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An Overview of the New HUMANS Analog Habitat

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Designing Analog Habitats for Moon-to-Mars missions has often separated human factors studies from life support technology development, or focused on isolated test rigs with limited architectural context. Existing analogs and research stations provide key insight on confinement and operations, but few offer a reconfigurable, ECLSS-centric habitat where architecture, operations, and resource cycles are treated as a single integrated system. HUMANS - Humans in the loop Moon and Mars Analog for Sustainability - is the newly born Analog Habitat of the IDEAS Interdepartmental Center at the Polytechnic University of Turin, Italy, created to address this gap. HUMANS is conceived as an interior analog with hybrid capabilities: a pressurized habitat core, configurable ECLSS racks, an operations control segment, and interfaces to ISRU emulators and external laboratories. A Human Metabolic Simulator (HMS) is integrated to reproduce crew loads without constant human presence, while a methane post-processing stage enables hydrogen recovery and carbon separation from the Sabatier outlet, reinforcing a design philosophy centered on resource circularity and sustainability. The facility will progress through phased campaigns: (i) uncrewed integrated tests of atmosphere, water, and waste loops on a physicochemical baseline; (ii) short human-in-the-loop campaigns focused on procedures, interfaces, and contingency operations; and (iii) extended campaigns in which bioregenerative, experimental, and low-TRL technologies are incrementally added to the baseline to explore higher closure and new operational envelopes across Moon-to-Mars mission archetypes. This paper presents the preliminary design of HUMANS, including layout, zoning of technical versus habitable spaces, ECLSS segregation and redundancy strategy, and routing of key utilities as primary architectural drivers. The architecture and design are supported by an integrated model-based workflow (MOSAiC) that links requirements, configurations, and simulations. HUMANS is intended as a long-term European infrastructure where habitat architecture, life support technologies, and sustainable terrestrial applications can co-evolve in a controlled analog environment.

Acronyms and Nomenclature

ACS	=	Atmosphere Control System
ARS	=	Atmosphere Revitalization System
C&DH	=	Command and Data Handling
CDR	=	Critical Design Review
COTS	=	Commercial Off-The-Shelf
CS	=	Crew Systems
ECLSS	=	Environmental Control and Life Support System
EPS	=	Electrical Power System

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FAT = Factory Acceptance Test
FDS = Fire Detection and Suppression
HMS = Human Metabolic Simulator
HUMANS = Humans in the Loop Moon and Mars Analog for Sustainability
ICD = Interface Control Document
ISRU = In-Situ Resource Utilization
MOSAiC = Modeling and Simulation Architecture for Integrated Complex Systems
MVH = Minimum Viable Habitat
ORR = Operational Readiness Review
P-ICD = Preliminary Interface Control Document
PDR = Preliminary Design Review
SAR = System Acceptance Review
SIR = System Integration Review
SM = Service Module
SRR = System Requirements Review
SVR = System Verification Review
THC = Temperature and Humidity Control
TRL = Technology Readiness Level
TRR = Test Readiness Review
WM = Waste Management
WRM = Water Recovery and Management

I. Introduction

ANALOG missions and analog habitats are established instruments to investigate crewed spaceflight through terrestrial, operationally constrained "real-life situations", enabling technology and procedure testing before committing to operational space systems [1] [2] [3] [4]. Within this landscape, analog habitats function as long-duration integrated testbeds where life support, habitability, and infrastructure are exercised as a single system, and system-level integration is a dominant driver of feasibility and operational realism [5] [6].

For Moon-to-Mars mission archetypes, the dominant constraint shifts from logistics-supported, partially open systems toward autonomous and highly regenerative architectures [7] [8], where tightly coupled Environmental Control and Life Support System (ECLSS) loops shape mass, power, reliability, operational flexibility, and verification outcomes [9] [10]. Under these conditions, architectural decisions and operational decisions cannot be treated independently: layout, zoning, redundancy, routing, and technology selection determine what is physically possible, while operating modes, procedures, and schedules determine what is demanded over time [9].

Despite extensive analog heritage, many developments either focus on confinement and crew operations without an ECLSS-centric architectural context, or isolate life-support technology into test rigs detached from the habitat operational scenario [6] [11]. In parallel, existing development practices often fragment the digital thread: MBSE artifacts describe the system, while analyses and simulations are produced as disconnected work products that drift in assumptions and parameters, delaying inconsistency detection and amplifying error propagation across design stages [12] [13] [14] [15]. The net effect is that architectural reconfigurability and operational realism are discussed qualitatively, while quantitative evidence becomes difficult to reproduce across configuration changes and across campaigns.

HUMANS (Humans in the loop Moon and Mars Analog for Sustainability) is being developed at the IDEAS Interdepartmental Center of Politecnico di Torino (Turin, IT) to address the lack of reconfigurable, ECLSS-centric analogs where architecture, operations, and resource cycles are treated as a single integrated system. HUMANS is conceived as an interior, rack-based testbed integrating a pressurized core, configurable ECLSS racks, an operations control segment, and standardized interfaces to external laboratories and ISRU emulators, where power, thermal rejection, data connectivity, and material exchanges are explicitly defined as external inputs through controlled interfaces, instead of being assumed as unlimited or unconstrained background conditions.

