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An Approach to Habitation for the Global Point of Departure (GPoD) Lunar Architecture

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The International Lunar Habitation Team (ILHT) was formed in late 2008 to support the International Architecture Working Group (IAWG) (Laurini, K., et al., IAC-10-A5.2.9) and Campaign Integration Team (CIT) (Culbert, C., et al., IAC-10-A3.2A) of the International Space Exploration Coordination Group (ISECG) in identifying the functions and operations required for conducting a collaborative campaign associated with a human return to the moon. A representative example architecture and notional mission manifest for human exploration developed by the IAWG called the “Global Point of Departure” (GPoD) served as the basis for “Habitation System” analysis and definition. Habitation, provided within safe pressurized volumes, is an essential function required to sustain human life in any exploration mission regardless of destination, while incorporating technical sustainability wherever possible.

The team’s responsibility was to use a systems engineering approach in identifying:

1. Key mission drivers that determine the approach to Habitation
2. Top level requirements for Habitation that are essential for any exploration mission
3. Mission operations that result from meeting these drivers and requirements
4. Functionality needed to carry out these mission operations

The systems approach, illustrated in Figure 1, describes the flow of decisions with an iterative loop that feeds back into the CIT campaigns. Variables, such as competing mission objectives and campaign manifesting options driven by different internationally provided lander options, influence the strategy for habitable volumes.
This paper is an overview of the collaborative work performed over the last 18 months in describing the analysis, products, and concepts, including insights from this work. It identifies opportunities for research and development, incorporation of technical sustainability, and standards that might enhance interoperability and standardization of interfaces.

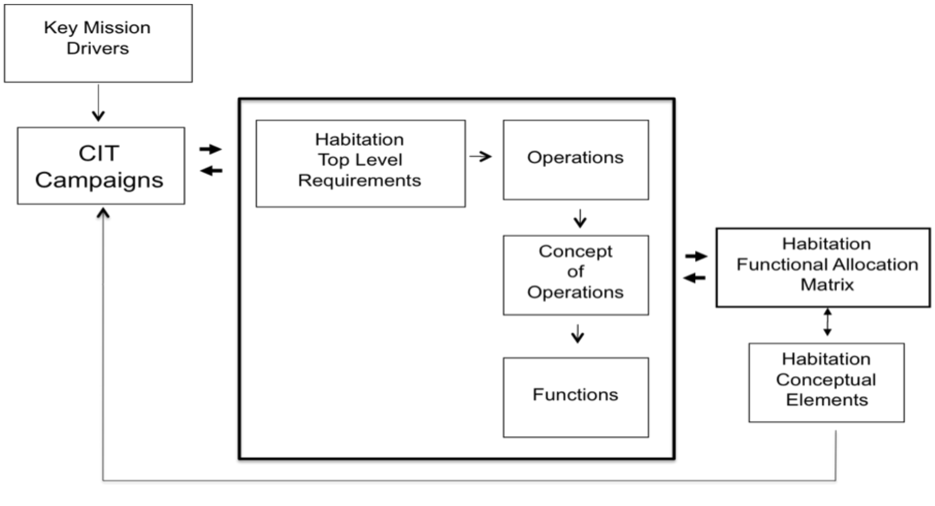


Figure 1 “International Lunar Habitation Team Systems Engineering Process”

INTRODUCTION

The International Lunar Habitation Team (ILHT) was tasked with identifying functions and operations required for conducting an international campaign of missions associated with a human return to the moon and with developing a set of high-level habitat concepts. In addition, a number of case studies and detailed lunar habitation studies were conducted to inform the Lunar Habitation System design.

The lunar habitation system defined within this international team supported and addressed all of the phasing identified within the GPoD Campaign, as described in (Culbert, C., et al, IAC-10-A3.2A).

