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# Human in the Loop: an evaluation process in support to the development of Gateway International Habitat

**Arianna Di Guida[a*], Abele Quaregna[a], Roberto De Amicis[a], Guido Taddia[a], Nona Zakoyan[a], Federica Vagnone[a], Barbara Imhof[b], René Waclavicek[b], Chris Gilbert[b], Ingo Retat[b], Peter Weiss[c], Mohamed Makthoum[c], Nisheet Singh[c].**

[a] *Thales Alenia Space Italy, Strada Antica di Collegno 253, Torino, 10146, Italy*
[b] *LIQUIFER Space Systems, Fahrenheitstraße 1, 28359 Bremen, Germany*
[c] *Spartan Space, 167 Plage de l'Estaque F, 13016 Marseille, France*

## Abstract

The work done for the ISS has allowed the European space community and Thales Alenia Space to mature a key heritage and background in the field of design and development of habitable pressurized modules and understand how to live in space.

Human space exploration beyond LEO is now posing new challenges: compatibility with last generation launchers, different mission environments, limitation on module mass at launch with consequent reduced size and volumes cause us to rethink the design of the interior of the modules, to try balancing in the most efficient way the system/ equipment accommodation with the need to preserve adequate room for the crew.

The Cislunar Gateway can be considered one of the closer-in-time new exploration frontiers: Thales Alenia Space has a key role on several of its elements, and in particular, as Prime Contractor to ESA, provides the Lunar International Habitat (I-Hab), the 'core' living quarters of the Gateway.

In the design process of the Gateway International Habitat it is crucial to implement a process that pinpoints potential issues related to human systems integration, in order to guarantee a more user-friendly design. For this reason, a dedicated process, called Human-in-the-Loop (HITL) and already employed for other habitable modules by major Space Agencies, has been deployed and customized for Lunar I-Hab needs and peculiarities.

The HITL evaluations, through assessments consisting in the performance of specific operative and utilization scenarios, aims at demonstrating that the design aligns with system requirements for effectiveness, efficiency, acceptability and safety. These assessments entail user-representative participants evaluating accessibility and operability of crew interfaces, while executing planned tasks using flight-representative hardware and procedures.

Since HITL is a living and iterative process, with scenarios repeated multiple times during the incremental design phases, ad-hoc physical mock-ups have been developed to reflect the design maturity at various stages, ranging from simple volumetric representation (low-fidelity mock-up) to a more detailed representation of the crew interfaces (medium-fidelity mock-up).

Lunar I-Hab developmental HITL plays a pivotal role because it enables the incorporation of the insights of the users and the expertise of crewmembers into the design of the habitation module, becoming an effective way to highlight potential issues already in the frame of the design phases in between subsystems PDR and system CDR.

**Keywords:** Lunar Gateway, Lunar I-Hab, Human-in-the-Loop, Mock-up.

**Acronyms/Abbreviations**

CDR Critical Design Review
ConOps Concept of Operations
ESA European Space Agency
EVA Extra-Vehicular Activities
GP Gateway Program
HCD Human-centred design
HF High Fidelity
HITL Human-in-the-Loop
HSI Human System Integration
HSR Human System Requirements
I-Hab International Habitat
IVA Intra-Vehicular Activities
LF Low Fidelity
MF Medium Fidelity
NASA National Aeronautics and Space Administration
PCC Private Crew Compartment
PDR Preliminary Design Review
R&MA Restraints and Mobility Aids
TA Task Analysis

| | |
|---|---|
| TC | Test Conductor |
| TM | Test Manager |
| TRR | Test Readiness Review |
| TS | Test Subject |
| VCN | Verification Closure Notice |
| WSA | Worksite Analysis |

## 1. Introduction

The Lunar Gateway is a pivotal element in the future of space exploration, representing a collaborative effort among international space agencies to establish a sustainable human presence beyond Earth's orbit. As humanity sets its sights on returning to the Moon and venturing further into deep space, the Gateway serves as a critical outpost for scientific research, technology demonstration, and international cooperation.