HUMANS will progress through phased campaigns, starting with short human-in-the-loop operations and extending to longer campaigns with bioregenerative systems. To protect early operational readiness against low-TRL elements, the project defines a Minimum Viable Habitat configuration enabling initial campaigns based on safety-critical and core life-support functions, with deferred commissioning of advanced subsystems within an explicit schedule buffer.

This paper presents the preliminary design of HUMANS as an ECLSS-driven analog habitat, focusing on (i) facility concept, boundaries, and interface philosophy; (ii) habitat layout and zoning and the resulting integration

architecture for rack-level ECLSS subsystems; and (iii) the phased campaign roadmap and verification logic that enable progressive insertion of experimental and bioregenerative technologies under configuration control. The design is supported by an integrated model-based workflow (MOSAiC - MOdeling and Simulation Architecture for integrated Complex systems [16] [17]) intended to preserve traceability between requirements, configurations, operating modes, and simulation evidence, reducing drift between architecture definition and quantitative assessment.

This paper is structured as follows. Section II presents some related studies for better context of the Reader. Section III defines the HUMANS mission context, facility scope, and boundary conditions, and introduces the capability drivers that make reconfigurability and ECLSS integration first-order requirements. Section IV describes the preliminary architecture, including habitat layout and zoning, rack-based subsystem integration, interface philosophy, and routing and redundancy considerations that enable configuration changes across campaigns. Section V details the phased campaign roadmap and associated verification logic, including the Minimum Viable Habitat (MVH) approach and integration sequence used to reach early operational readiness. Section VI summarizes the supporting model-based workflow and how requirements, configurations, operating modes, and simulation evidence are kept coherent across design iterations. Section VII discusses expected research applications and differentiators relative to existing analog infrastructures, and Section VIII concludes with the facility's development outlook and planned evolution.

II. Related Studies

Analog research for human spaceflight encompasses a broad spectrum of facilities and programs, ranging from field-based EVA analogs and behavioral confinement studies to closed-loop life-support technology demonstrators.

The dominant category of interior analog habitat in the current landscape is the behavioral confinement study facility, in which the habitat itself is a controlled experimental environment for studying crew health, performance, and team dynamics under simulated deep-space isolation conditions. HERA [18], operated at NASA Johnson Space Center, is a three-story, 148.6 m^3 habitat designed for missions of 14 to 60 days and used to study behavioral health, cognitive performance, sleep, and human-systems integration under conditions of isolation, confinement, and communication delay. HI-SEAS [19], operated on the slopes of Mauna Loa, Hawaii, conducted six NASA-funded missions of four to twelve months duration between 2013 and 2018, focusing on crew composition, team dynamics, autonomy, and food psychology. The CHAPEA (Crew Health and Performance Exploration Analog) [20] program, using the Mars Dune Alpha 3D-printed habitat at JSC, completed its first 378-day mission in 2024 with a focus on behavioral health, food systems, resource management, and a 22-minute communication delay simulation. The Concordia station, a French-Italian Antarctic research base used by ESA for long-duration biomedical studies, has supported two decades of medical, psychological, neuroscientific, and cardiovascular research in an extremely isolated environment.

In all of these facilities, life support systems are operational infrastructure, not research variables [6]. The ECLSS functions that keep the crew alive (encompassing atmosphere control, water recovery, CO_2 removal) are provided as baseline services and are not the subject of reconfiguration, technology insertion, or integrated loop verification across campaign phases. This design choice is appropriate to the human factors mission these facilities serve, but it means that no operational knowledge about ECLSS architecture, technology readiness, loop closure, or contingency behavior is generated in these environments.

The review by [6], which examined 22 analog habitats and a selection of extreme-environment research stations, formally identifies this structural separation: facilities are categorized by primary purpose (field geology, human factors, or technology testing) and the three objectives are rarely pursued simultaneously in a single integrated system. Their conclusion that no existing habitat functions as a functional prototype for lunar or Martian base architecture defines the gap that HUMANS is designed to address.

The principal life support technology demonstrators in the literature occupy the opposite end of the spectrum from behavioral analog habitats: they treat ECLSS as the primary system under investigation, without introducing the habitability context, operational scenario structure, or reconfigurable architecture that characterize an analog habitat. The MELiSSA (Micro-Ecological Life Support System Alternative) program [21], initiated by ESA in 1989 and now involving more than 30 research organizations, is the most ambitious European effort to develop and validate a fully closed bioregenerative life support loop. The MELiSSA Pilot Plant at the Universitat Autònoma de Barcelona interconnects bioreactor compartments for organic waste processing, nitrification, photosynthetic production, and crew compartment simulation, using rats as a metabolic proxy for human presence. MELiSSA has generated fundamental science on closed-loop stoichiometry, microbial ecosystem stability, and technology readiness for bioregenerative ECLSS components. However, MELiSSA has never been operated in a human-rated, crewed configuration, and its architecture is not designed for reconfigurable technology insertion or for the kind of mode-scoped operational verification that an analog habitat demands.

