertion into 100km x 100 km LLO from LTO (arrival C3 of 0.8 km^2/s^2).
5	Structural/subsystem sizing extrapolated from CLTV CDF study
6	ISP of the Cryogenic Propulsion system was assumed to be 450 s
7	ISP of the Bi-Propellant Propulsion system was assumed to be 320 s
8	(Option – not taken in consideration in the sizing) The Tug is to perform the support functions required by the habitat during transfer, such as Attitude and Orbit Control, survival Power Supply and TT&C.

Table 5: System Assumptions
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

The mass of the Tug was broken into 4 components [4]:

1. The propellant mass, calculated using Tsiolkovsky equation.

$$\Delta V = I\text{sp}\ g0 \ln (m0/mf)$$

2. The structural support mass, which is the component of dry mass that is dependent on payload mass. This was assumed to be 0.19 of the payload mass, as was the case for the CLTV study.

3. The propulsion system dry mass, a component of dry mass that is assumed proportional to propellant mass. This was assumed to be 0.19 of the propellant mass, as was the case for the CLTV study.

4. Avionics/other subsystems mass which are assumed to not scale with the dimensions of the Tug were introduced in the model as a fixed value of 877 kg, also derived from the conclusions of the CLTV study

Results are presented in **Figure 4**. As expected, a cryogenic subsystem, having a higher ISP, is able to provide the required delta-V for a given payload mass with a lower launch wet mass. Both options are considered for the study.

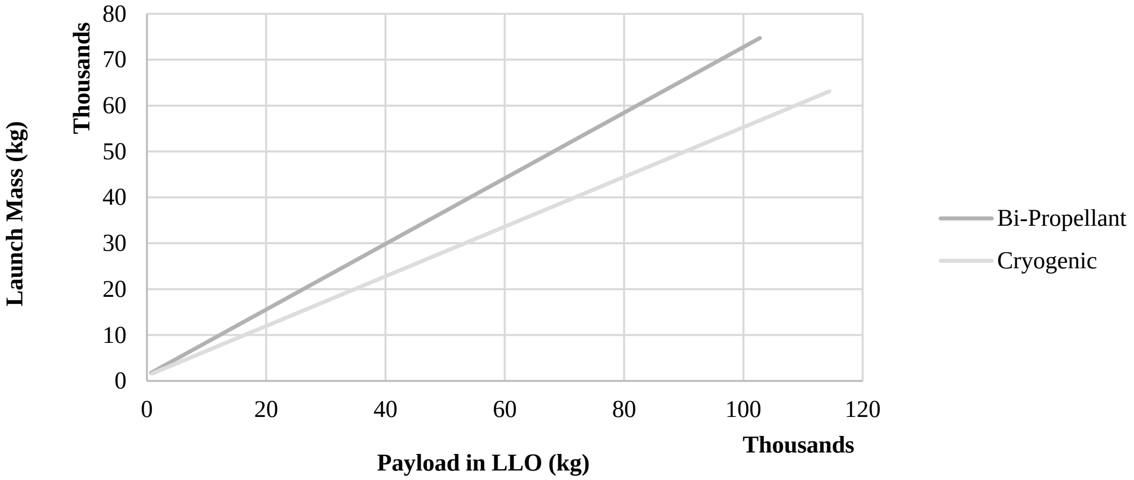


Figure 4: Tug Launch Mass (with fuel, no payload) vs payload mass in LLO
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

G. Launch Scenarios

The transportation system limits the mass and scale of habitation systems but in this study, the team took into consideration two categories of launch capability which included a heavy lift launcher under advanced development and a newer launcher which is still being designed and engineered but which is at a lower stage of development at the time of this exercise. The launch scenario categories are summarized below with additional information about the scenarios in reference [4]:

1. SLS Scenarios: These scenarios assume the use of launch capability currently under advanced state of development. The baseline is therefore based in the Space Launch System Block 2, which was at the time of writing the best performing launcher, also in with regards to its suitability to human exploration missions, able to launch up to 45 000 kg to lunar vicinity, assuming a TLI with C3 = -0.99 km2/s2, as per [10] (a slightly higher performance was taken, 45.75 tons, as a departure C3 = - 2 km2/s2 was taken). For these Scenarios, the available mass that would be available for the Habitat is derived from the launcher performance, taking into account the need to also launch the lander and tug elements, and assuming several options for the number of launchers and combination of elements.

2. New Launcher for Full Habitat: In this scenario, the reference mass of the Habitat as provided in the beginning of the study was considered (47.960 kg). Then, the Tug and Lander are scaled accordingly, and the required performance for a novel Launcher is derived (one possibility is the SpaceX Starship, although with a different launch profile). The best performing scenario from the SLS Scenarios was chosen as the one to be assessed for this novel launcher assessment.

An option to launch with the SpaceX Starship could be the best solution, managing to launch the full habitat and support equipment to the lunar surface with a single launch.

Starship Launch Option		
Habitat Total Wet Mass		68173
Power Station		6713
Thermal Surface Radiators		4721
Airlock Module		9000
Mobile Crane		13000
Launch Adapter (allocation)		1000
Launch Mass (kg)		**102607**

Assumed StarShip Performance (kg)		**100000**
Potential Launch Performance Margin		-2607

Table 6: Launch Mass (All Mission Components) – Starship Option

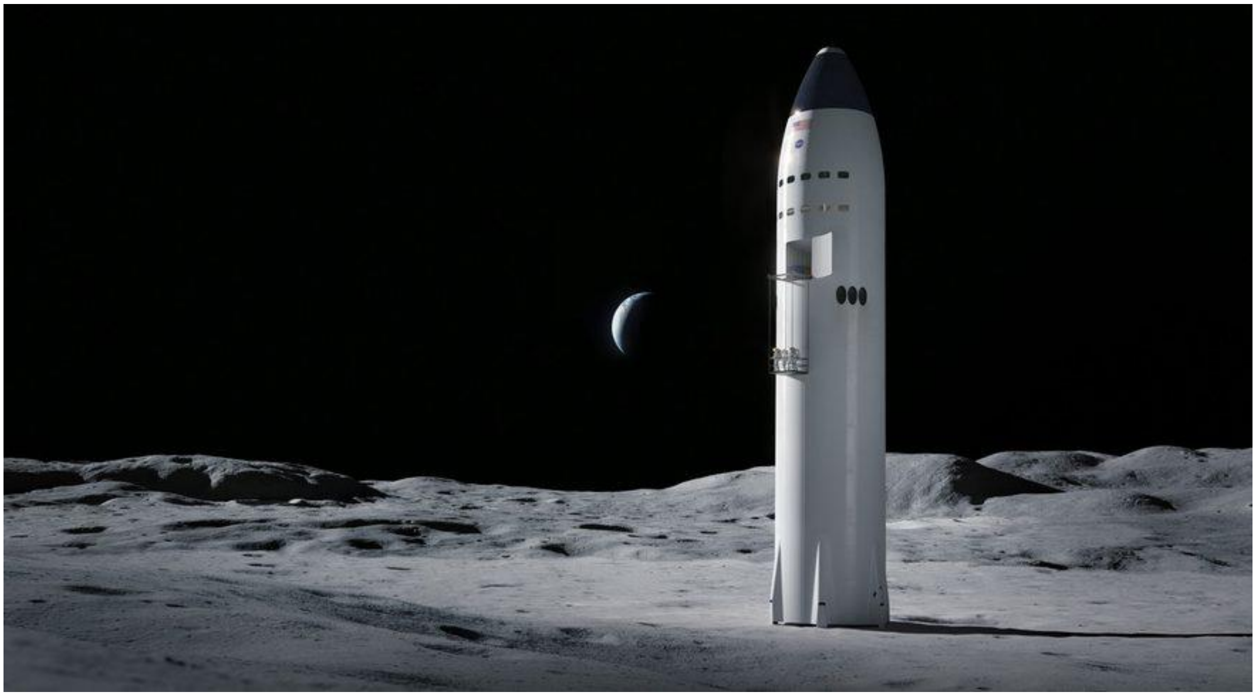
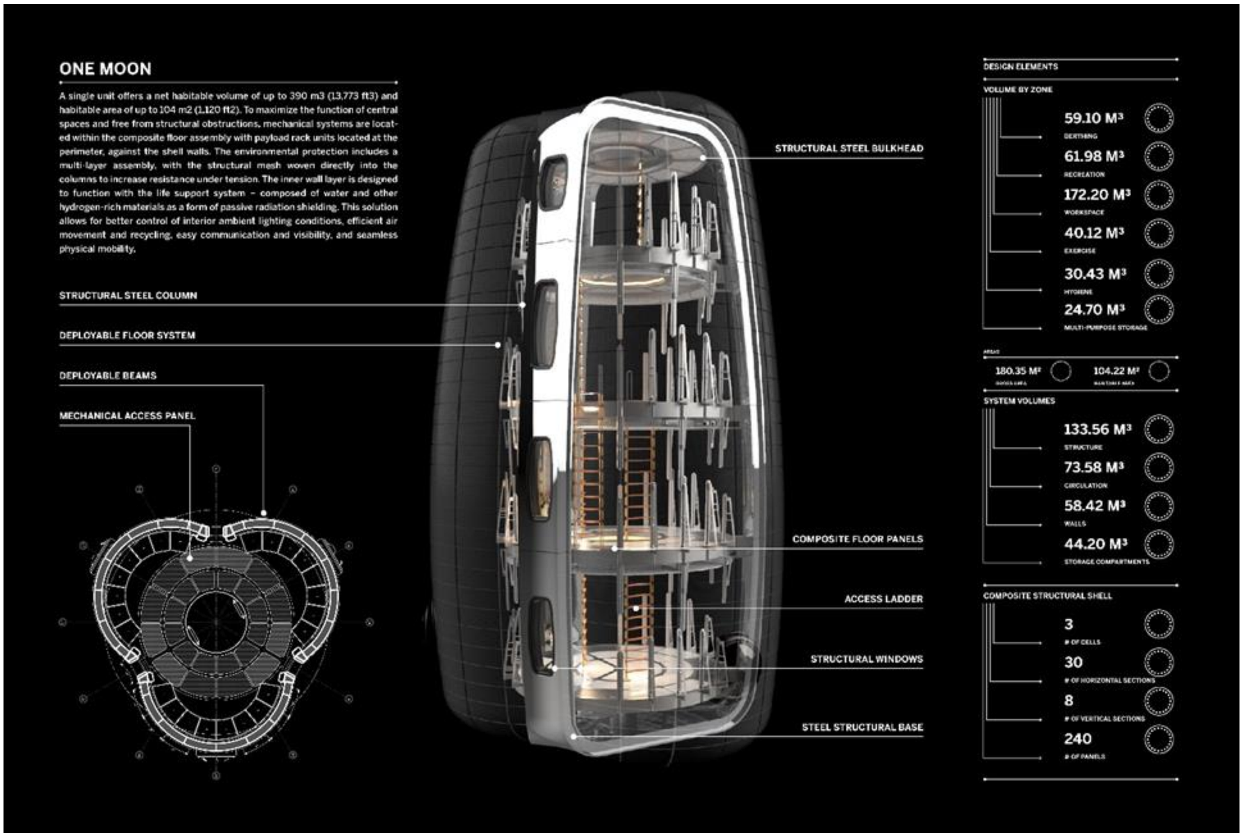