Thales Alenia Space has been chosen as Prime Contractor of ESA for the development of Lunar International Habitat, one of the components of the Lunar Gateway, which is designed to accommodate astronauts for extended periods, offering life support systems, workspaces, and facilities for scientific experiments. Lunar I-Hab plays a crucial role in ensuring the Gateway's functionality as a hub for deep space exploration, enabling long-duration missions and enhancing the safety and well-being of the crew.

It will be the living, sleeping and dining room for the astronauts, as well as allowing experiments to run both inside and outside the module.[1]

Fig. 1. Lunar I-Hab on Gateway[1]

In designing the Gateway International Habitat, it is essential to implement human-centred design process (HCD) that identifies potential challenges related to human systems integration, ensuring a more user-friendly design. To achieve this, a specialized process known as Human-in-the-Loop (HITL)—already used by major Space Agencies for other habitable modules—has been adapted and tailored to meet the specific needs and unique characteristics of the Lunar I-Hab module.

## 2. Lunar I-Hab HITL process

The Gateway Human System Requirements (HSR) establish both requirements and verification methodologies to ensure the proper integration of humans within the Gateway Program (GP).

Lunar I-Hab must comply with these human rating requirements, which drive the design to accommodate human capabilities and limitations while ensuring the safety of the crew. The HSR is a critical component of human rating for exploration systems, ensuring compliance with mandatory standards in Health and Medical, Safety and Mission Assurance, and Engineering.

The application of the HITL process, which involves the performance of HITL evaluations, is essential for verifying some of these requirements for the International Habitation module. Therefore, tests must be conducted with a sample of participants to accomplish the requirement verification and/or to perform a preliminary assessment on that.

The Lunar I-Hab HITL process covers IVA (Intra-Vehicular Activities) on-orbit tasks.

HITL evaluations are scenario-based events used to identify potential issues with human systems integration (HSI), which are used to demonstrate that the design and operational concept meet system requirements for effectiveness, efficiency, acceptability, and safety.[2] They involve user-representative participants performing planned tasks with flight-representative hardware, software, and procedures.

The HITL evaluations consists in the execution, in 1g environment, of scenarios representing typical nominal, off-nominal and emergency on-orbit situations.

To be noted that tasks execution on ground/1g environment vs on-orbit/0g environment is a challenge for the design and manufacturing of the test articles.

For EVA (Extra-Vehicular Activities), the tasks will be reviewed during the design phase by the NASA EVA Team and tested (in terms of accessibility and feasibility) in the NBL (Neutral Buoyancy Laboratory) facility in Houston, under NASA's responsibility.

HITL includes both test and non-test evaluations and specific evaluations of required human interaction with the rest of the system. The HITL is based on program requirements, Concept of Operations (ConOps) and on typical Human Factor Engineering tools such as Task Analysis (TA) and Worksite Analysis (WSA), which are two pillars of the HCD approach.

HITL evaluations are often used during design and development, for design trade decision making or to evaluate concerns raised during development.

These can start by creating a high-level list of identified HITL test scenarios based on the overall ConOps. Then, refining them as hardware and task definition matures and associate each one to the typical on-orbit tasks defined by NASA, whose execution is linked to the verification of a specific requirement.

HITL execution involves user-representative participants performing planned tasks with flight-representative hardware, software, and procedures.

The test subjects' sample selection shall be performed considering the whole anthropometric range so that the design can be verified versus different percentiles.

As part of the human-centred design process, HITL tests are carried out using physical mock-ups of increasing fidelity along the design path, including tests on the (proto)flight model of the system to validate the human systems integration of the final design.

*2.1 Developmental HITL vs Verification HITL*

HITL evaluations are divided in two main categories: Developmental and Verification HITL.

*Developmental HITL* evaluations are conducted to support design and development efforts and ensure a smooth path to verification. These evaluations offer an opportunity to aid in technical trade decisions, refine the design, and enhance ConOps based on human system performance. Additionally, they help identifying potential issues associated with human-system interfaces.

For this reason, the primary objective during test execution is to gather data and feedback that can be translated into design enhancements, thereby making it more user-friendly.

A standard Developmental HITL consists in test subject (TS) evaluation of accessibility and of the anthropometric range of motion to reach an equipment used in the daily life on-orbit. Another important goal of Developmental HITL is to identify all the restraints and mobility aids (R&MA) type and position, to allow crew moving inside the module and to allow task execution for each worksite.