The ILHT performed analysis of the "Habitation System" defined as the pressurized volumes within lunar surface elements that provide :

(1) a safe living and working environment for the crew

(2) functionality in support of the lunar missions, such as Extravehicular Activity (EVA) suit maintenance and science workstations, and

(3) a set of carriers for the delivery of crew logistics supplies, pressurized cabins within crew mobility systems, and interfaces for EVA System elements (e.g., suit maintenance workstation, airlock, suitlock, or hybrid).

The Habitation System is a distributed system that essentially exists wherever the crew may be on the lunar surface and, therefore, it integrates various crew and mission support subsystems.

This is shown in Table 1, "Habitation Subsystems & Subsystem Description."

SUBSYSTEM	SUBSYSTEM DESCRIPTION
Structures/Enclosure	Basic structure and substructure providing the enclosure to contain internal pressure and sustain transportation loads.
Environmental Control & Life Support System (ECLSS)	Life support system that provides the habitat internal environment (atmospheric composition, pressurization, temperature and humidity), potable water, waste management, & emergency systems. May include waste management storage or recycling equipment in a closed system.
Extra-Vehicular Activity (EVA) System	Those systems and equipment required to enable EVA from the pressurized interior of the habitat and support suit servicing.
Thermal Control System	System for collecting and safely dissipating heat generated by the habitat systems and crew.
Power Management & Distribution (PMAD) System	The system that receives power from an external power source, conditions the power, and distributes it throughout the habitat.
Avionics / Communications Systems	Computers, data management systems, and communications systems within the habitat elements.
Crew Accommodations	Those items needed to outfit the habitat interior (e.g., crew quarters, food preparation and exercise/countermeasure equipment).
Science Accommodations	Mission-specific science and experimentation equipment and laboratory workstations.
Stowage System	Storage volume required for personal and mission related equipment (including mission spares).

Table 1
Habitation Subsytems & Subsystem Description

The ILHT identified the following criteria for developing a lunar habitation system:

1. *Key mission drivers* that determine the approach to the Lunar Habitation System
2. *Top level habitation requirements* for any lunar exploration mission
3. *Mission operations* that result from meeting these drivers and requirements
4. *Functionality* required to carry out these mission operations

The primary task of the ILHT was to identify those functions required to support the health, well being, productivity and safety of the crew. The secondary task involved allocating those identified functions among elements of the GPoD campaign.

KEY MISSION DRIVERS

The ILHT began by analyzing those aspects of a campaign that are *Key Mission Drivers* for habitation, addressing the question, "what are those quantitative and qualitative aspects that need to be included in any campaign to provide the information required to perform a proper assessment of the proposed campaign approach?" A total of 21 Primary *Key Mission Drivers* (see Table 2) and 24 Sub Mission Drivers were identified and analyzed.

1. Mission Objectives
2. Earliest Date Required
3. Number of Visits and Frequency
4. Crew Size
5. Mission Duration
6. Manned Operations during Lunar Day and/or Night Cycle
7. Operations in an Unmanned Mode including Night Survival
8. Provide Radiation Protection for the Crew
9. EVA Interaction
10. Extendibility (having an interface that allows connection to other habitation elements)
11. Habitation Mobility (Yes / No for each) (See Figure 2 for a representative example)
12. Surface Transportation (i.e., Mobility other than Habitat)
13. Logistics & Consumables Strategy
14. Power Supply (external or internal)
15. Unload from Lander (See Figure 3 for a representative example)
16. Location on Surface (Global, Mid-Latitude, Polar)
17. Lifetime Requirement
18. Mars Extensibility standards
19. Transportation Architecture Constraints
20. Launch Vehicle Options
21. Lander Vehicle Options