Figure 5: Starship Lunar Lander Visualization
Credit: SpaceX

H. Baseline Solution

The habitat concept titled One Moon aimed to address functional, environmental, and performance constraints but also placed an emphasis on human-centered design principles which are characterized in architectural features expressed in the unique hybrid structural system to allow for enhanced internal functions. The single unit offers a net habitable volume of up to 390 m^3 (13,773) ft3 and a net habitable area of up to 104 m2 (1,120 ft2). To maximize the function of central spaces and maintain a clear central zone free from structural obstructions, structural columns are placed at the perimeter integrated with windows and secondary mechanical distribution systems. Primary mechanical systems are located within the composite floor assembly with payload rack units mounted near the center in the stowed configuration but displaced to the perimeter walls during occupancy. The environmental protection system includes a multi-layer assembly with the structural mesh, responsible for supporting the internal pressure loads, directly woven into the mega-columns to increase resistance under tension. The inner wall layer which is part of the assembly is intended to function as an augmented part of the life support system – composed of water and other hydrogen-rich materials as a form of passive radiation shielding which mitigates the adverse effects of radiation in space which is a major challenge to human health and safety but also sensitive equipment. The visualization of the design in **Figure 6** illustrates the vertical structure and distribution of primary systems. The displacement of the structure as a solution requires further testing and engineering in future phases but is grounded on principles of human-centered design which allow for a higher floor to ceiling dimension, centralized volume for better control of lighting conditions, efficient air movement and recycling, easy communication, and visibility, and smoother physical mobility. [11]



ONE MOON

A single unit offers a net habitable volume of up to 390 m3 (13,773 ft3) and habitable area of up to 104 m2 (1,120 ft2). To maximize the function of central spaces and free from structural obstructions, mechanical systems are located within the composite floor assembly with payload rack units located at the perimeter, against the shell walls. The environmental protection includes a multi-layer assembly, with the structural mesh woven directly into the columns to increase resistance under tension. The inner wall layer is designed to function with the life support system – composed of water and other hydrogen-rich materials as a form of passive radiation shielding. This solution allows for better control of interior ambient lighting conditions, efficient air movement and recycling, easy communication and visibility, and seamless physical mobility.

Figure 6: Habitat Concept Design Systems Axonometric
Source: Inocente et.al "Master Planning and Space Architecture for a Moon Village: 70th IAC, 2019.

IV. Crew Accommodation

Crew accommodation centers on the human element of the design process, where tasks and the required resources and equipment to support various activities are analyzed. The volumetric and area requirements stem from the crew operations during a mission and individual tasks are combined or co-located within provided zones to determine the total volume required. Anthropometric dimensional constraints such as vertical reach and the required motions for basic human operations such as living, hygiene, working, stationary, stowage, suiting, egress, and translation in a reduced gravity environment function as volume drivers and establishing adjacencies.

The crew accommodation subsystem also presents several challenges following the concept of operations. Testing of the habitat interfaces, equipment, and accommodation subsystem will need to be performed to reduce human error, increase productivity, and improve overall safety and comfort.

A. Accommodation Functionalities

The crew habitat is designed to support a crew of four on the lunar surface for up to 500 days for which the following functions are required at the minimum.

- Private Quarters
- Dining and Communal Spaces
- Workspaces
- Exercise Area & Equipment
- EVA Suit Donning & Doffing
- Medical Care
- Hygiene
- Translation Corridors

B. Crew Accommodation Requirements

In this study, recommendations for habitable volume were examined by looking at the net habitable volume for the ISS (85.17 m^3), and previous stations including the Skylab (120.33 m^3), Mir (45 m^3), and Salyut (33.5 m^3) with varied mission durations. Given the long duration mission of this concept, a net habitable volume of 80 m^3 per person was recommended. [4]

C. Partial Gravity Challenges

Partial gravity presents additional environmental constraints regarding mobility within the habitat. Considering anthropometric dimensional control and accessibility in a 1/6th gravity environment raises concerns regarding movement, safety, and health. Some of these constraints are included [12], [13]:

- Walking (slower)
- Running (slower, tendency to slip)
- Jumping (higher and farther)
- Loping (most comfortable in partial g)
- Posture (forward inclination)
- Traction (reduced – balance and locomotion hazardous).

Due to reduced gravity, higher elevations become more accessible to occupants, and providing restraints and mobility aids can assist in reaching higher elevations with better control of movement. Restraints and mobility aids can be located at or near human interfaces, translation corridors, and compartments to provide the crew with needed control. At the working level, the design of the habitat locates mobility aids and restraint features near lighting fixtures along the perimeter for better visibility and proximity to workstations or equipment **Figure 7**. Additional restraints and aids are located on the vertical access ladders but also within the individual crew quarters and other facilities.

Figure 7: Habitat Workstation Level Visualization

Source: Inocente et.al "Master Planning and Space Architecture for a Moon Village: 70th IAC, 2019.

D. Budgets

As part of the Crew Systems, the Galley is responsible for providing all food preparation systems and equipment for the duration of the mission. These food preparation systems include a sink, oven, freezer, dishwasher, cooking supplies, food storage, eating supplies, and a communal space for crew gatherings. In the design of the habitat, a series of specialized compartments are designated for food preparation located on the working level to maximize the utility of a unified space. Round tables are placed near the center of the space. These tables are adjustable to multiple heights for multiple uses in addition to deployable table surfaces located within the walls of the rack units.

Table 7 by Stilwell et al. [14], shows the mass and volume budgets for the galley and food system, not including life support system elements.

Galley and Food System	**Mass**	**Mass Subtotal (kg)**	**Volume**	**Volume Subtotal (m³)**
*** Habitat**				
Oven/microwave oven	50 kg	50	0.3 m³	0.3
Freezers	100 kg	100	0.5 m³	0.5
Sink, spigot for hydration of food and drinking water	15 kg	15	0.0135 m³	0.0135
Dishwasher	40 kg	40	0.56 m³	0.56
1 Rack (ISPR)	104 kg	104	1.571 m³ (internal volume)	
*** Cargo delivery**				
Cooking/eating supplies	2 kg/p	8	0.0056 m³/p	0.0224

Table 7: Mass and Volume Budget of the Galley and Food System

E. Waste Collection and Hygiene

Waste collection and hygiene facilities have design considerations and requirements that allow crew members to perform body waste management, body cleansing, oral hygiene, and grooming in a manner that is reliable and maintainable. The body waste management systems should be psychologically and physiologically pleasing to the occupants by designing these spaces with sufficient separation from common spaces, isolated from view and within soundproof walls. Additionally, cleansing in microgravity requires many more supplies such as (tissues, disinfectants, vacuums, and other housekeeping equipment.

Based on recommendations by Stilwell et al.,
Table 8 shows the necessary mass and volume for the waste collection and hygiene area, not including life support system elements.