The most operationally mature crewed bioregenerative testbed in the world is the Yuegong-1 (Lunar Palace 1) [22] facility at Beihang University (Beijing, China), which completed the Yuegong-365 experiment in 2018: 370 days of continuous crewed operation of a fully closed bioregenerative life support system, including atmosphere, water, food production via wheat, vegetables, and mealworms, and waste processing. This remains the longest crewed closed-loop test on record. The facility demonstrates that long-duration closure is operationally achievable and has produced valuable data on microbial ecosystem dynamics and system reliability. However, Yuegong-1 is not a rack-reconfigurable technology testbed: its architecture is fixed around a specific bioregenerative configuration.

The literature consistently identifies a persistent structural gap: most analog habitats are optimized for behavioral and human factors research (HERA, HI-SEAS, CHAPEA, Concordia) without closed-loop ECLSS as a research variable. On the other hand, dedicated life support testbeds (like MELiSSA) focus on technologies not integrated into an operational facility, and do not provide a habitability context or realistic operational protocols. Finally, reconfigurability is rarely taken into account even in mature crewed testbeds. For example, Yuegong-1 establishes the operational feasibility of long-duration closure, it cannot be used to compare alternative ECLSS strategies under equivalent crewed conditions, nor to evaluate how architectural changes propagate through system performance and crew experience.

A significant precedent is HESTIA (Human Exploration Spacecraft Testbed for Integration and Advancement), a pressurized chamber at NASA Johnson Space Center designed to test ECLSS within a representative habitat context rather than in isolated rigs [23]. Unlike behavioral analog facilities, HESTIA was designed to evaluate ECLSS performance and habitability together, with architectural studies conducted as part of its validation. It represents the current state of the art for ECLSS-integrated habitat testing at NASA.

HUMANS builds on this precedent in three respects: a hypobaric high-O_2 operating capability as a dedicated experimental variable; a modular rack-based architecture enabling technology insertion without depressurization; and integration with a digital workflow, which maintains configuration-conditioned traceability across campaign configurations. These features address constraints inherent to fixed-configuration, single-atmosphere test facilities.

In this context, HUMANS does not compete with any single existing facility but addresses the integration gap between them. It provides an environment in which ECLSS technologies can be tested in an integrated, human-rated, and operationally controlled habitat – including under hypobaric high-O_2 conditions representative of lunar surface operations – while the phased campaign structure and HMS enable extended, reproducible loop-closure studies that neither behavioral analogs nor isolated engineering testbeds currently provide.

III. Facility scope, boundary conditions, and capability drivers

HUMANS is designed as an interior, rack-based analog facility. The system of interest is the pressurized habitat and its operational definition, including atmosphere revitalization, water and waste loops, sensing and control, and the internal utilities required to interconnect these functions. External services – power, thermal rejection, data connectivity, and exchange ports to laboratories and ISRU emulators – are handled as boundary conditions through defined, instrumented interfaces. The operations control segment is included in the facility scope because monitoring, procedure execution, and mode transitions directly affect ECLSS demands and therefore condition facility sizing, margins, and verification outcome.

The design is currently in Phase 0/A, with requirements being defined and organized around six principal categories: (i) structural and physical (pressure integrity, structural margins, material compatibility with the high-O_2 environment, rack mounting provisions); (ii) environmental control (atmosphere composition ranges, temperature and humidity bounds, CO2 and contaminant concentration limits, water recovery performance targets); (iii) safety (flammability certification, fire detection and suppression performance, emergency venting capability, egress layout); (iv) operability and maintainability (tool-less access at frequent-maintenance interfaces, reconfigurability through standard mechanical connections, loose-part hazard control on fasteners); (v) interfaces and leakage (maximum leakage rates, configurable penetration provisions, hermetic standards for pipes and cables); and (vi) habitability (interior clearances, noise isolation, sensor feedthrough placements). Requirements are allocated to subsystems within the facility digital model and linked to a declared verification method (test, analysis, inspection, or demonstration). This makes verification a facility-level property rather than a collection of subsystem acceptance tests [24] [25].

The facility, shown in Figure 1, is preliminarly sized as a 500 m^2 infrastructure including a control room, a dedicated testbench area, and a laboratory comprising the habitat and its service module. The pressurized habitat core is an 8 m x Ø3.5 m module with a total volume of approximately 77 m^3 and a habitable volume of approximately 70 m^3. HUMANS is designed for hypobaric operation down to 0.56 atm (8.2 psia) with an atmosphere composition of up to 34% O_2. These boundary conditions impose a stringent integration environment, in which materials selection, leakage control, ventilation distribution, and fire safety become primary architectural constraints rather than

downstream subsystem considerations [10] [26]. A Human Metabolic Simulator (HMS) is also envisioned to simulate the presence of up to four crew members.