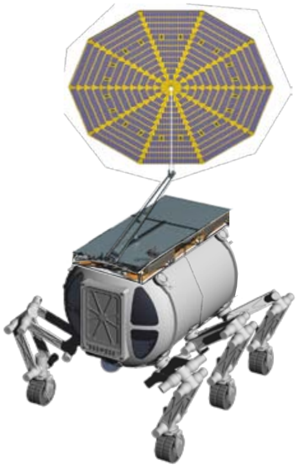


Figure 2

Mobile Habitat Approach

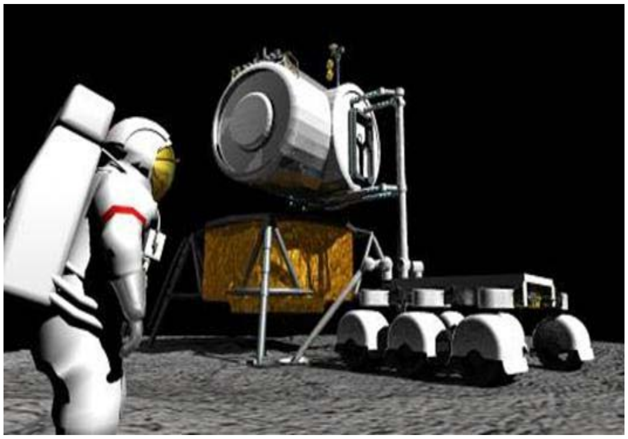


Figure 3

Cradle Unloader

TOP LEVEL HABITATION REQUIREMENTS

Following the identification of key and sub-mission drivers, the ILHT then identified 12 *Habitation Top Level Requirements* and their associated rationales that would be applicable regardless of location, mission duration or mission objectives. The 12 *Habitation Top Level Requirements* and rationales are given in Table 3, "Habitation System Top-Level Requirements & Associated Rationales."

Table 3

Habitation System Top-Level Requirements & Associated Rationales

ID	***Habitation Top-level Requirement***	***Rationale***
H1	Habitation is required for any crew operation on the lunar surface, regardless of crew size or stay time	Providing a habitable environment is required to insure crew health, safety and performance during lunar surface missions. The crew size, duration of mission and level of safety required will determine the extent of the habitation required.
H2	Habitation provides a "shirt-sleeve" environment for the crew	Habitation provides the subsystems and consumables necessary to sustain crew operations within a pressurized environment.
H3	Habitation supports activities at any location on the lunar surface (i.e., global surface exploration)	Access to sunlight for electrical power and thermal conditions varies widely on the Moon. To accommodate the range of siting and exploration options, habitation elements should be designed for all locations.
H4	Habitation supports progressive, sustainable and continuous human presence during lunar day and/or night cycles	To support the initial crew landings, exploration and in-situ resource utilization, habitation elements should be designed to accommodate the early short stay mission while growing to support the potential of continuous presence.
H5	Habitation supports interoperability across multiple lunar surface elements	Interoperability is defined as the capability to interact with other elements on the surface, such as rovers and other pressurized elements (including interfaces required).
H6	Habitation supports EVA capability	EVA provides a transition between fixed or mobile habitation elements and the surface. They are designed to regulate pressure differential, minimize loss of consumables, control dust contamination and provide for suit maintenance and repair.
H7	Habitation provides pressurized logistics resupply	Logistics are necessary for crew survival. Since the logistics will need to be delivered from Earth, habitation must provide a pressurized environment for those logistics, requiring an interface to the main habitable environment.
H8	Habitation supports crew health and performance	Health and medical support is required on the lunar surface, including exercise and medical treatment capability within the habitation element(s). The extent of this support is determined by mission duration and amount of internal volume available. The strategy for medical treatment is still being defined by the "Medical Community" and will eventually be implemented within the Habitation System. "Medical Treatment" could range from limited scale (remotely) to requirements for emergency treatment and transport to LLO or Earth.
H9	Habitation supports IVA scientific work inside the habitable environment	IVA scientific work includes geo-science, biomedical/life science, and potentially physical and fluid science. In-situ scientific analysis is possible for many science experiments and is very cost-efficient compared to transport of samples back to Earth. This support capability includes storage of samples, instruments and materials supporting the analysis within the pressurized environment.
H10	Habitation supports monitoring and control of external scientific activities	Lunar scientific work includes activities performed external to the habitat (both EVA and/or robotic). These activities may occur some distance away. Therefore, the habitat needs to ensure the most efficient monitoring and control of those external activities.
H11	Habitation allows for pressurized and unpressurized interfaces	Habitation approaches will require interfaces to both unpressurized and pressurized assets. For example, unpressurized assets may include external power systems and structural attachments; pressurized assets may include mating adapters, rovers, logistics, and airlocks. These interfaces should be standardized.
H12	Habitation supports communications links to Earth or a Lunar Relay Satellite (depending on location), to a Low Lunar Orbit station (if applicable), to other lunar surface elements, vehicles and EVA	The Habitation System will need to support the main communication "hub" for the lunar surface as well as from the lunar surface. The extent of that support will be determined by the communications strategy provided by the Communications and Navigations Function Team and the Campaign Integration Team.