The Lunar I-Hab Developmental HITL test campaign has been executed in May 2024 between subsystems PDR and system CDR, when eventual feedbacks of the TSs can be reflected in the design, which is not yet fully finalized.

The test has been performed using a dedicated full-scale LF Mock-up by crew and non-crew test subjects-in Thales Alenia Space in Turin.

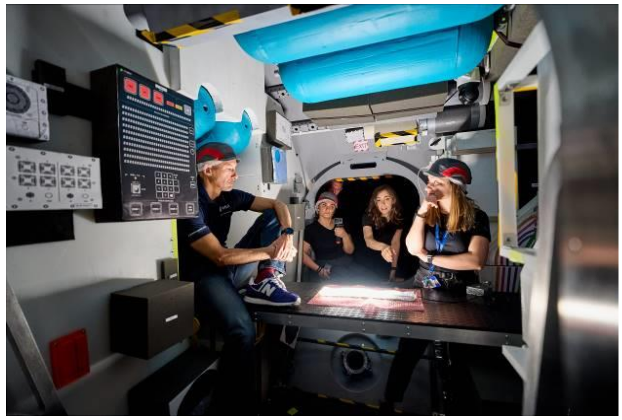

Fig. 2. Test team and TS during Developmental HITL[3]

*Verification HITL* tests are conducted to close Human System requirements through verification closure notices (VCNs). They occur in the highest fidelity mock-up possible, including also flight model.

A typical Verification HITL test objective is to verify the physical operability of crew interfaces (e.g. remove and replace of a box for maintainability).

The Lunar I-Hab Verification HITLs are foreseen to be executed in two different timeframes: one on the MF Mock-up right after the System CDR (beginning of 2026), one later directly on the flight model in 2027.

They will be performed after the CDR in order to verify the quality of the final design. The selection of test scenarios will be made together with the Agencies and based on the outcomes of the TA and WSA provided at CDR and also on the critical issues that emerged during the execution of the Developmental HITL.

*2.2 HITL phases*

The process is divided into several phases: Strategic, Tactical, Operational, and Post-Test Phase.

During the Strategic Phase, the test scenarios to be executed are selected and included in the Strategic Plan, which is then validated by the Agencies. Since the tests involves human subjects, the Medical Review Package that includes evaluation of risks/discomforts and mitigating measures, clarification regarding how the resulting data will be used and a description of data protection measures is released and submitted to Agencies Medical Board.

In the Tactical Phase, the test procedures are submitted to the agencies for review.

The preparation of the procedure is quite complex, as it involves continuous iterations and must adapt to design change in the case of Developmental HITL, when the baseline design of the flight model is not yet fully finalized. This preparation shall also consider all the limitations of the mock-up and the fact that execution happens in 1g conditions, emphasizing the differences with the related on-orbit task. In this phase, tests dry runs were performed by Thales Alenia Space test subjects to verify the correctness of the procedures and to identify in advance potential issues in procedures execution, on test hardware and on the availability of support hardware/tools.

The Operational Phase is the real test campaign. The tests execution start after the Test Readiness Review confirms that documentation and Mock-up are ready for testing.

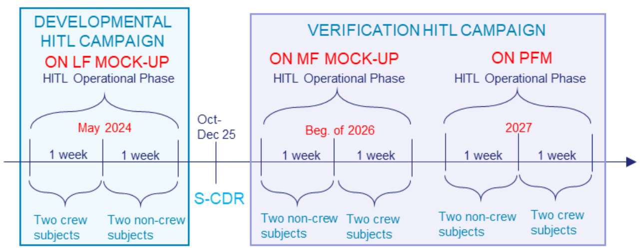


Fig. 3. HITL Operational Phases timeline

In the Post-Test Phase, the Post Test Review (PTR), upon verifying that all tests have been successfully executed and completed, states the official conclusion of the testing phase and the subsequent dismantling of the test setup.

The data analysis is summarized in the test reports. It includes the processing of all the typologies of data collected during the tests: Video Data, Anthropometric Data, Test Feedbacks Data.