These high-level parameters were selected on the basis of scientific representativeness, fabrication feasibility, and operational realism. The 8 m length and 3.5 m internal diameter enable for representativeness of a diverse range of configurations in early lunar outpost architectures, while remaining cost-effective, compatible with standard industrial fabrication of cylindrical pressure vessels, and consistent with the floor-area constraints of the IDEAS building. Notably, Thales Alenia Space's Multi-Purpose Habitat (MPH) [27], designed for ASI under the Artemis programme as the first permanent lunar surface outpost, targets a module approximately 6 m long and 3 m wide, HUMANS exceeds these dimensions slightly to provide additional rack volume and layout flexibility while remaining within the same architectural family.

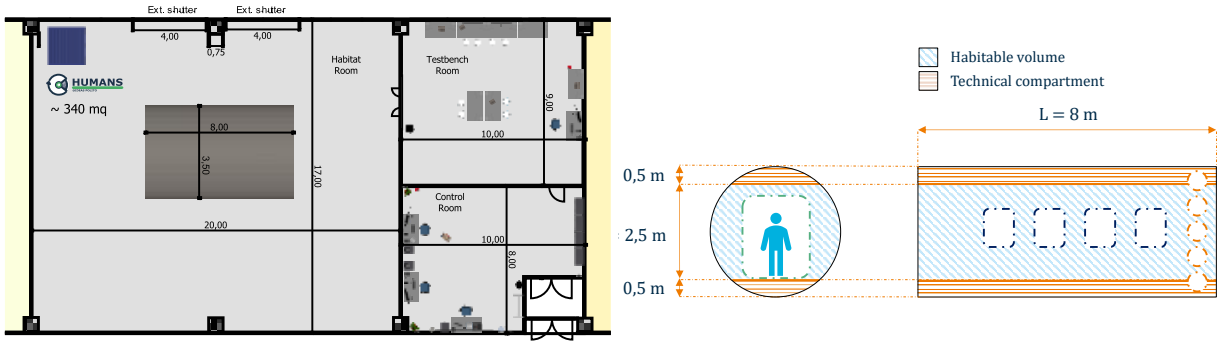


Figure 1. HUMANS Facility layout and habitat high level sizing.

At the same time, the size directly supports the goal of a reconfigurable, ECLSS-centric testing: the volume must be large enough to host multiple full-height racks and reconfigure them between campaigns.

A larger diameter, while beneficial for habitability, would exceed the building envelope and standard fabrication processes; a smaller one would not allow crew members to stand upright or install full-height racks. The resulting habitable volume of approximately 70 m^3, supporting a crew of up to four – real (for short duration campaigns) or simulated through the HMS – is consistent with NASA Human Integration Design Handbook [28] minimum thresholds for confined operations and compact enough to keep atmospheric and thermal gradients within the ECLSS control envelope. The crew size of four was selected as the minimum functionally representative number for Moon-to-Mars mission archetypes. Across the Artemis programme, from the Artemis II lunar flyby to planned Artemis IV surface missions [29], four-person crews are the standard operational unit. The Lunar Gateway's I-HAB module [30], also developed by Thales Alenia Space, is designed to host four-person crews for periods of one to three months. Designing HUMANS for four crew members, therefore, anchors its metabolic load assumptions, ECLSS sizing, and ConOps directly to the reference mission architecture it is intended to study.

The hypobaric setpoint of 0.56 atm with 34% O_2 provides an oxygen partial pressure equivalent to standard sea-level air (approximately 21.3 kPa). This enables physiologically representative operations while imposing the materials, fire safety, and ECLSS integration constraints characteristic of reduced-pressure mission architectures.

HUMANS is designed to evolve through phased operations – as will be discussed in further sections –, beginning with short human-in-the-loop activities and progressing toward extended campaigns with incremental introduction of higher-closure and bioregenerative functions. The key capability driver for the facility is, however, **controlled reconfiguration**: the baseline must be stable enough for repeatable experiments while remaining modular enough to accept new technologies and architectural configurations without re-baselining the habitat.

The architecture will be in fact organized around the pressurized structure with modular racks able to host third-party technologies for testing functions such as: thermal and humidity control, atmosphere control and supply, fire detection and suppression, atmosphere revitalization and sampling, water recovery and management, waste management, crew-support interfaces, command and data handling, and communications. At the same time, the interior structure will be equipped with anchor points spaced sufficiently apart to allow for both the insertion of new technologies and the reconfiguration of interior spaces. This, combined with the possibility to incorporate Augmented Reality (AR) into the loop to enhance crew immersion, will enable the simulation of various operational scenarios, minimizing the volume of the habitat as much as possible.

A key additional driver for this feature is the ease and reduction of time for the habitat re-configurations. In this sense, all interfaces will be designed to enable plug-in integration of experimental or demonstrator hardware without

modifying or interrupting the baseline configuration. This boundary and interface philosophy is treated as a design requirement: power, fluids, gases, data links, and material exchanges with external laboratories or ISRU emulators pass through predefined, instrumented connection points with declared capacities and constraints. This allows each campaign to declare exactly which interfaces are active and under what conditions, supporting configuration control and reproducible evidence generation.