OPERATIONS

The ILHT then identified high-level *Operations* required to meet the Top Level Requirements. The following are the five main operational areas:

1. *Crew Operations – IVA*

Sustain crew on lunar surface for mission. These functions are necessary to insure the safety of the crew, including providing the functions necessary to sustain the crew from a health and well being perspective.

2. *Crew Operations – Supporting EVA* (see Figure 4)

Enable Redundant EVA Function & Enhanced EVA Capability. These functions are necessary to provide the crew with additional means to conduct routine EVAs. The extent of EVA support provided is driven by the mission duration and the number of EVAs required to conduct that mission.

3. *Mission Operations* (see Figure 5)

Enable Enhanced Mission Operations Capability. These functions are necessary to enable the lunar surface crew to conduct surface operations in concert with the Earth-based “mission control.” For longer surface stays, it establishes autonomy from the Earth-based "mission control,” enabling local command and control with other surface assets, such as rovers, landers, etc.

Figure 4
Crew Operations – Supporting EVA

Figure 5
Mission Operations

4. *Science Operations* (see Figure 6)

Enable IVA Bio/Life Science & GeoScience Capability. These functions are necessary to conduct the science involved with lunar missions. This function includes such operations as sample collection, sample analyses, sample prioritization (“high-grading”) and storage, and any sample return required. It also includes "environmental" requirements specific to Life Science or GeoScience

5. *Logistics and Maintenance Operations – IVA & EVA*

Enable Maintenance, Resupply, & Spares Cache. These functions allow for maintaining the surface assets during recognized maintenance intervals. It includes those functions necessary to resupply the habitat(s) with consumables (both pressurized and unpressurized) to support the crew for the mission. It also includes the functions to deliver and store the necessary spares related to planned maintenance and unexpected failures.

The ILHT traced these identified Habitation System Operations to the Top Level Requirements identified previously. Finally, the ILHT identified the detailed Habitation functions required by decomposing Habitation System Operations. Table 4 summarizes this decomposition

Figure 6
Science Operations

Table 4
Habitation System Functions Decomposed from
Top-Level Requirements & Operations

Requirement Supported (refer to Table 3)	***Operation***	***Function to Support Requirements & Operations***
H1, H2, H3, H8	Crew Operations - IVA	
		Waste & Hygiene
		Food Preparation
		Wardroom
		Dust Mitigation
		Crew Work Stations
		Sleep Areas
H1, H6	Crew Operations – Supporting EVA	
		EVA: External Porch (includes dust porch, ramp, lights, electrostatic curtain for dust mitigation, tool carrier)
		EVA: Suitlock / Suit port / Airlock
		EVA: Airlock / Suitlock System
		EVA: Airlock / Suitlock Services in Dust Containment Area
		EVA: Additional Suit Stowage
		EVA: Suit Maintenance
		EVA: Stowage
H1, H2, H3, H5, H9, H12	Mission Operations	
		Work Stations (Data Management/C&DH)
		Communications
H8, H9, H10	Science Operations	
		Bio Lab Work Station / Tools / Instrumentation
		Geo-Science Lab Equipment / Glovebox
		Geo-Science Work Station / Tools / Instrumentation
H4, H5, H7, H11	Logistics and Maintenance Operations – IVA & EVA	
		Diagnostics & Repair
		Tool Stowage
		Work Surface & Area
		Resupply / Spares
		Stowage, Inventory, Trash Management