In particular, participants' feedback is analyzed in relation to their anthropometric parameters to ascertain whether the execution of a specific task is influenced by factors such as height, limbs length and shoulder width.

The Lunar I-Hab HITL process is tailored and simplified compared to the standard process dictated by NASA, as it involves fewer test campaigns, fewer test subjects and utilization of flight hardware instead of high fidelity mock-ups. This simplification is feasible because Thales Alenia Space anticipate numerous evaluations using virtual reality tools. All these analyses are conducted for different percentiles and are distributed throughout the entire duration of the project. Therefore, continuous checks are conducted on the accessibility and operability of a certain equipment.

*2.3 Test tools*

*2.3.1 Lunar I-Hab Mock-up*

As a full scale replica of the Lunar I-Hab flight module, the Lunar I-Hab Mock-up is provided by the LIQUIFER Space Systems industrial consortium, which include SPARTAN Space, in charge of the design, manufacturing and integration. It consists of a main structure (primary structure) and a cabin interior with two different levels of outfitting: low fidelity interior outfitting and medium fidelity interior outfitting, that differ in the fidelity of the equipment representation.

The Mock-Up Primary Structure design and configuration consists of four cylindrical sections joined by five circular rings.

Fig. 4. Mock-up Primary Structure with stairs and support structure. (Copyright: Thales Alenia Space)

It has a fixed orientation, and it is attached to a support structure with wheels and levelling mechanism. Stairs are used to enter the structure and springboards, positioned along the Mock-up longitudinal axis, allow test subjects to move and perform operations in 1g inside the module.

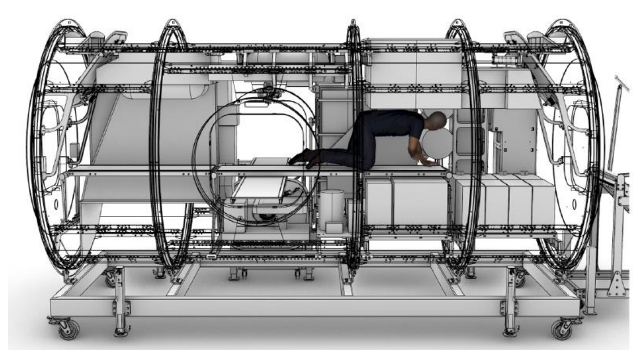

Fig. 5. Mock-up section showing TS motion on the springboards. (Copyright: LIQUIFER Space Systems)

The main objective of the Mock-up primary structure is to provide an accurate overall representative interior volume of the Lunar I-Hab module, entrances to and exits from the module, and structural stability to support the load of the low and medium fidelity interior outfitting items, together with the weight of the personnel involved in the tests.

The LF Mock-up (the Mock-up with the LF interior outfitting) has been used for the Developmental HITL test campaign in May 2024 and it will continue to support the design phase until the System CDR, the milestone that consolidates the design and marks the beginning of the assembly, integration, and verification phases.

Then, the Mock-up will be upgraded to increase its fidelity, incorporating interfaces to simulate more complex operations and the cabin interior will become a medium fidelity cabin outfitting.

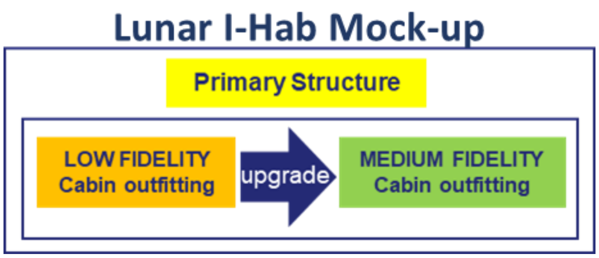


Fig. 6. Lunar I-Hab Mock-up fidelity evolution

LF mock-up boxes are volumetric representations of flight equipment. The boundaries of each internal layout element are converted to the nearest possible shape for volumetric representation. This simplified approach uses materials like foam, plastic, and wood to create a basic and flexible representation of the interior elements. Visual impacts are often conveyed through stickers or labels.