IV. Architecture and preliminary design

HUMANS is organized around its pressurized core volume, which hosts configurable rack-level subsystems and their associated distribution networks, complemented by an operations control segment for supervision, procedure execution, monitoring, and explicit management of mode transitions. The facility also incorporates standardized physical and data interfaces to external laboratories and ISRU emulators, so that resource exchanges and external test articles are integrated as boundary-conditioned interfaces rather than through implicit terrestrial assumptions. Figure 2 shows a preliminary high-level schematic of the HUMANS Habitat, along with the Service Module (SM), which will be described in detail in the continuation of this section. It is worth noting that the schematic does not include redundant systems and their relative routing, which are being evaluated in detail at the moment of writing this work.

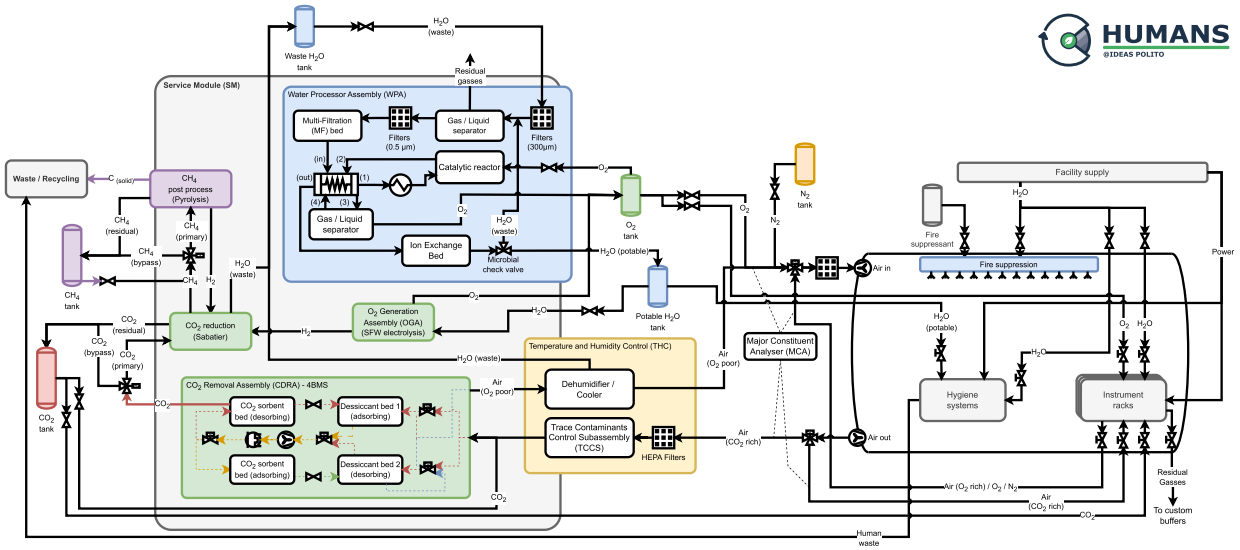


Figure 2. HUMANS preliminary baseline schematic*.

A. Pressurized core, racks, and service module concept

The primary structural element is the cylindrical pressure vessel rated to 8.2 ± 0.2 psia internal pressure, with critical load-bearing components designed to a structural safety factor of at least 2.5 for a negative pressure differential of at least 45 kPa (6.5 psid). Air leakage is imposed not to exceed 0.02% of internal volume per day under nominal conditions. All structural materials and coatings are to be certified for the 34% O_2 environment in accordance with applicable flammability standards (e.g., NASA-STD-6001 [31] or equivalent), whilst also avoiding any reaction with the atmospheric loop (e.g., mold generation, etc.).

The module includes a human-sized entry opening (highlighted in green in Figure 1) with provisions for a third-party airlock or custom pressure hatch, configurable penetrations for pipes, cables, and sensor feedthroughs (highlighted in orange), viewports along the longitudinal axis (highlighted in dark blue). The pressurized habitat structure serves also as the primary integration backbone, with standardized mounting points on the floor, walls, and ceiling for rack installation and internal layout reconfiguration.

The detailed construction approach for the pressure vessel (including material selection, fabrication method, and rack attachment architecture) is currently under definition in consultation with industrial partners experienced in pressurized laboratory and aerospace module fabrication. Key trades under evaluation include the pressure vessel wall

* While the baseline functional design is to be considered fixed, the technology choice might be subject to modifications after design optimization.

material (aluminium alloy versus stainless steel, driven by weight, weldability, and O_2 compatibility), rack attachment philosophy (bolted hard-points versus tool-less sliding rail systems, driven by reconfiguration time and loose-part hazard control), and front-access versus pull-out rack servicing concepts. Floor plan zoning (specifically the allocation of the 8 m length between crew-facing habitable zones and rack-dense technical zones) is being defined in parallel and will be reported at PDR. These decisions are architecturally consequential and are being treated as such; the current baseline establishes the interface and performance requirements that will constrain the detailed design choices.