Waste Collection and Hygiene	**Mass**	**Mass Subtotal (kg)**	**Volume**	**Volume Subtotal (m³)**	**Mass Margin (%)**
*** Habitat**					
Vacuum	2 x 4 kg	8	2 x 0.02 m³	0.0400	5
2 Racks (ISPR)	104 kg/rack	208	1.571 m³ (internal volume/rack)		5
*** Cargo delivery**					
Hygiene supplies (consumables)	0.075 kg/p/d	150	0.0015 m³/p/d	3.0000	5
Personal hygiene kit	1.8 kg/p	7.2	0.005 m³/p	0.0200	5

Table 8: Mass and volume budget of the waste collection and hygiene system (excluding life support elements)

Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

F. Sleep Accommodation, Health, and Clothing

The habitat design currently includes private quarters for 4 crew members with personal space allocations needed to conduct private conferences, personal recreation, sleeping, and working functions. The quarters were designed with privacy and protection in mind while also providing personalized temperature control, ventilation, and lighting conditions. The concept introduces the idea of pod-like units that are stacked and divided along the perimeter of a designated habitat level. The design incorporates additional radiation shielding along the walls where the pod walls and exterior shell interface. As an alternative to conventional sleeping units, this design illustrated in **Figure 8** provides efficient use of space for private functions while encouraging crew members to maximize the use of common spaces. The crew spaces also need to include all of the necessary information technologies needed to stay connected, informed in addition to having their well being monitored. A pod type sleeping quarter allows for the complete integration of hardware, making more effective use of surface areas within reach. The individual crew quarters also required an adequate amount of space for supporting individual tasks and storing private possessions. Equipment such as a washing machine and dryer are also needed to clean maintain a clean supply of clothing. Additionally, medical facilities and supplies will be necessary for the health and safety of the crew. In this concept, those functions are placed at the workstation level, within specialized compartments that are open to the central space, allowing for generous amounts of volume to perform needed procedures in case of emergency. The health of crew members will also require special equipment to exercise such as a treadmill and stationary bicycle. These functions should be located near a common space but also usable in isolation if possible. Exercise will be essential to the well being of the crew and should be anticipated to consume a large portion of their daily activities.

Based on recommendations by Stilwell et al.,
Table 9 shows the mass and volume budgets for sleep accommodation, health, and clothing.

Sleep Accommodation, Health, and Clothing	**Mass**	**Mass Subtotal (kg)**	**Volume**	**Volume Subtotal (m³)**
*** Habitat**				
Private crew quarters (basic outfitting: bed and foldable desk)	100 kg/p	400	>2.5 m³/p	10
Washing machine and dryer	100-160 kg	100-160	0.75-1.5 m³	0.75-1.5
Medical/surgical/dental suite (TBD)	500 kg	500	2.00 m³	2
4 Rack (ISPR)	104 kg	416	1.571 m³ (internal volume)	
*** Cargo delivery**				
Personal stowage and recreational equipment	25 kg/p	100	0.38 m³/p	1.5200
Clothing	4.6 kg/p	18.4	0.0033 m³/kg	0.0610
Exercise equipment	145-300 kg	145-300	0.19 m³	0.1900
Medical consumables	250 kg	250	1.30 m³	1.300

Table 9: Mass and volume budget of the sleep accommodation and clothing system

Source: European Space Agency “CDF Study Report: CDF-202(A),” ESA, 2020.

Figure 8: Habitat Crew Quarters Visualization

Source: Inocente et.al “Master Planning and Space Architecture for a Moon Village: 70th IAC, 2019

G. Operational Supplies and Maintenance

On the workstation level, there will be designated compartments and rack units dedicated to operational supplies for the crew to perform necessary repairs and maintenance work. Additional compartments and rack units will need to exist at the lower level where EVA preparations take place. Some of the needed equipment in these compartments include hand tools, larger machines, 3d printers, and hardware supplies.

Based on recommendations by Stilwel et al.,

Table 10 gives the mass and volume estimates for operational supplies and maintenance.

Operational Supplies and Maintenance	**Mass**	**Mass Subtotal (kg)**	**Volume**	**Volume Subtotal (m^3)**	**Mass Margin (%)**
*** Habitat**					
Restraints and mobility aids	50 kg	50	0.27 m^3/kg	13.5	5
3 Racks (ISPR)	104 kg/rack	312	1.571 m^3 (internal volume/rack)		5
*** Cargo delivery**					
Operational supplies (velcro, tape, ziplocks, etc.)	20 kg/p	80	0.002 m^3/p	0.008	5
Hand tools and accessories	200 kg	200	0.066 m^3	0.66	5
Spare parts/equipment & consumables	TBD				
Fixtures, large machine tools, gloveboxes, etc.	600 kg	600	3 m^3	3	5
Test equipment (oscilloscopes, gauges, etc.)	300 kg	300	0.9 m^3	0.9	5

Table 10: Mass and volume budget of the operational supplies and maintenance system for all repairs in habitable areas

Source: European Space Agency “CDF Study Report: CDF-202(A),” ESA, 2020.

H. Airlocks

The habitat design includes 3 interfaces for airlock elements, these airlock units are expected to be separate from the habitat and would allow the crew to connect the habitat to other airlock elements such as pressurized rovers, tunnels, or adjacent habitat units. The airlocks are critical elements to the function of the habitat and are also expected to be used at a minimum once per week for EVAs. These airlock units serve as EVA preparation units where suits are donned or doffed. Each airlock unit is estimated to have a mass between 1000-1500 kg with a pressurized volume between 5-10m^3 [15] [16].

I. Power Requirements

Based on suggestions by Eckart et al. for missions that extend beyond 180 days there would be a power demand of 10kw/person at minimum for the habitat systems, not including airlock and other external elements.

Based on recommendations by Stilwell et al. [14], **Table 11** shows the power consumption estimates for electrical hardware for a 500-day mission in a lunar surface habitat.

Power Consumption of Crew Accommodation Hardware	**Average Power (kW)**	**Powered Time (% of a day)**	**Energy (kWh)**
Galley and Food System			
Microwave ovens	1.80	6	1296
Freezers	1.40	100	16800
Dishwasher	1.20	8	1152
Waste Collection System and Hygiene			
Vacuum	0.40	1.00	48
Crew Quarters, Clothing, Health			
Washing machine & clothes dryer	4.00	8.00	3840
Personal stowage	0.70	4.00	336
Exercise equipment	0.15	50.00	870
Medical/surgical/dental suite	1.50	1.00	180
Operational Maintenance			
Fixtures, large machine tools, glove boxes, etc.	1.00	0.10	12
Test equipment (oscilloscopes, gauges, etc.)	1.00	0.10	12
TOTAL (kWh)			**24546**

Table 10: Power consumption budget of the electrical hardware in the crew accommodation

J. Total Budgets for All Crew Accommodation Elements

Based on recommendations by Stilwell et al. [14],
Table shows the total budget estimates for a 500-day mission in a lunar surface habitat.

Total Budgets	**Total Mass incl. Margins (kg)**	**Total Volume (m³)**	**Total Energy (kWh)**
Galley and food system (excl. life support elements)	**346.35**	**1.3959**	**19248**
- Habitat	337.95	1.3735	
- Cargo delivery	8.4	0.0224	
Waste collection and hygiene (excl. life support elements)	**391.86**	**3.0600**	**48**
- Habitat	226.80	0.0400	

Total Budgets	Total Mass incl. Margins (kg)	Total Volume (m³)	Total Energy (kWh)
- Cargo delivery	165.06	3.0200	
Sleep accommodation and clothing, health	**2125.87**	**15.821**	**5226**
- Habitat	1586.80	12.7500	
- Cargo delivery	539.07	3.0710	
Operational supplies and maintenance (all repairs within habitable areas)	**1619.10**	**18.068**	**24**
- Habitat	380.10	13.5000	
- Cargo delivery	1239.00	4.5680	
TOTAL	**2531.65 (Hab. Equipment) + 1951.53 (Cargo)**	**38.3449**	**24546**

Table 11: Total mass, volume, and power consumption budget of the crew accommodation
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

V. Structures

One Moon is designed as a hybrid pre-integrated structure which is composed of two key elements, the rigid exterior frame with integrated windows and expandable structural shell. The rigid structure includes three primary columns (1200mmx400mm) which span vertically between the base and top structural bulkhead. The columns serve to support the exterior deployable shell while also supporting multiple levels. The floor system between columns consists of a composite frame structure with mechanical and storage compartments within the floor assembly. It is important to highlight that both primary and secondary structures would need to be tested and engineered to withstand launch vibration and transport loads. Nevertheless, due to the reduced gravity loads, opportunities to minimize the required mass and thickness of these structures allows for unique deployable floor configurations which are stowed during launch and released once on the lunar surface. Unlike previous inflatable designs, which place primary support structures and mechanical zones at the center, this design eliminates intruding elements and provides a completely open central space by placing mechanical systems within floors and structure at the perimeter.

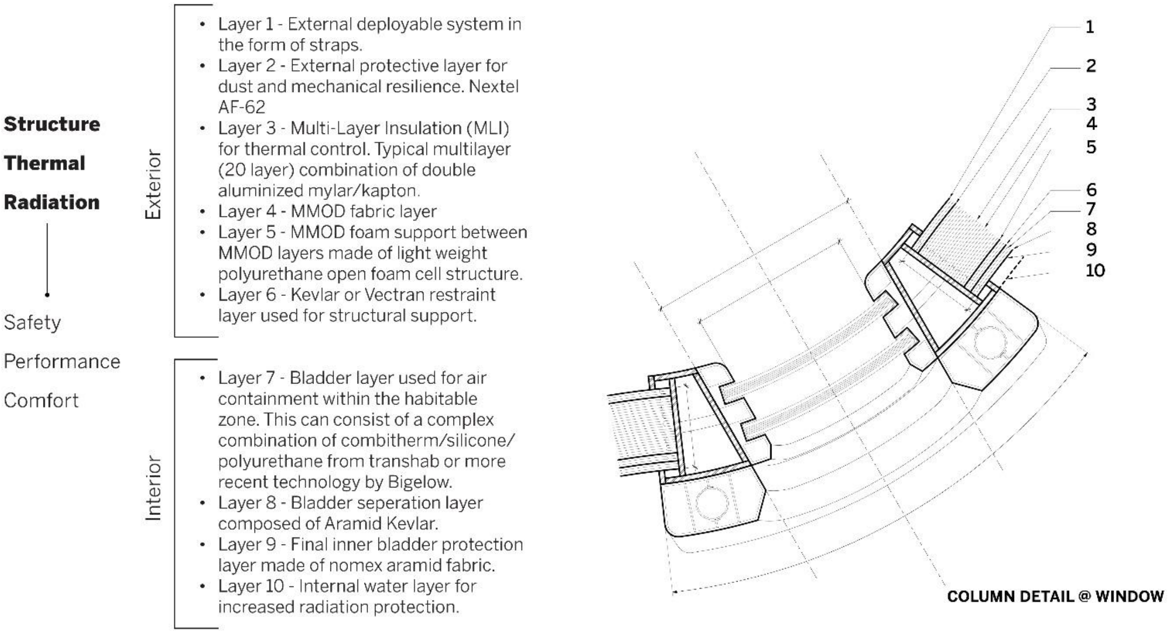
Habitat Structures Mass Estimation	Mass (kg)	Mass Margin (%)	Mass Including Margin (kg)
Accessibility	649.50	20.00	779.40
Adapters	3439.00	20.00	4126.80
Ceiling Panels	1023.00	20.00	1227.60
Central Floor Panels	772.40	20.00	926.88
Deployable Shell	7195.00	20.00	8634.00
Extended Ceiling Panels	272.10	20.00	326.52
Extended Floor Panels	308.60	20.00	370.32
Exterior Frame	5072.00	20.00	6086.40
Exterior Frame Interface	131.90	20.00	158.28
Secondary Floor Structure	4435.30	20.00	5322.36
Window Frames	259.60	20.00	311.52
Windows	1640.88	20.00	1969.06
Grand Total	**25199.28**	**20.00**	**30239.14**