Fig. 7. LF Mock-up interior outfitting in cardboard, plastic and foam

The cabin outfitting includes also two Medium Fidelity items, a functional hatch and a tilting secondary structure. Both of them replicate the physical motion of the corresponding flight models using mechanical devices like counterweights and pistons to unload their own weight.

The Lunar I-Hab LF cabin outfitting does not contain any active devices: the only item electrically powered are the Mock-up lights with manual dimmers.

The transition from LF to MF mock-ups of the cabin interior involves upgrading from basic volumetric shapes to more detailed and functional components.

While the LF mock-up boxes are Velcro-secured foams, the MF mock-up boxes will be realized in metal and will have components that help the simulation of actual operational features such as real mechanical fixations (e.g. brackets and screws).

The MF mock-ups focus on reproducing boxes boundaries with higher accuracy, using 3D printing and closely related commercial off-the-shelf (COTS) products.

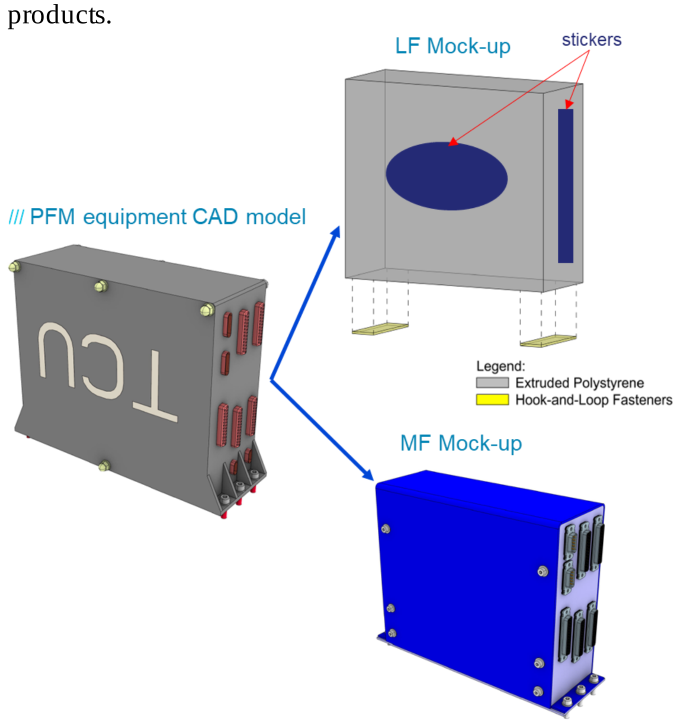


Fig. 8. PFM box LF Mock-up vs MF Mock-up

The Lunar I-Hab MF Mock-up (the Mock-up with the MF interior outfitting) will be used for the Verification HITL campaign.

*2.3.1.1 Benefits of Mock-up projecting*

The Lunar I-Hab Low Fidelity and Medium Fidelity mock-ups projecting brings significant benefits, particularly in identifying and addressing design challenges before final deployment. The two outfitting stages offer opportunities for cost-efficient improvements and play a critical role in extending the design process beyond the capabilities of CAD models. The main benefits are listed as follows.

*Identifying design and integration issues*

Both LF and MF mock-ups help uncover design and integration problems early in the process. By simulating the habitat in a physical space, mock-ups allow for the identification of potential issues in system designs interfaces, and human-system interactions. This early identification is crucial for making cost-effective adjustments before final production.

*Enhancing human task performance*

Transitioning from CAD models to interactive 3D Mock-ups enables designers to better understand how users will interact with the system. This hands-on approach is vital for ensuring that the habitat meets ergonomic and operational needs, which is particularly important for tasks that require precision and efficiency.

*Evaluating habitable volume and emergency procedures*

The mock-ups are also instrumental in evaluating the net habitable volume and the crew's ability to move around within the system. They are useful also to assess critical aspects of crew operations, such as vehicle egress and emergency procedures. Evaluating these scenarios in a controlled mock-up environment allows for improvements in safety and efficiency. Additionally, these mock-ups help in testing the effectiveness of stowage solutions, environmental systems, and overall habitability, ensuring that the final habitat design supports long-term crew well-being.