HABITATION INNOVATION IDEAS

While supporting the CIT and identifying required functionality of the proposed campaign approaches, two areas of possible innovation were explored.

- "LOGISTICS-TO-LIVING CONCEPT."
The first innovative idea was an approach to the logistics delivery that converted logistics packaging and hardware into outfitting for the interiors of the habitation elements.

- "LLM REUSE."
The second innovative idea involved the conversion of a logistics carrier, the Logistics-to-Living Module (LLM), into a true habitable element.

LOGISTICS-TO-LIVING CONCEPT

Typically, spacecraft, such as the International Space Station (ISS), provide adequate volume for living and working. The consumables, such as food, clothing, and spares, are usually launched in resupply spacecraft using a logistics system that incorporates soft bags and dedicated lockers (e.g., Space Shuttle, Soyuz).

When developing inputs for the GPoD, the ILHT found it important to address one of the IAWG's top-level objectives – Sustainability. To that end, the ILHT studied an innovative approach named "Logistics-to-Living." The basics of this approach:

1. Proposes the re-purposing of elements used for resupply, such as pressurized logistics carriers to provide additional habitable volume for the crew
2. Proposes the re-purposing of the soft goods carriers and substructure, inside the pressurized logistics carriers, to provide internal outfitting

Sustainability is realized through:

1. A consolidation of dedicated elements needed for habitation and pressurized logistics elements, thereby reducing the overall number of pressurized elements necessary in the manifest.
2. The reduction of the mass and amount of internal outfitting required for habitation functions, such as crew bunks, work surfaces, radiation protection, and dividers by "recycling."

By requiring that all packaging systems be dual-use, it should be possible to reduce the overall mass for the GPoD. The ILHT concept for a dual use of the logistics delivery and packaging system produces a "kit-of-parts" that can be reconfigured and assembled later into other structures and potential uses.

LLM REUSE

LLM Overview

The LLM is a pressurized module used to deliver consumables and hardware to the lunar surface. It is 3.5 m in diameter with a length determined by the amount of logistics to be delivered and accommodations for reusability. The LLM has two end-domes; one is a pressure bulkhead without an opening and the other has a common pressurized element interface with a hatchway for crew access (see Figure 7). The module is dependent upon attached resources for electrical power, thermal control and environmental control and life support functions and, for planning purposes, uses the modularity of Cargo Transfer Bag Equivalents (CTBEs) for internal packaging of the module.

Figure 7

Logistics-to-Living Module (LLM)

Purpose for Reuse

The GPoD requires frequent deliveries of logistics from the Earth to support crew activities on the lunar surface. Once the consumables and hardware in the LLM are used or distributed, it can be discarded or reused. Reuse is the preferred answer. The first LLM is delivered during the Polar Exploration/Systems Validation phase and, by the HLM+12 of the Long Duration phase, five LLMs will have been delivered, making the spent LLM's potential elements for additional habitation functionality.