Table 12: Structures Mass Budget

Source: European Space Agency “CDF Study Report: CDF-202(A),” ESA, 2020.

K. Shell

The key challenges associated with the exterior structural shell in the design of One Moon addressed during this study include intensive leak testing, testing of a rigid to deployable shell interface, folding for transport-deployment, and the mechanical-structural integrity of this design. The baseline materials of the shell are driven by function, safety, and performance divided into two major groups which include the exterior materials exposed to the environment (extreme temperatures, dust, micro-meteoroids, outgassing, cosmic, and ionizing/non-ionizing radiation). The layers and sequence from the exterior to the interior are illustrated in **Figure 9**.



Structure
Thermal
Radiation

Safety
Performance
Comfort

Exterior

- Layer 1 - External deployable system in the form of straps.
- Layer 2 - External protective layer for dust and mechanical resilience. Nextel AF-62
- Layer 3 - Multi-Layer Insulation (MLI) for thermal control. Typical multilayer (20 layer) combination of double aluminized mylar/kapton.
- Layer 4 - MMOD fabric layer
- Layer 5 - MMOD foam support between MMOD layers made of light weight polyurethane open foam cell structure.
- Layer 6 - Kevlar or Vectran restraint layer used for structural support.

Interior

- Layer 7 - Bladder layer used for air containment within the habitable zone. This can consist of a complex combination of combitherm/silicone/polyurethane from transhab or more recent technology by Bigelow.
- Layer 8 - Bladder seperation layer composed of Aramid Kevlar.
- Layer 9 - Final inner bladder protection layer made of nomex aramid fabric.
- Layer 10 - Internal water layer for increased radiation protection.

Figure 9: Exterior Shell Material Assembly
Credit: SOM

L. Structural Design

The primary structural elements which support the exterior shell are the columns at the perimeter. These columns were designed to maximize the performance of the overall mesh and frame structure in the fully functioning state. Once the module is emplaced at its location, the atmospheric pressure rigidizes the shell and projecting it outward until a tangential relationship with the columns is achieved. The geometry for both the column and shell is an integrated part of the form as shown in **Figure 10**. This also allows for the greatest distribution of internal pressure forces, placing all structural materials under tension and ensuring each system performs at its best. As the columns terminate at the ground floor, they tie directly into a base plate which serves as a footing for the weight of the entire structure and follows the same geometric articulation to continue a smoother distribution of the pressure loads. At the top of the structure, a bulkhead ties into the columns also taking on the form of the pressure loads and a tangential continuous tangential geometric relationship throughout the interface between the columns and shell.

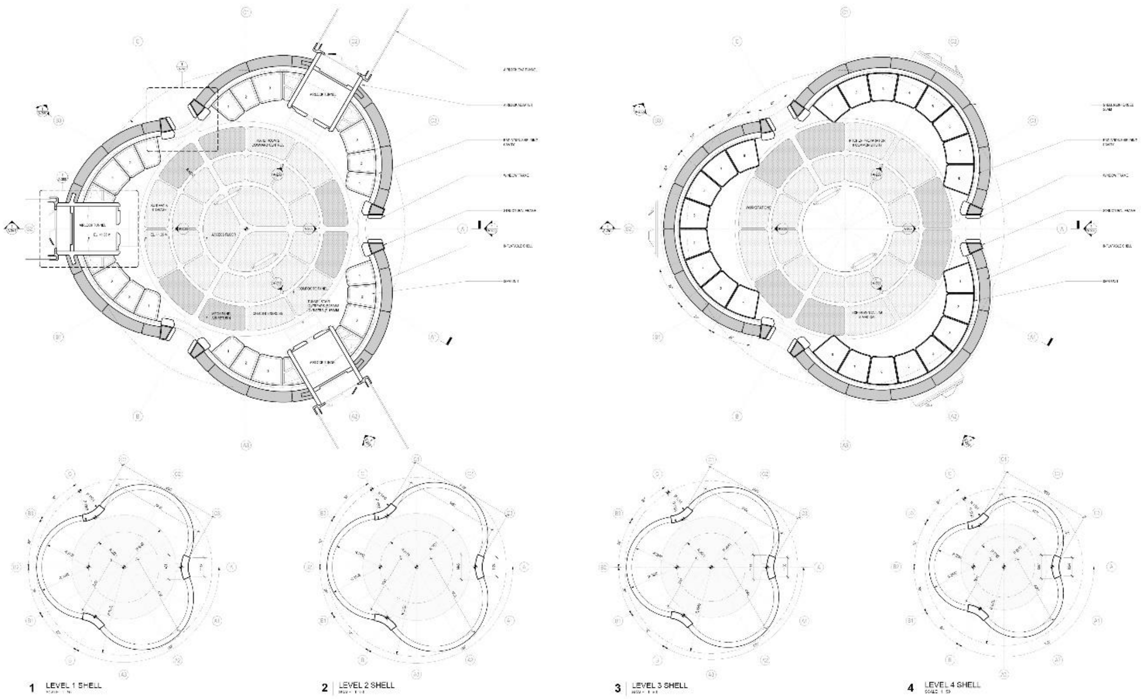


Figure 10: Habitat Plan Diagrams
Credit: SOM

M. Floor System

The floor system in the habitat includes two parts, the central floor structure, and the deployable floor structure as shown in **Figure 11**. The central floor system spans between columns to support gravity and live loads with a significant part of the mechanical systems placed in between the finish floor and ceiling. This area of the floor system is assumed to be permanent and fixed during launch and once in operation. It serves as structural support for mechanical systems but also as temporary support for rack units and the perimeter beam holds several anchor points to hold the mesh in its packed configuration.

The secondary deployable floor system is configured in an undeployed vertical condition during launch and expanding or deploying once the habitat is pressurized and the shell is in its outward condition. The design includes 4 total floors with 5 beams at each segment of the shell on any given floor. This means a total of 60 beams and hinges would be installed on the habitat.

The following assumptions were made for each hinge sizing and performance [4].

Habitat Diameter: ~4.5 m (stowed) / ~8.5 m (deployed)
Flooring to hold: ~400 kg/m^2 (including floor panel mass & racks)
Floor Thickness: 0.2 m
Habitat Design: 5 beams on each of the 4 floors, for each of the 3 inflatable volumes (a total of 60)
This leads to the following torque and force estimations:
Torque on each hinge beam: 472 Nm
Load on each hinge: 2.4 kN

For these loads, 200 g hinges can be used. The total mass of 60 hinges is thus ~12 kg. This does not include the structural mass of floor beams, panels, or local reinforcements needed if composite floors are used. A 30% proposed margin is to be added.

A second load case will come from the launch vibrations. Assuming a mass of a single deployable beam of 100 kg, a peak acceleration of 10 g, and 6 additional restrain points, the magnitude of load for each hinge can be estimated to be 9.81*100*10/(6+1)~1.5 kN, with is the same order of magnitude as the load estimated from the lunar gravity.