A dedicated external Service Module (SM) has been included to provide an ECLSS baseline and modular connection points for gas, water, power, and data. It allows technology demonstrators to be connected or disconnected without depressurizing the habitat, thus ensuring operational flexibility. Technology insertion, therefore, occurs through defined ports and rack interfaces, thereby preserving configuration control and repeatability across campaigns. This design choice can be traced back to the main reconfiguration and operational test driver. The positioning of the SM outside the pressurized volume, with only a limited set of baseline functions inside the habitat (FDS, some THC, and water management), increases the net available volume for test racks and operational simulations. This configuration offers a distinct advantage, particularly in the context of test campaigns, where interventions on the ECLSS baseline are possible. Additionally, the flexibility to add or modify components without directly impacting the habitat itself is a notable benefit.

The physical architecture model organizes ECLSS functions into rack-level subsystems with defined distribution networks, interface constraints, and sensing and control allocations. This level of detail is necessary because loop closure, fault isolation, and safe mode transitions depend on how components are physically connected and isolated, not on individual component performance alone. Connectivity topology, valve placement, cross-strapping, and monitoring points together determine what can be reconfigured or recovered during operations.

B. Integrated utilities: distribution as an architectural driver

The architecture considers distribution and connectivity – piping, ducting, gas lines, condensate drains, electrical buses, and data links – as first-class design elements rather than as detailing to be resolved during integration. Each subsystem interface is represented with declared inlets, outlets, and connection types at the architectural level, so that the routing topology is visible and verifiable before physical installation begins.

For the atmosphere revitalization chain, this includes the physical routing between CO_2 removal, Sabatier processing, methane storage and post-processing, and associated water return lines, with explicit representation of valve placements, flow directions, and isolation boundaries. A similar approach is applied to the water recovery chain, where condensate collection lines from the thermal/humidity control function feed into the water processing loop, and wastewater return paths are defined alongside fresh water distribution. The power distribution network is modeled with bus segmentation and load allocation at rack level, identifying which subsystems share a common power path and which are on isolated circuits. These representations are kept consistent with the architecture digital model in MOSAiC, so that routing assumptions in ECLSS simulations match the declared connection topology rather than an idealized abstraction.

This level of detail is architecturally necessary for three reasons. First, loop closure depends on physical routing: a Sabatier unit that is functionally integrated but lacks a declared condensate return path to the water recovery system is not operationally closed, regardless of component performance. Second, fault isolation and safe mode transitions require that every fluid or gas path can be interrupted at a defined point; valve placement and cross-connection topology determine whether a fault in one subsystem can be contained or propagated to adjacent loops. Third, technology insertion – adding or replacing a rack-level subsystem in a later campaign – is only bounded if its interfaces are physically defined. Without declared connection points, what appears to be a localized substitution may require re-routing across the habitat, introducing undocumented configuration changes that undermine campaign-to-campaign comparability.

For HUMANS, the practical consequence is that routing, penetration locations, labeling conventions, and interface verification are specified as design requirements before fabrication, not resolved ad hoc during integration. Reconfigurability is only achievable if the physical architecture supports it from the start.

C. Core environmental control functions and their coupling

The habitat's environmental control architecture must satisfy a set of coupled requirements that are more demanding than typical terrestrial laboratory conditions. The nominal cabin pressure is set at 8.2 ± 0.2 psia (0.56 atm), with an oxygen fraction of up to 34% to maintain a partial pressure of oxygen equivalent to that at sea level. This combination requires that the atmosphere management subsystem regulate both total pressure and oxygen fraction simultaneously, since a drift in either parameter shifts the effective oxygen partial pressure outside the acceptable physiological range. The allowed air leakage is $\leq 0.02\%$ of total cabin volume per day under nominal conditions, with

a maximum tolerable leakage of 0.14%/day; both figures are referenced to the 8.2 psia setpoint and constrain the structural seal design as well as the replenishment budget for stored gases.

Temperature control is targeted at 22 ± 4°C across occupied zones, with humidity maintained at 50 ± 10% relative humidity. These are not independent setpoints: at the operating pressure and oxygen fraction of HUMANS, the psychrometric relationships differ from sea-level norms, and the thermal control loops must account for reduced convective heat transfer at 0.56 atm. The condensing heat exchanger that handles latent load in the temperature and humidity control chain, therefore, also functions as the primary water recovery input, linking the atmosphere revitalization loop directly to the water recovery subsystem. This coupling means that a change in metabolic water generation rate – driven by crew size or activity level – propagates simultaneously into both the thermal and water mass balance, and must be accommodated without manual retuning of either loop.

Carbon dioxide removal is a further coupling point. The CO_2 partial pressure limit for continuous habitation is derived from established spaceflight standards; the target is to remain below 5.3 mmHg (0.7 kPa) as a chronic exposure limit, with a short-duration ceiling of 7.6 mmHg (1.0 kPa). At the reduced total pressure of HUMANS, the same CO_2 mole fraction produces a lower partial pressure than it would at 1 atm, which relaxes the volumetric efficiency requirement on the removal system but does not eliminate it. The removed CO_2 can either be vented – acceptable for short campaigns where consumable resupply is straightforward – or processed through a reactor to recover oxygen and produce water, closing the loop with both the oxygen makeup and water recovery chains. Whether a Sabatier unit is incorporated in the final design depends on campaign duration and resupply assumptions that are still under trade.