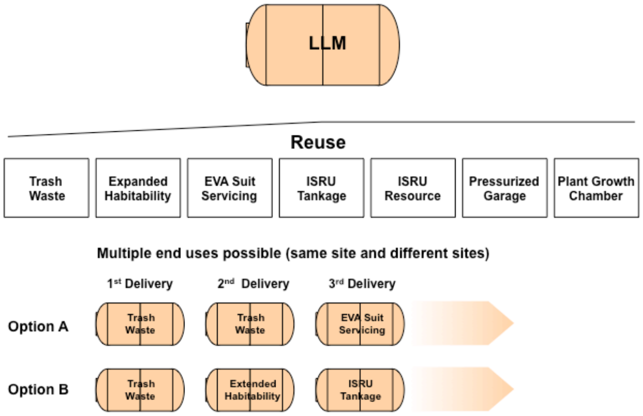


Figure 8 LLM Reuse Options

As shown in Figure 8, eight reuse options were identified. These options are:

1. <u>Trash/Waste:</u> This option replaces the consumed logistics with waste and trash produced by the crew. This function will be required throughout the life of the outpost, but because of enhanced disposal methods, less volume will be required in the out years.
2. <u>Expanded Habitability</u>: The Long-Duration Habitat delivered for the Long Duration phase accommodates the functional requirements, but does not offer much additional volume. An Expanded Habitability LLM can serve many functions, but one would be pre-configured for a galley/wardroom
3. <u>Expanded GeoScience</u>: By the time Long-Duration Habitat is delivered to the Moon, there will have been eight years of geo-science exploration. Furthermore, delivery of the Long-Duration Habitat begins the Long Duration phase of the campaign. For these reasons, the Long-Duration Habitat is equipped to stress biological science. However, to still accommodate the geo-sciences, this option is pre-configured to support this function.
4. <u>EVA Suit Servicing:</u> Prior to the arrival of the Long-Duration Habitat, all mission durations were within the scheduled EVA suit servicing limit (i.e., 28 days). However, the 70-day stay will experience two scheduled service periods. For this option, the LLM would be pre-configured to support test, checkout and re-certification of the EVA suits.
5. <u>ISRU Tankage</u>: There are residual gases in the lander and the ISRU activities at the pole are also producing gases. For this option, the LLM is used as a pressure vessel for gas or liquid storage. One disadvantage is that the structural design is sized for an operating pressure of 8 psi and typically gasses are stored at much higher pressures.
6. <u>ISRU Resource</u>: The LLM is made of known materials that have value. This option uses the LLM principally for its materials, not excluding other creative applications of the hardware.
7. <u>Pressurized Garage</u>: Over time, external hardware will require maintenance or repair. Rather than constraining the time and precision to EVA, an LLM garage would allow shirtsleeved crew members to service and check out equipment in a pressurized environment.
8. <u>Plant Growth Chamber</u>: A plant growth chamber has been identified as contributing to the Environmental Control and Life Support System and to long term sustainability. This option would be pre-configured to serve the end use of growing and harvesting plants.