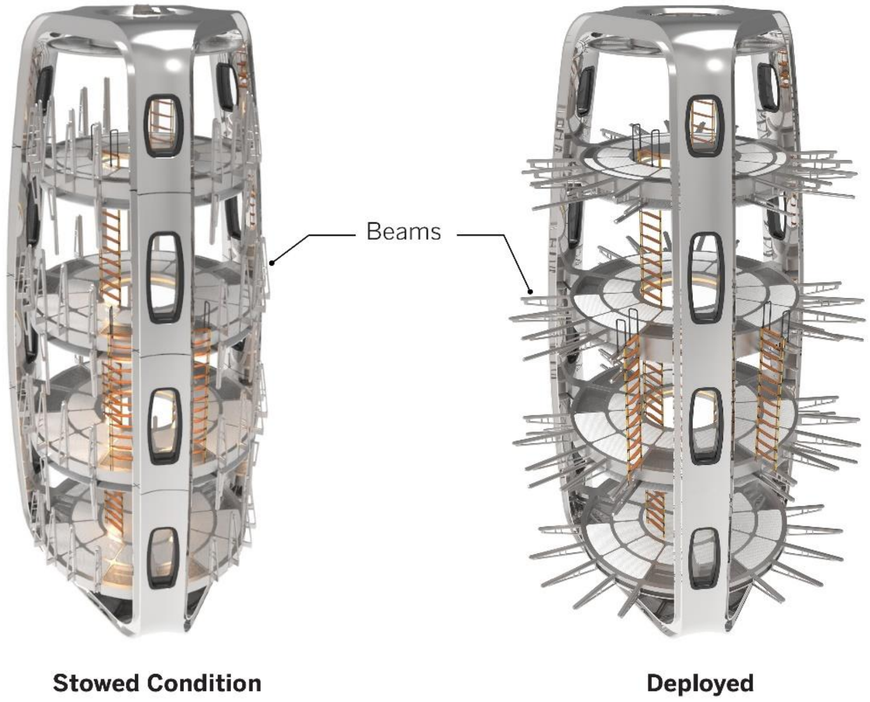


Figure 11: Habitat Floor Structure Diagrams
Credit: SOM

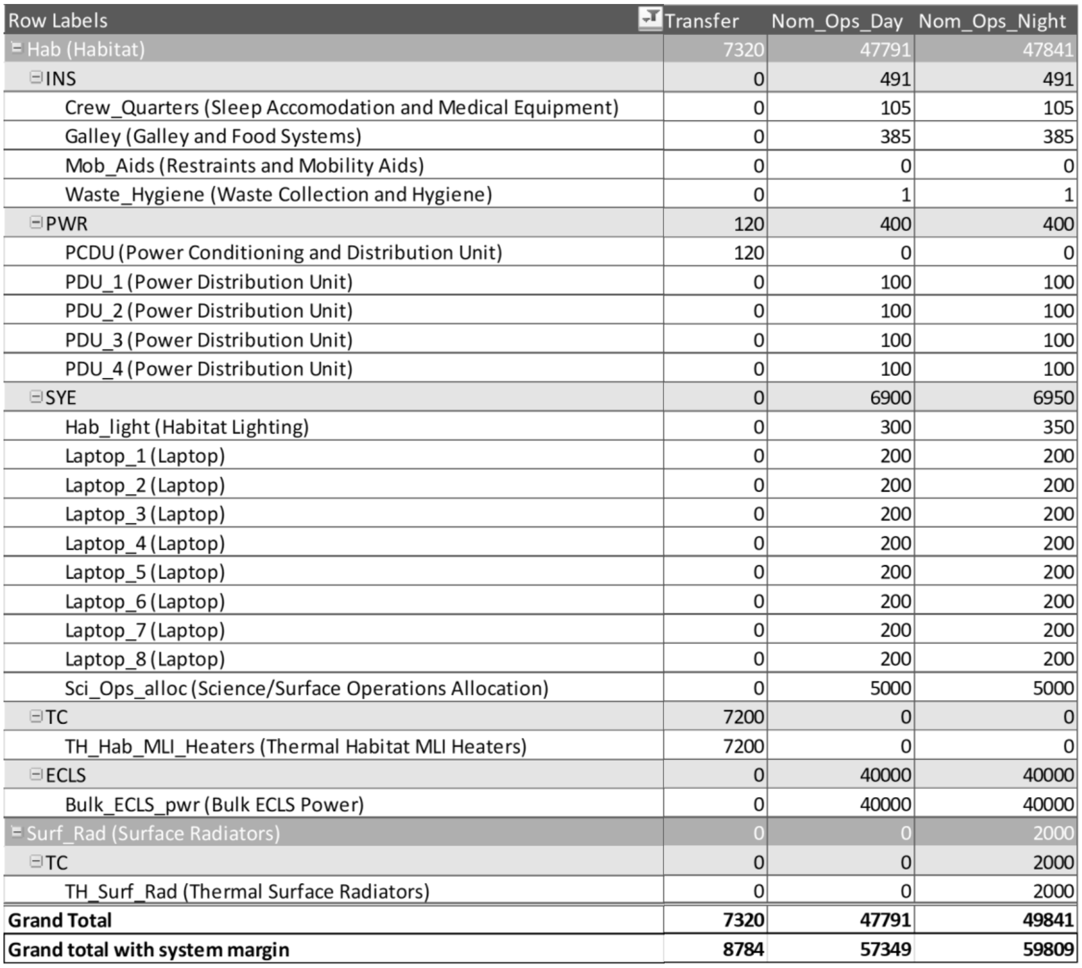
VI. Power

In this study, the International Space Station was used as a reference for data on power requirements although it was understood that the ISS is typically has a crew of 6 and is in Earth orbit. The ISS has a power delivery system of 84 kW and a maximum of 108kW with 25-35 kW available for payload operations.

N. Design Requirements and Assumptions

An estimation of power requirements for the habitat was conducted at the subsystem level and for some components at the equipment level (**Table 13**). While the habitat is in transit the power required is primarily for maintaining the internal environment of the habitat and its critical components within an acceptable range. During normal operations for both the lunar night and day, the power requirements are primarily driven by the Environmental Control and Life Support System (ECLSS).

In total, including a 20% system margin, the average power requirement is 57 kW during the day and 60 kW during the night. [4]



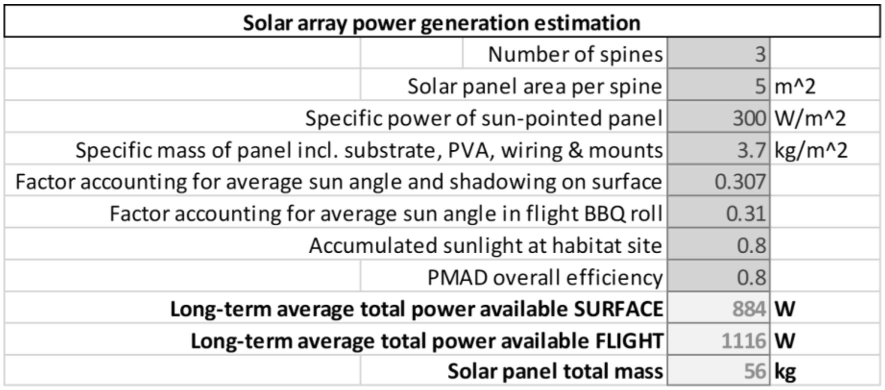
Row Labels	Transfer	Nom_Ops_Day	Nom_Ops_Night
⊟ Hab (Habitat)	7320	47791	47841
⊟INS	0	491	491
Crew_Quarters (Sleep Accomodation and Medical Equipment)	0	105	105
Galley (Galley and Food Systems)	0	385	385
Mob_Aids (Restraints and Mobility Aids)	0	0	0
Waste_Hygiene (Waste Collection and Hygiene)	0	1	1
⊟PWR	120	400	400
PCDU (Power Conditioning and Distribution Unit)	120	0	0
PDU_1 (Power Distribution Unit)	0	100	100
PDU_2 (Power Distribution Unit)	0	100	100
PDU_3 (Power Distribution Unit)	0	100	100
PDU_4 (Power Distribution Unit)	0	100	100
⊟SYE	0	6900	6950
Hab_light (Habitat Lighting)	0	300	350
Laptop_1 (Laptop)	0	200	200
Laptop_2 (Laptop)	0	200	200
Laptop_3 (Laptop)	0	200	200
Laptop_4 (Laptop)	0	200	200
Laptop_5 (Laptop)	0	200	200
Laptop_6 (Laptop)	0	200	200
Laptop_7 (Laptop)	0	200	200
Laptop_8 (Laptop)	0	200	200
Sci_Ops_alloc (Science/Surface Operations Allocation)	0	5000	5000
⊟TC	7200	0	0
TH_Hab_MLI_Heaters (Thermal Habitat MLI Heaters)	7200	0	0
⊟ECLS	0	40000	40000
Bulk_ECLS_pwr (Bulk ECLS Power)	0	40000	40000
⊟ Surf_Rad (Surface Radiators)	0	0	2000
⊟TC	0	0	2000
TH_Surf_Rad (Thermal Surface Radiators)	0	0	2000
Grand Total	**7320**	**47791**	**49841**
Grand total with system margin	**8784**	**57349**	**59809**

Table 13: Power requirements for each system mode (time-averaged power in watts)
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

O. Solar Power

The study included a requirement of about 15m^2 of solar panel area mounted directly on the habitat with a total mass of 56 kg. These panels would generate about 1100 W during the transfer and on the lunar surface depending on the altitude of the habitat and orientation. This would depend on the availability of solar exposure and the site's topographic conditions. After studying illumination conditions for potential sites at the southern pole, the study provided an accumulated illumination of about 80% with an average power generation of 900W [4].

These power and mass calculations are further detailed in **Table 14**.

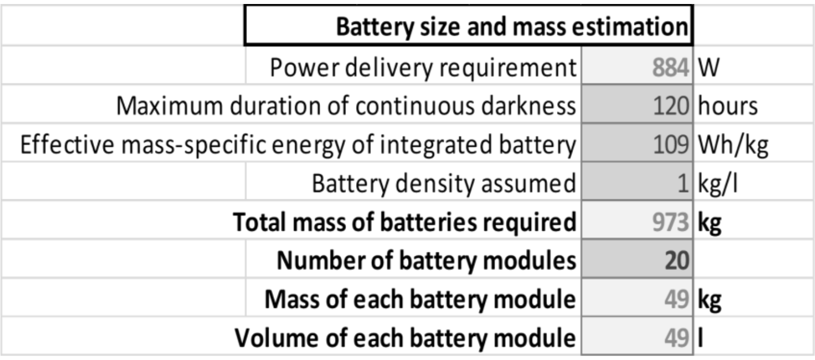


Solar array power generation estimation		
Number of spines	3	
Solar panel area per spine	5	m^2
Specific power of sun-pointed panel	300	W/m^2
Specific mass of panel incl. substrate, PVA, wiring & mounts	3.7	kg/m^2
Factor accounting for average sun angle and shadowing on surface	0.307	
Factor accounting for average sun angle in flight BBQ roll	0.31	
Accumulated sunlight at habitat site	0.8	
PMAD overall efficiency	0.8	
Long-term average total power available SURFACE	884	**W**
Long-term average total power available FLIGHT	1116	**W**
Solar panel total mass	56	**kg**

Table 14: Power generated by solar panels, and mass estimate
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

P. Battery, Power Conditioning and Distribution

To supply the habitat with continuous power for both dark and light conditions the habitat requires a storage capability in the form of a battery system of 20 separate 49kg modules (49 liters each).