*2.3.2 Test facility*

As Lunar I-Hab HITL marked the inaugural instance of conducting an HITL campaign in Europe, a dedicated facility was set up in Thales Alenia Space in Italy.

This facility is planned to be utilized for the next steps of the Lunar I-Hab HITL test campaigns and will be available for similar activities on other additional Gateway elements as well as potentially for future habitation modules. It must adhere to specific requirements to ensure the test is performed in the optimal and safe manner.

Moreover, the area must be sufficiently large to accommodate the mock-up and any necessary tools for accessing the interior of the mock-up. It must be equipped with cameras and monitors to record and display the test execution inside the mock-up to the audience in real-time.

Fig. 9. Lunar I-Hab HITL test facility[3]

## 3. Developmental HITL tests execution

According to the Lunar I-Hab customized HITL process, first of all, the test scenarios were defined by Thales Alenia Space technical team and then reviewed by the Agencies.

The test procedures prepared by technical team for each test scenarios were validated by Agencies at the Test Readiness Review (TRR).

The Developmental campaign was divided in 2 weeks. Four test subjects were engaged to perform test scenarios: two crew subjects in the first week and two non-crew subjects in the second week.

The two crew subjects had extensive experience from previous missions on the International Space Station that brought valuable feedback, helping Thales Alenia Space I-Hab programme staff in understanding how to organise the habitat to support life and IVA operations. They are two big percentiles.

The 2 non-crew subjects are from ESA technical staff, with working experience on ISS programmes, one small percentile and one big percentile.

The test subjects were surrounded by test team, organized as follows:

- Test Manager (TM) coordinated the test execution and together with the Quality Control Inspector (QC) was inside the Mock-up and monitored the test subjects throughout each step of the procedure's execution, ensuring that the execution is conducted in a safe manner and guaranteeing support to the test subject.
- Test Conductor (TC) read the procedures step-by-step and clarified unclear steps and answer to eventual test subject's question.
- One test team member was positioned outside the mock-up in a dedicated station to collect

real-time feedbacks from astronauts at each step of the procedure. His role also included asking targeted questions to understand if the feedback could have potential design implications.

Fig. 10. TM and crew TS inside the Mock-up[3]

Fig. 11. TC and crew TS discussing about procedures[3]

Since different test scenarios correspond to different Mock-up internal configurations, before the execution of some test scenarios, a reconfiguration of some Mock-up areas and of springboards was done by Thales Alenia Space personnel.

During the test, the only test subject inside the Mock-up was the one executing the test scenario. The second test subject observed the execution from the outside, interacting with the one inside the Mock-up whenever deemed necessary.

Mainly, the same procedure steps were performed by the first test subjects and then repeated by the second one, whereas some scenarios/steps were required to be performed by both TSs together. Each test subject performs each test scenario only once.

The procedures were executed following main steps as a guide, but a proper sequence was left to allow freedom for TSs considerations on sequence variation and including additional aspects relevant to the task's execution.

All the test scenarios agreed in the Strategic Phase, had been grouped per similarity of actions and worksite in five tests:

*TEST#1*: evaluation of location, accessibility and the anthropometric range of motion to access command panels and typical crew interfaces used by crew in their daily life.

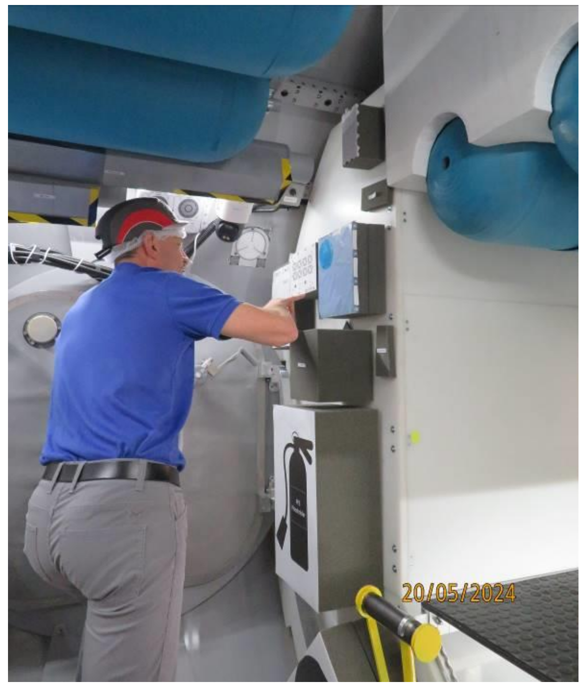


Fig. 12. TS evaluating accessibility during Test#1. (Copyright: Thales Alenia Space)