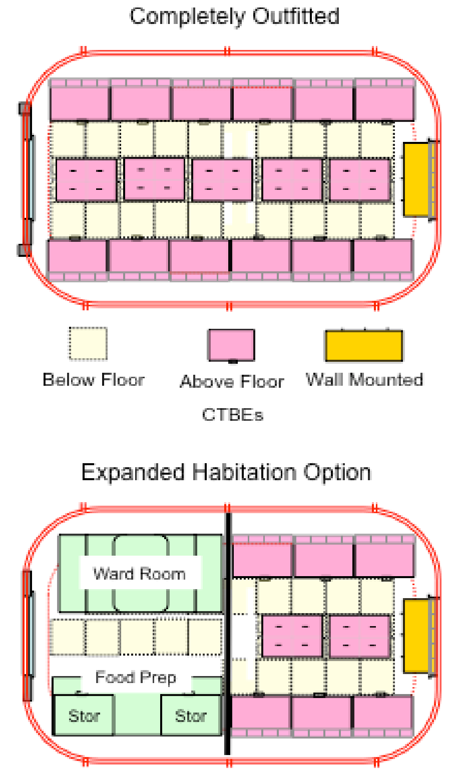
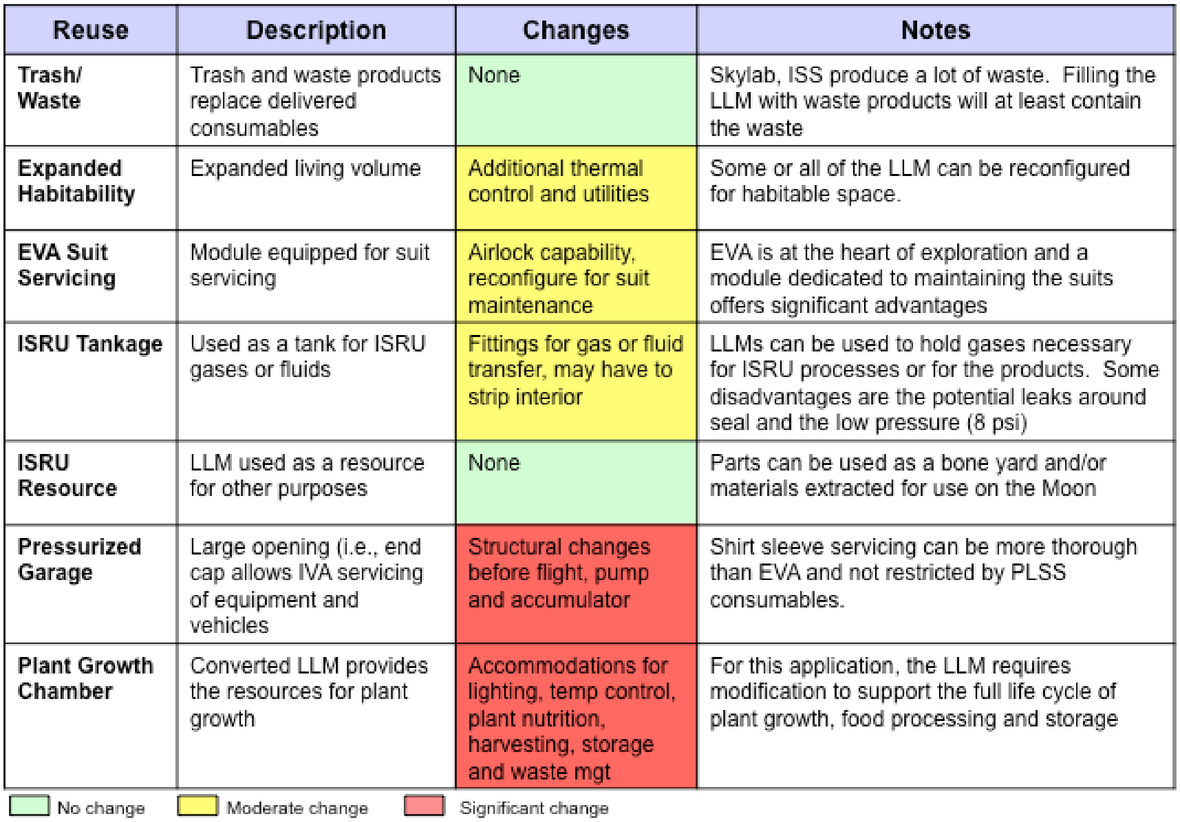


Figure 9 – LLM Reuse as Expanded Habitation

Figure 9 shows an example topology schematic for potential reuse of an outfitted LLM transitioned into the Expanded Habitation Option.
(CTBE = Cargo Transfer Bag Equivalent)

Impact of LMM Reuse

Some options allow reuse of the “bare bones” LLM without changes to the subsystems, while other reuse options require modifications. Figure 10 shows a preliminary assessment of the impact to the LLM to accommodate the options.