Battery size and mass estimation		
Power delivery requirement	884	W
Maximum duration of continuous darkness	120	hours
Effective mass-specific energy of integrated battery	109	Wh/kg
Battery density assumed	1	kg/l
Total mass of batteries required	973	**kg**
Number of battery modules	**20**	
Mass of each battery module	49	**kg**
Volume of each battery module	49	**l**

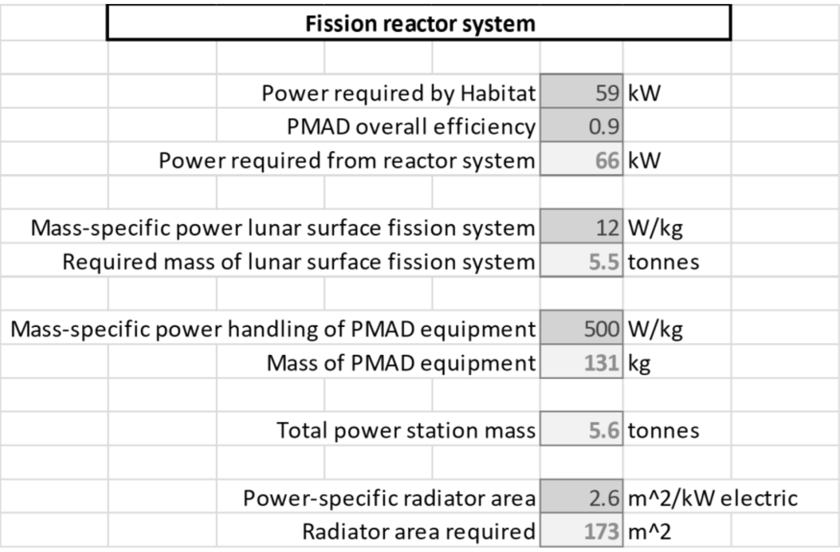
Table 15: Battery size and mass estimate
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

In addition to battery capability, a mass allocation of 15kg was estimated for the PDCU to manage and distribute the `1kW of power delivery by the solar panel system.

Q. Power Station

To power, the habitat at full capacity, a solar and nuclear fission power station was compared. In this section, we only include the nuclear fission power plant option which is also the lower mass solution. There were various challenges associated with a solar power station which included high mass estimates, power continuity, occlusion by neighboring solar towers, and a large energy storage requirement.

Nuclear fission reactors for lunar applications are already being developed by NASA. To protect the crew and habitat from the ionizing radiation emitted by a reactor the system would need to be buried or shielded by regolith. For the habitat requirement, the mass of the fission surface power system was assumed to be 12W/kg based on various studies. The system for the habitat would need to provide 59kW of continuous power. The fission reactor system mass estimation is calculated in Table



Fission reactor system		
Power required by Habitat	59	kW
PMAD overall efficiency	0.9	
Power required from reactor system	66	kW
Mass-specific power lunar surface fission system	12	W/kg
Required mass of lunar surface fission system	5.5	tonnes
Mass-specific power handling of PMAD equipment	500	W/kg
Mass of PMAD equipment	131	kg
Total power station mass	5.6	tonnes
Power-specific radiator area	2.6	m^2/kW electric
Radiator area required	173	m^2

Table 16: Assumptions and mass estimate for a nuclear fission power station
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

The fission reactor system is much more compact and mass efficient than a solar power plant. This capability also offers the opportunity to power other elements and can be applied to any site conditions on the Moon, with or without solar illumination.

VII. Thermal

The primary function of the thermal control system is to maintain the habitats components and hardware systems within its design temperature ranges during the various mission phases. Thermal control ensures that integrated hardware and components essential to the mission and habitat architecture perform under optimal conditions. The thermal control system needed to achieve the required temperature during transfer, where insulated compartments were kept at 10ºC and non-insulated compartments at -20ºC. Once on the lunar surface, the average temperature inside the habitat needs to be kept at 22ºC.

R. Challenges

During the transfer from Earth to the Moon the interior of the habitat is kept within required temperatures by MLI insulation and the temperature is regulated using heaters. The thermal design and exterior shell need to be designed so that deployment of the habitat can be achieved successfully. The MLI is part of the overall deployment strategy and is capable of being configured in the habitats stowed condition through the use of folding and packing techniques. The MLI should adapt to undeployed and deployed configurations while maintaining its insulation performance properties. Since conditioning during transfer is still required, some power should be provided. Once the habitat is in Lunar Orbit, the planning phase for landing will need to take into account any heat transmission from thrusters to the habitat and heat gain by sun exposure.

S. Baseline Design

Various external thermal protection coatings were considered for the habitat that would perform the same during transfer and operations once on the lunar surface. This meant that the external layer coating needed to be flexible enough to perform in the stowed and deployed configuration. Three possible MLI variations were analyzed and compared, taking into account the performance properties of the external layers, the impact of the lunar dust, and heater power loads. The possible coatings for thermal protection and calculations are presented in (F

	The temperature inside the habitat [°C]	**VDA**	**Kapton**	**BetaCloth**	**Comments**
Transfer	0°C	2.8 kW	12.2 kW	12.4 kW	BoL optical properties

	The temperature inside the habitat [°C]	**VDA**	**Kapton**	**BetaCloth**	**Comments**
Lunar night	22°C	9.6 kW	17.6 kW	17.6 kW	EoL optical properties
Lunar day	22°C	-46.5* kW	-4.7* kW	0.1 kW	

** In this case the amount of reported heat is the heat to be rejected additionally to heat dissipated inside the habitat.*

Table 17: Heater power estimation, all values are in kW

Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

VIII. Radiation

Radiation was one of the primary concerns in this study as it is also one of the greatest challenges for human exploration and there is limited information about the effects of radiation risks on the Moon. In this study, we looked at strategies to minimize the effect of potential radiation risks and made a concerted effort to improve the level of shielding required by the habitat. The types of radiation we considered included Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE).

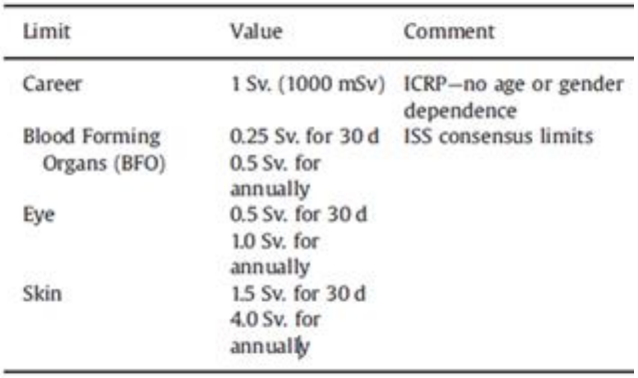
T. Challenges

Radiation damage to biological systems includes direct damage, when radiation interacts directly with DNA, but the most common process is indirect damage, when radiation mainly interacts with H2O and creates free radicals that in the end will interact with DNA. Health effects can also be divided into acute and delayed. Delayed effects include cancer and genetic effects. Acute effects occur within a few days or less and includes vomiting, nausea, loss of appetite, and fatigue. [14]

- The space radiation effects on humans can be classified into two main categories:
- **Stochastic effects** (cancer, leukaemia, hereditary effects)
- No threshold dose, exposure provide an increased risk
- Probability of the effects increases with the dose, not the severity
- No definitively associated with the radiation dose received
- **Deterministic effects** (cataracts, dermatitis, sterility, radiation syndrome, etc.)
- Threshold dose, above which they always appear
- Damage grows usually with the dose intensity
- Typically they manifest soon after exposure.

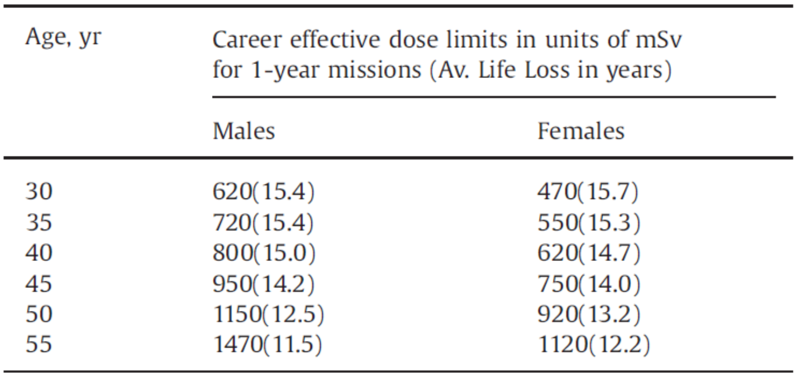
U. Radiation Shielding

Radiation limits set by ESA for LEO missions are shown in Table 18. Career effective dose limits from NASA given in mSV for a 1-year mission are listed in Table 18, the average life-time loss due to the radiation exposure is also included within brackets. The ECSS-E-10-04 space environment standard provides additional limitations and recommendations. Comparisons with other Space Agencies dose limits can be found in 0.