It must be in fact noted that Figure 2 reflects the functional architecture as currently defined – the subsystem boundaries, inter-loop connections, and mass/energy flows shown are considered stable – but the specific technology selections underlying each function remain to be confirmed. The CO_2 removal technology (e.g., solid amine, molecular sieve, or electrochemical), the water recovery process (membrane distillation, vapor compression, or vapor phase catalytic), and the oxygen generation method (electrolysis or pressure-swing from stored supply) are all subject to ongoing trade studies and procurement constraints within the IDEAS facility. The numerical targets cited above drive the selection criteria for these trades but do not yet map to a single baselined solution. The design presented here should therefore be read as a requirements-driven functional baseline, not as a committed hardware configuration.

D. Instrumentation, control, and operations supervision as part of the system boundary

The operations control segment is included within the system boundary because monitoring, procedure execution, and mode transitions determine which configuration is active at any given time and therefore condition both facility sizing and verification outcomes. The control room provides real-time telemetry monitoring, alarm management, command capability, voice/video communications, and data archiving for post-campaign analysis.

In the architectural baseline, scenarios define mission-like timelines with explicit assumptions about crew activity profiles and interface availability. Operating modes specify which subsystems are active, which flows are enabled, which setpoints apply, and which transitions to other modes are permitted. Configuration changes in HUMANS are treated as mode-scoped updates – not simply hardware swaps – which is what allows verification criteria to be stated and evaluated in terms specific to each campaign.

E. Architectural implications of high-O_2 hypobaric operation

The habitat is designed for operation down to 0.56 atm (8.2 psia) with 34% O_2, which drives the architectural emphasis on redundant sensing, safety interlocks, emergency venting, and fire protection. Materials and flammability control, rapid detection, suppression agent compatibility with high-O_2 conditions, emergency ventilation, and atmosphere dump capabilities are treated as system-level requirements. These are enabling constraints for hypobaric high-O_2 operation: without them, the facility cannot credibly provide a safe and repeatable experimental environment.

The high-O_2 hypobaric environment requires a set of architectural safety constraints applied throughout the design and procurement process. All materials and coatings within the pressurized volume are selected and certified for oxygen-enriched atmospheres per applicable flammability standards (such as NASA-STD-6001 or equivalent), and a formal materials approval process is embedded in the design workflow. Electrical equipment, wiring, and connectors comply with high-O_2 compatible design rules. The fire detection and suppression system provides full volumetric coverage, with suppression agents compatible with both the oxygen-enriched atmosphere and occupied operation. An emergency atmosphere dump capability is incorporated as a last-resort fire mitigation measure, accessible from both inside and outside the pressurized volume. The internal layout preserves unobstructed crew access to emergency egress paths at all times (a layout requirement established during preliminary design to ensure safe crew egress at all times), and emergency egress procedures are a mandatory verification item before any crewed campaign. The suppression agents are selected to remain effective at elevated partial pressures of O_2 without presenting secondary hazards in an occupied environment.

V. Phased campaigns and verification logic

HUMANS is planned to evolve through phased operational campaigns that progressively increase functional closure and experimental envelope, rather than attempting to commission a fully regenerative architecture at initial operations. The roadmap, represented in Figure 3, starts with short human-in-the-loop activities and then transitions to extended campaigns where higher-closure and bioregenerative functions are incrementally introduced, enabling technology insertion while preserving a stable baseline for repeatable experimentation.

Subsystem development and delivery are organized around two distinct phases: a Design phase covering conceptual through detailed design, culminating in SRR, PDR, and CDR milestones, and a Realization phase covering procurement, fabrication, and delivery of hardware. Individual realization work packages progress through their own FAT-SAR sequence asynchronously, bounded by two system-level constraints: all subsystem CDRs must be completed before fabrication is authorized, and the critical systems (EPS, C&DH, FDS, COMM, THC, ACS) must achieve delivery and integration clearance before ECLSS core integration begins. This sequencing reflects the physical and functional dependency chain of the habitat: structural integrity must be verified before backbone installation, and