Reuse	Description	Changes	Notes
Trash/ Waste	Trash and waste products replace delivered consumables	None	Skylab, ISS produce a lot of waste. Filling the LLM with waste products will at least contain the waste
Expanded Habitability	Expanded living volume	Additional thermal control and utilities	Some or all of the LLM can be reconfigured for habitable space.
EVA Suit Servicing	Module equipped for suit servicing	Airlock capability, reconfigure for suit maintenance	EVA is at the heart of exploration and a module dedicated to maintaining the suits offers significant advantages
ISRU Tankage	Used as a tank for ISRU gases or fluids	Fittings for gas or fluid transfer, may have to strip interior	LLMs can be used to hold gases necessary for ISRU processes or for the products. Some disadvantages are the potential leaks around seal and the low pressure (8 psi)
ISRU Resource	LLM used as a resource for other purposes	None	Parts can be used as a bone yard and/or materials extracted for use on the Moon
Pressurized Garage	Large opening (i.e., end cap allows IVA servicing of equipment and vehicles	Structural changes before flight, pump and accumulator	Shirt sleeve servicing can be more thorough than EVA and not restricted by PLSS consumables.
Plant Growth Chamber	Converted LLM provides the resources for plant growth	Accommodations for lighting, temp control, plant nutrition, harvesting, storage and waste mgt	For this application, the LLM requires modification to support the full life cycle of plant growth, food processing and storage

🟩 No change 🟨 Moderate change 🟥 Significant change

Figure 10 – Preliminary assessment of LLM Reuse

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The ILHT and its support of the CIT have initiated the formation of a basic collaboration of habitation experts from NASA, ESA and JAXA. It has been invaluable in the sharing of previous work and studies amongst the participants. A valuable lesson learned has been that the generic, but comprehensive and structured approach to analyzing the habitation function, proved useful and beneficial. It provided the capability of handling all scenarios given by the GPoD Campaign. However, there have been no schedule or resources provided to perform any new, detailed, truly international analysis that resulted from the campaign work.

Therefore, the proposed future work involves a more rigorous collaboration among NASA, ESA, JAXA and possibly other space agencies on particular topics and represents a consensus of all inputs from all agency team members.

General Habitation:

- Conduct an international Analog Volume Workshop to look at Earth and Space analogs and their applicability in determining volume requirements and operations concepts for habitats applicable to various missions beyond low Earth orbit.
- Identify areas of opportunity for demonstration on ISS of relevant habitation technologies and demonstrations.
- Promote more international participation and collaboration in analog field tests (not just NASA, but international analogs).
- International elements should be further detailed, which will make it easier to integrate them into future campaign work.
- Integrate international elements into the developed classification and Concept of Operations.
- Provide an opportunity for “out-of-the-box thinking” and development of innovative concepts (e.g. greenhouses, and a step further, e.g. crewed hopper).
- Perform a more detailed evaluation of the Logistics-to-Living concept, including hardware, softgoods, packaging and operational concepts.
- Assess architectural habitation approaches that maximize the potential for technology and operational commonality between lunar surface missions and other planetary surface and deep space mission types.
- Develop a Mobile Habitat architecture. Analyze vehicles for different size landers, assess design changes for polar and equatorial operations and examine exploration alternatives.
- Study feasibility of creating lunar habitats using existing international space systems.

EVA:

- Hybrid (suit port within suitlock) development work to support contingency and nominal maintenance operations while minimizing consumable use and dust transfer.
- Assess architecture for ECLSS and EVA Portable Life Support System (PLSS) commonality.
- Study feasibility of creating a minimum set of science and maintenance tools for use by both humans and robots.
- Continue increasing fidelity of the formulation of ISS demonstrations, pre-cursor mission experiments, and other analogs.

ECLSS :

- Continue technology development to increase the degree of closure achievable in life support oxygen and water loops and to efficiently manage wastes.
- Pursue opportunities to demonstrate long-duration operation of advanced life support technologies on the ISS and in other suitable analogs.
- Assess life support architectural approaches that maximize the potential for technology and operational commonality between lunar surface missions and other planetary surface and deep space mission types.

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