*TEST#2*: evaluation of position and physical accessibility of egress handrails and FWD (forward) hatch and the anthropometric range of motion to go through translation path and hatch with and without payloads and cargo bags. The test includes also the evaluation of position and physical accessibility to stowage areas and the range of motion of the crew to configure stowage areas, such as stow/un-stow CTBs (cargo transfer bag) and operation of launch constraints.

Fig. 13. TS evaluating stowage areas during Test#2. (Copyright: Thales Alenia Space)

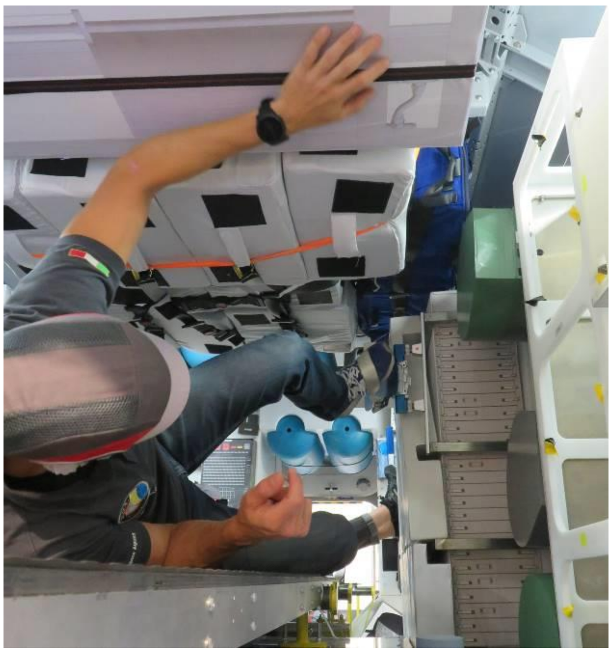

Fig. 14. TS evaluating handrails locations during Test#2. (Copyright: Thales Alenia Space)

*TEST#3*: evaluating location, accessibility and the anthropometric range of motion to access emergency equipment like portable fire extinguisher (PFE) and breathing masks.


Fig. 15. TS evaluating PFE position. (Copyright: Thales Alenia Space)

*TEST#4*: evaluation of the anthropometric range of motion in the galley area with and without table and assessment of location and accessibility of equipment used during meals such as food warmer, potable water dispenser and trash bags and of the equipment to be cleaned during housekeeping.

TEST#5: assessment of physical accessibility to maintainable items accommodated on a tilting structure and also of the anthropometric range of motion to tilt the structure and to access the equipment mounted on it, evaluating R&MAs best locations to operate in the correct position w.r.t. the structure.

Fig. 16. TM demonstrating to TS how to tilt the structure. (Copyright: Thales Alenia Space)

Every testing session has been recorded and all the videos organized in a database.

During the execution, Thales Alenia Space personnel has collected in real time TSs feedback for each step of the procedures file.

After each test execution, test subjects reported personal detailed feedbacks/notes on a dedicated template. In addition, two typologies of questionnaires were required to be submitted to the TSs for human rating and useful to identify design issues that can be fixed prior Lunar I-Hab System CDR.

Each test subject completed the questionnaires independently after finishing their task, while the other subject was still performing the test. This method was chosen both to save time and to ensure that the responses in the questionnaire were not influenced by the other participant or by technical staff considerations.

The first questionnaire scale measures the usability of the crew interfaces, since this is an essential component of error prevention and acceptability of the system. It quantifies the ease of use of the site, application, or environment being tested. It can be used to measure progress of system design over time.

This questionnaire is a mix of positive and negative statements to be evaluated by the test subject using a scale of 5 choices between “strongly disagree” and “strongly agree”.