Limit	Value	Comment
Career	1 Sv. (1000 mSv)	ICRP—no age or gender dependence
Blood Forming Organs (BFO)	0.25 Sv. for 30 d 0.5 Sv. for annually	ISS consensus limits
Eye	0.5 Sv. for 30 d 1.0 Sv. for annually	
Skin	1.5 Sv. for 30 d 4.0 Sv. for annually	

ESA dose limits, from 0



Age, yr	Career effective dose limits in units of mSv for 1-year missions (Av. Life Loss in years)	
	Males	Females
30	620(15.4)	470(15.7)
35	720(15.4)	550(15.3)
40	800(15.0)	620(14.7)
45	950(14.2)	750(14.0)
50	1150(12.5)	920(13.2)
55	1470(11.5)	1120(12.2)

Table 18: Examples of career effective dose limits for male and female astronauts by NASA. Corresponding estimates of average life-time loss due to radiation exposure are shown in brackets. Table is obtained from 0

V. Radiation Shielding

The largest exposed area to radiation in the design is the exterior shell which alone does not provide sufficient radiation shielding to meet the exposure limits. In this study, we looked at strategies to augment the shielding of the habitat by including additional materials such as water in the interior and regolith to the exterior at different locations.

Three different configurations studied for this design include [4]:

Configuration 1: Includes the habitat without any additional radiation shielding.

Configuration 2: This configuration has been obtained as a result of a parametric study performed by iterating the Ray Tracing analysis, varying the shielding thickness and location. The resulting configuration includes the habitat plus the minimum shielding required to obtain a total BFO Average Dose of 500 mSv/year and 250 mSv/30 days. The additional material is used to:

Shield the entire inflatable structure, 2 cm of sintered lunar regolith (equivalent to 4 cm of loose regolith): this is the minimum thickness to get a BFO Average Dose Equivalent below 250 mSv/year in the most exposed part of the habitat, i.e., the top floor.

Create a sheltered area located in the ground floor with the minimum shielding required to obtain a BFO Average. Dose Equivalent of 250 mSv (corresponding to 30 days limit dose) during the chosen SPE. The shelter is obtained shielding the ground floor with an additional 20 cm of sintered lunar regolith (equivalent to 40 cm of loose lunar regolith) and including a water tank with around 10 cm of water in the shelter roof.

Configuration 3: This is a safer option, used as a reference case to demonstrate the advantages of additional shielding by placing part of the habitat underground and surrounding the structure by 25 cm of sintered lunar regolith (equivalent to 50 cm of loose lunar regolith). In addition, a water tank with 20 cm of water covers the habitat.

	Thickness (cm)	Average density (g/cm^3)	Area density (g/cm^2)	Mass (kg)
Inflatables	25	0.7	1.7	7,205
Configuration 2 Loose (or sintered) lunar regolith covering all inflatable surfaces	4 (2)	1.5 (3)	6	25,238
Configuration 2 Loose (or sintered) lunar regolith for shelter	40 (20)	1.5 (3)	60	118,187
Configuration 2 Water (in roof of shelter or habitat)	10	1	10	~8,000
Configuration 3 Loose (or sintered) lunar regolith surrounding the habitat	50 (25)	1.5 (3)	75	492,798
Configuration 3 Water (in roof above habitat)	20	1	20	~16,000

Table 19: The characteristics of the inflatables and the habitat radiation shielding for different configurations

Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

The results of these studies for each configuration are demonstrated in the following tables:

	SPE, ground floor (mSv)	GCR, ground floor (mSv/year)	GCR, top floor (mSv/year)	Annual total (mSv)
Configuration 1: No shielding	887 (300)	228	280	1167
Configuration 2: Minimum shielding	323 (117)	203	252	575
Configuration 3: Additional shielding	106 (40)	131	208	314

Table 20: The estimates effective dose equivalent for the ground floor and top floor of the habitat, for three different configurations. The SPE Effective dose equivalent for an average SPE is given within brackets in column 1. The annual total effective dose equivalent (Column 4) is the sum of the SPE Effective dose equivalent (Column 1) on the ground floor and the GCR Effective dose equivalent (Column 3) in the top floor.

Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

	SPE, ground floor (mSv)	GCR, ground floor (mSv/year)	GCR, top floor (mSv/year)	Annual total (mSv)
Configuration 1: No shielding	720 (241)	225	274	994
Configuration 2: Minimum shielding	228 (82)	201	248	466
Configuration 3: Additional shielding	71 (27)	128	206	277

Table 22: The estimates BFO average dose equivalents for the ground floor and top floor of the habitat, for three different configurations. The SPE BFO Average dose equivalent for an average SPE is given within brackets in column 1. The annual total BFO average dose equivalent (Column 4) is the sum of the SPE BFO average dose equivalent (Column 1) on the ground floor and the GCR BFO average dose equivalent (Column 3) in the top floor.

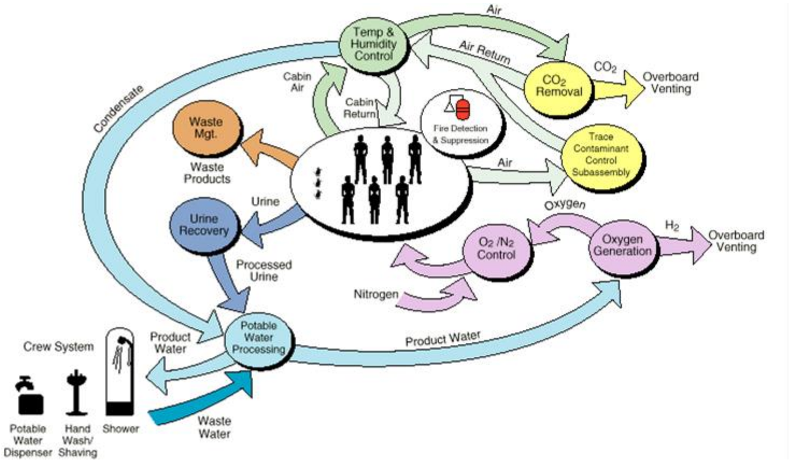
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

The analysis indicates that the habitat will require additional radiation shielding and also illustrates the results of different proposed configurations that can help reduce radiation exposure. As an early concept study, more work will need to be done in terms of developing shielding strategies and technologies.

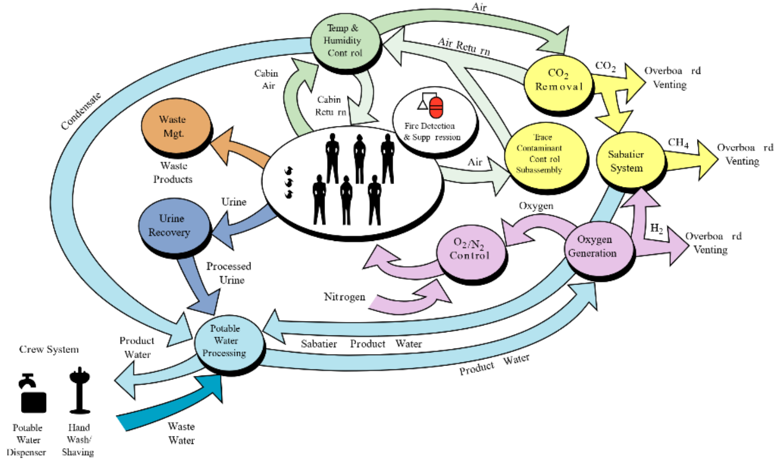
IX. Life Support

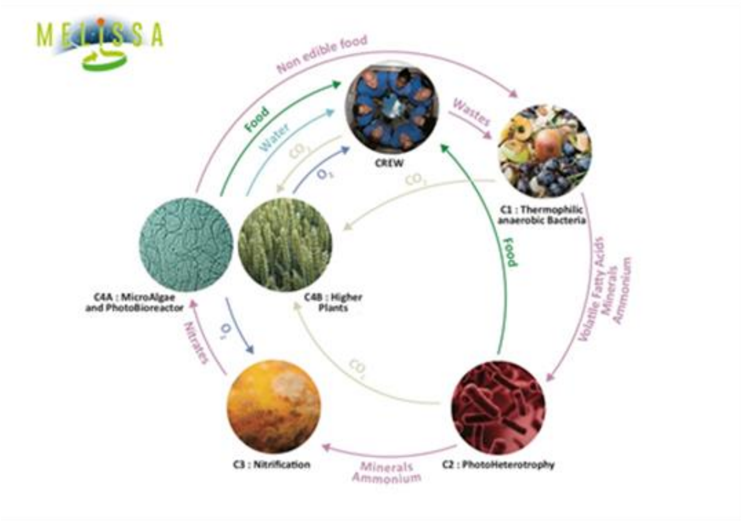
The proposed habitat is entirely new in its scale, architecture, and application which presents various challenges for the life support system. As a conceptual driver, the following illustration shows the multiple life support systems architectures with varying degrees of closure.

Current Life Support baseline on-board ISS, for a large part in open loop



With an additional level of resources regeneration





The closed-loop regenerative approach of the MELiSSA project (courtesy of the MELiSSA Foundation)
Figure 12: Various Life Support Systems Architectures

In this study, the specifics of the mission duration, crew, and assumption that there would be at a minimum, one resupply from Earth per year were used to develop drivers takes from the reference [4] below.

- Regenerative closed-loop systems for air and water are recommended, with as high as possible recovery efficiencies, to reduce supply from Earth;
- The first step towards on-site food production is highly desirable, i.e. production limited to up to 5% of the daily diet, to prepare for future bigger crew sizes when supply–from-Earth strategy will become economically unsustainable;
- On-site storage of wastes, preferably outside the habitat, is proposed at this stage; recycling of wastes would become attractive when food production would become fully operational and therefore resulting in the generation of a significant mass of inedible biomass.
- Full redundancy (i.e. based on different technologies) seems mandatory in the current context, to address all kinds of emergencies with the appropriate safety level.

The study includes the following core technologies needed for a life support system.

- For air revitalization: ESA's Advanced Closed Loop, Implemented cold redundant with a MELiSSA Compartment 4A based photobioreactor, colonized by *Limnospira Indica*, an edible microorganism commercialized on Earth as food supplement under the name "Spirulina";
- By operating a photobioreactor such as mentioned here above, up to 5% of food can be produced;
- For water recycling: the currently on-board ISS Water Recycling System (WRS), Implemented cold redundant with MELISSA Compartment 3 based Urine Treatment Unit.

Besides these core technologies, additional systems, multiple interfaces and ancillary equipment will be necessary:

- For atmosphere monitoring and control:
    - Ventilation
    - Temperature, humidity, and pressure control
    - Gas trace contaminants monitoring (e.g. ESA ANITA 0)
    - Microbial contamination monitoring
- For food production and preparation:
    - A biomass harvesting unit
    - A food processing unit
- For waste collection and handling:
    - A Space toilet
    - A waste compaction/inertion unit (e.g. NASA Heat Melt Compactor 0)

- Storage tanks for water and gases (oxygen, nitrogen)
- All necessary piping and instrumentation.

For consumables water was the highest in terms of mass at about 3kg/day/crew member minimum. Oxygen and food were calculated at about 1kg/day/crew member. These calculations are represented in Figure

Consumables	Description	kg/CM.d
Water	Potable water: drinking water and water for food hydration	3.8
	Hygienic water: urinal flush, personal hygiene, shower, laundry, dish-washing	15
	Medical water	0.5
Oxygen		0.82
Dry food		0.6
Dry food packaging		0.3
Other	cleaning wipes for personal hygiene, household wipes, disinfection wipes…	0.2

Table 23: quantities of consumables needed per day and per crew member
Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

For both water and oxygen quantities, a large amount can be supplied by the regenerative life support systems.

- 95% recovery for water (from the collection and recycling of urine, habitat condensates, hygienic and medical wastewater), meaning 5% has to be re-supplied.
- 99% recovery for oxygen (from the collection and processing of carbon dioxide), meaning 1% has to be re-supplied.

Description	Number of items	Dry mass per item (kg)	Mass margin (%)	Total mass (kg)
Gas tank (132L, 200 bars, 35kg metal for 35kg gas)	30	35	5	1,103
Per gas tank, piping and instrumentation (30kg)	30	30	20	1,080
Water tank (300L, 28.5 kg material for 280kg water) and	7	28.5	5	209
Per water tank, piping, and instrumentation (30kg)	7	30	20	252
ACLS for 4 CM	1	850	10	935
MELiSSA C4a compartment (photobioreactor) for 4 CM	1	1,300	20	1,560
Urine Treatment Unit for 4CM	1	250	20	300

Description	Number of items	Dry mass per item (kg)	Mass margin (%)	Total mass (kg)
Grey Water Treatment Unit for 4 CM	1	600	20	720
WRS (UPA+WPA) for 4 CM	1	1,383	10	1,521
Biomass Harvesting	2(1)	100	20	240
Food processing unit	2(1)	50	20	120
Waste compaction/inertion	2(1)	50	20	120
Space toilet	2(1)	50	10	110
Gas trace contaminants monitoring	2(1)	30	10	66
Microbial contamination monitoring	2(1)	30	20	72
Temperature and humidity control	6(2)	230	20	1,656
All interfaces	1(3)	400	30	520
(1)2 redundant units (2)6 subsystems distributed over the habitat (3)bulk estimation **TOTAL**				**10,584**

Table 24: Overall Mass Budget for Equipment

Source: European Space Agency "CDF Study Report: CDF-202(A)," ESA, 2020.

From this very preliminary assessment study, it is established that approximately 11 tons of equipment and 5.7 tons of consumables would have to be shipped from Earth to allow for the safe living of the 4 member crew over 500 days. The corresponding bulk power budget is estimated at around 40 kW.

X. Conclusion

This study took an in-depth look at the requirements for long-term surface habitat architecture. The habitat concept presents a wide range of unique challenges that inspired the team to discover the key constraints and possible solutions to a mission of this scale for an architecture that would require various advances in space technology capabilities. The design was reviewed across disciplines including structures, configuration, radiation, thermal and power, life support, and internal architectural systems. The study looked closely at all logistics for the habitat from transfer and thermal maintenance to deployment on the lunar surface. It was understood that for a long-term human-centered concept such as this the landed mass capabilities of a launcher and lander would need to evolve to meet the performance requirements. There are many more elements that become scaled as a result of the mass and duration of any habitat architecture. The premise of this study was that the key to developing a design that is highly integrated and can provide access to other planetary surfaces for long term sustainable human exploration is a new generation of habitat architecture.

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References

[1] ESA, Enabling & Support, Space Engineering & Technology, CDF, URL: https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Concurrent_Design_Facility [retrieved September 2020].

[2] Cohen, M. M., and Benaroya, H., “Lunar-Base Structures,” Out of This World: The New Field of Space Architecture, edited by A. S. Howe and B. Sherwood, AIAA, Reston, VA, 2009, Chapter 15, pp. 179–204.

[3] Cohen, Marc, and Kriss J. Kennedy, “Habitats and Surface Construction Technology and Development Roadmap,” Presented to the AIAA Structures Technical Committee, September 4, 1997, Hampton, VA

[4] European Space Agency “CDF Study Report: CDF-202(A),” ESA, March 2020.

[5] Review and Analysis of (European) Building Blocks for a Future Moon Village, Conference Paper, David Binns et al., 68th International Astronautical Congress (IAC), Adelaide (Australia), 25-29/09/ 2017

[6] Encyclopedia Astornautica, URL: http://www.astronautix.com/index.html [retrieved September 2020]

[7] MAS Working Paper No. 603 "Human Lunar Exploration Precursor Program" - Mission Analysis Guidelines - ESA HSO-K-TN-0008, F. Renk, R. Jehn, W. Martens, L. Bucci, B. De Vogeleer, Issue 0, Revision 3

[8] M. Braun, N.G. Veronica Trivino, S. Hosseini, R. Schonenborg, M. Landgraf, Human lunar return: An analysis of human lunar exploration scenarios within the upcoming decade, Acta Astronautica (2020), doi: https://doi.org/10.1016/j.actaastro.2020.03.037

[9] Lunar and Interplanetary Trajectories, Book, Robin Biesbroek, ISBN 978-3-319-26981-8, Springer International Publishing, 2016

[10] Space Launch System (SLS) Mission Planner's Guide, David Alan Smith, NASA Marshall Space Flight Center, Huntsville, AL, United States, Revision A, 19/12/2018, available at https://ntrs.nasa.gov/search.jsp?R=20170005323

[11] Inocente et al, “Master Planning and Space Architecture for a Moon Village”: 70th International Astronautical Congress, October 2019.

[12] Partial Gravity Habitat Study with Application to Lunar Base Design. Technical Report NASA-CR-186048. S. Capps, J. Lorandos, E. Akhidime, M. Bunch, D. Lund, N. Moore, K. Murakawa, L. Bell, G. Trotti, D. Neubek, Sisakawa International Center for Space Architecture, January 01, 1989

[13] Energetics and mechanics for partial gravity locomotion. Aviation, space, and environmental medicine. 65. 815-23. Newman, Dava & Alexander, H & Webbon, Bruce. 1994

[14] Crew Accommodations, Chapter 18 by D. Stilwell, R. Boutros, J. H. Connolly in: Human Spaceflight: Mission Analysis and Design, Ed. W.J. Larson, L.K. Pranke, New York, NY McGraw-Hill 2007, ISBN-13: 9780072368116

[15] Designing, Sizing, and Integrating a Surface Base, Chapter 13 by P. Eckart, Y. Ishikawa, K.J. Kennedy in: Human Spaceflight: Mission Analysis and Design, Ed. W.J. Larson, L.K. Pranke, New York, NY McGraw-Hill 2007, ISBN-13: 9780072368116

[16] Minimum Acceptable Net Habitable Volume for Long-Duration Exploration Missions, Subject Matter Expert Consensus Session Report NASA Human Research Program, NASA/TM-2015-218564, A. Whitmire, L. Leveton, H. Broughton, M. Basner, [17] A. Kearney, L. Ikuma, M. Morris, April 2015, https://ston.jsc.nasa.gov/collections/trs/_techrep/TM-2015-218564.pdf

[18] M.A. Gibson at al. “NASA’s Kilopower Reactor Development and the Path to Higher Power Missions”, IEEE Aerospace Conference, Big Sky, Montana, March 4, 2017, NASA/TM—2017-219467.

[19] “Feasibility study of astronaut standardized career dose limits in LEO and the outlook for BLEO”, Susan McKenna-Lawlor, http://dx.doi.org/10.1016/j.actaastro.2014.07.011

[20] ANITA2 Trace Gas Analyser for the ISS-Flight Model Finalization and ground test results, 49th International Conference on Environmental Systems, ICES-2019-67, July 2019

[21] Space Mission Utility and Requirements for a Heat Melt Compactor, John W. Fisher, 46th International Conference on Environmental Systems, ICES-2016-377, July 2016