Each answer is assigned a specific score. If the total score is greater than or equal to 85, the test is passed. On the other hand, scores below 85 indicate the need to carefully consider comments made by the participants, since they point to potential accessibility and usability issues.

The second questionnaire scale is a one-dimensional rating tool created to measure the user's spare mental capacity while performing a task (spare capacity is the number of available resources that can be used for other concurrent/secondary tasks).

The single dimension is assessed using a hierarchical decision tree that guides the test subject through a ten point rating scale, each point of which is accompanied by the description of the associated level of workload.

The subject is asked to consider their spare capacity regarding the three rank ordinal structure whether it was possible to complete the task, the workload was tolerable, or the workload was satisfactory without reduction.

Then, within the groups under each rank, the TS chooses the demand level text that most closely aligns with their workload level. This yields the corresponding workload rating that the evaluator will record.

High scores obtained through this test campaign indicate areas where changes to the proposed layout are required.

Even if these tests focus on usability and workload, their submission is intended to mainly capture the test subjects' feedback on the accessibility of the equipment in the module, since this is the main goal of the first step in the HITL process, the Developmental HITL. A deeper evaluation of usability and workload will be conducted during Verification HITL tests.

For this reason, test subjects’ scores in the questionnaires shall be considered alongside their feedback/notes to understand the recommendations resulting from this HITL campaign.


Fig. 17. TS explaining main feedback to test team. (Copyright: Thales Alenia Space)

At the end of each test day, a wrap-up of feedback and questionnaires scores from test subjects was done by the Test team.

## 4. Results

Test results consist of the collection of test subjects’ feedback on Lunar I-Hab design.

The overall Developmental HITL tests success is based on data collection made up of questionnaires filled by TSs, TSs qualitative feedback and eventual technical team evaluation.

These feedbacks translate into potential changes to the baseline design whose implementation must be evaluated on a case-by-case basis by Thales Alenia Space personnel.

In many cases, during execution, the test subjects have also suggested how to update the baseline configuration to implement their needs and to make the design more user-friendly. Then, the technical team evaluated the implementation feasibility, considering all system aspects that could be influenced by this change.

A striking example of how and how much the HITL evaluations have been useful concerns the galley area, particularly the vertical walls of the Private Crew Compartments (PCC) where items used daily by the crew were mounted.

Fig. 18. TS reconfiguring the two PCC walls. (Copyright: Thales Alenia Space)

Test subjects have reconfigured the area to make it more user-friendly:

- the equipment with similar functions that shall be used simultaneously (e.g. control panels) has been grouped and located on the same wall, so to obtain an airplane cockpit-like configuration;
- the items with no daily use have been removed from the walls and relocated in less accessible zones of the module, in order to gain space for more frequently used equipment;
- some boxes have been re-oriented either to guarantee a better accessibility to command buttons or to ensure that its connectors and cables do not obstruct operations on adjacent boxes.

Particular attention has been given to emergency equipment, as they shall be obviously in a convenient and easy to reach position.

So, this area has undergone a significant reconfiguration by the test subjects. This was made possible thanks to the versatility of LF Mock-up, in which the boxes are in foam and attached with Velcro straps to the PCC walls so they can be easily reconfigured.

After the tests, technical staff evaluated the TSs proposed configuration and after implementing some enhancements, the PCC walls HITL configuration is now part of the Lunar I-Hab baseline configuration.

Therefore, the PCC walls represent a specific case from the entire campaign for which the TS feedback has brought concrete improvements to the design, making it more user-friendly and these improvements are now part of the baseline configuration because of human involvement in the design process.

## 5. Conclusions

Incorporating human involvement through the HITL approach is crucial in the design and development process as it ensures that the final product or system is both user-centric and feasible. The HITL methodology allows for real-time feedback and iterative improvements based on actual user interactions and experiences. By integrating user input throughout the design phase, Lunar I-Hab technical team can better align the system's functionalities with user needs, preferences, and anthropometric limitations. This not only enhances usability and effectiveness but also helps identify potential issues and mitigate risks early in the development cycle. Ultimately, HITL fosters a more robust and user-friendly design, leading to higher satisfaction and better overall functionality of the final product.

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