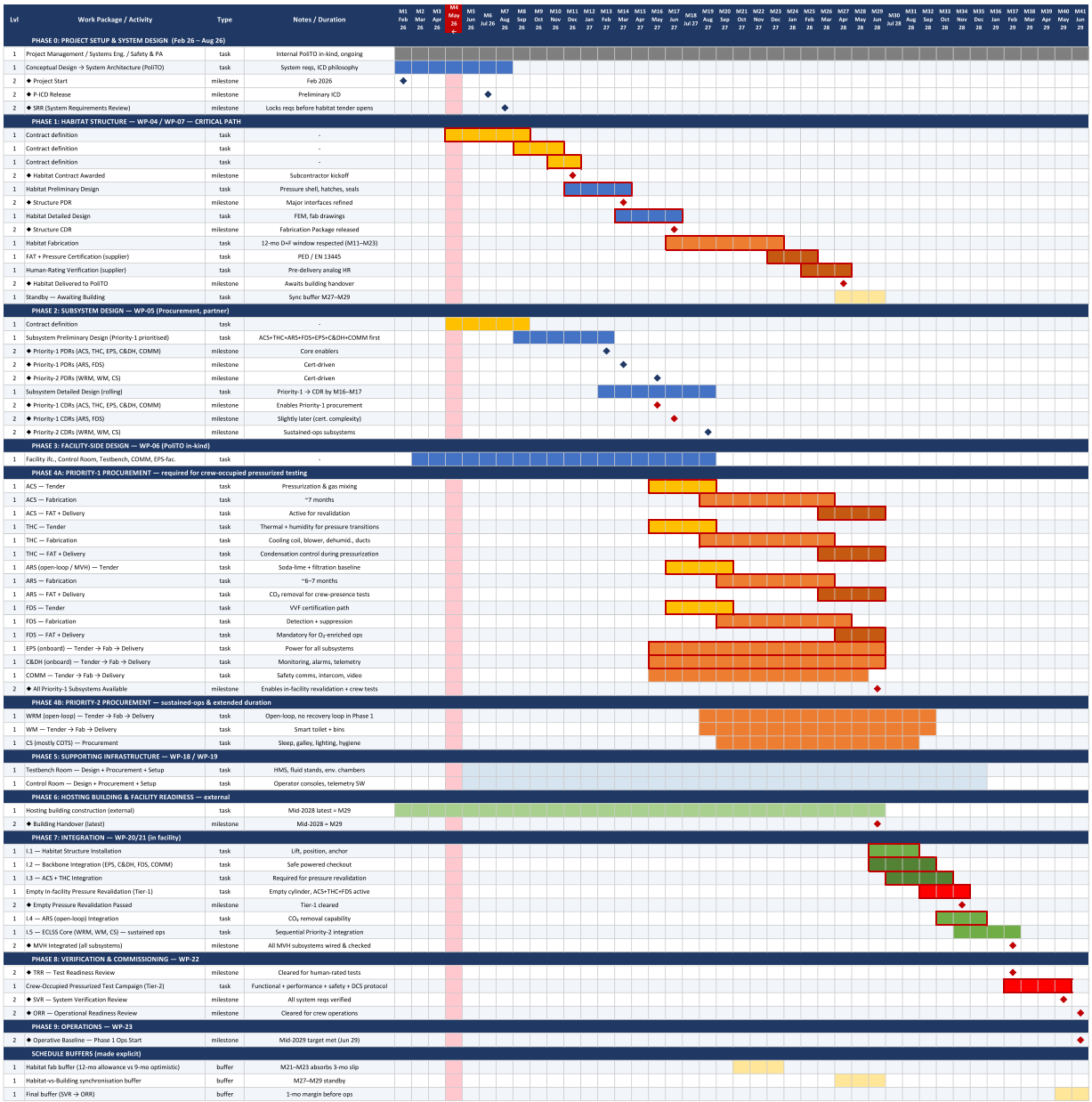


Figure 3. HUMANS GANTT chart.

backbone power, data, and environmental control infrastructure must be commissioned before life-support subsystems can be energized and tested. The rolling procurement and fabrication window (M19-M34) reduces peak procurement and integration load while preserving traceability - each subsystem is accepted against its own FAT and SAR prior to being incorporated into the integrated configuration. Subsystems that miss their nominal delivery slot without impacting the critical path are absorbed into the M35-M40 schedule buffer.

Phase 1 is oriented toward early operational readiness with short duration (few hours) human-in-the-loop tests or medium duration (few days) HMS-enabled tests. The primary objective is to validate facility operability under controlled scenarios: crew procedures, human-system interfaces, supervision and alarm handling, mode transitions, MVH validation and contingency operations under hypobaric high-O_2 boundary conditions. In this phase, "success" is not closure performance; it is demonstrated operational control of coupled loops, safe and repeatable configuration changes, and credible evidence generation for later technology insertion.

Phase 2 targets more extended campaigns (up to weeks), in which regenerative and experimental/low-TRL subsystems are added incrementally to the baseline. The key facility property in Phase 2 is controlled variability: each insertion is treated as a bounded configuration delta with defined interfaces, defined operating modes, and scenario-conditioned verification criteria. This ensures that differences observed between campaigns reflect the effect of the inserted technology, and not silent changes to the facility baseline - such as sensor drift, component replacements, or setpoint adjustments - that would otherwise make cross-configuration comparisons unreliable.

To protect the Phase 1 start date against asynchronous maturation of advanced subsystems, HUMANS adopts a Minimum Viable Habitat (MVH) configuration that enables limited but safe operations, with safety-critical and core life-support functions commissioned first, while allowing the deferred commissioning of low-TRL elements within an explicit buffer. The MVH includes a non-regenerative CO_2 removal baseline for early atmosphere revitalization; regenerative CO_2 removal and advanced trace contaminant control functions are treated as evolutionary capabilities to be commissioned progressively after the MVH milestone.

MVH is not a "reduced ambition" baseline. It is an architectural and programmatic option that decouples operational readiness from technology readiness, while keeping the facility structurally prepared for progressive closure increases without re-baselining the entire habitat. The Service Module philosophy - concentrating all baseline ECLSS subsystem cores in an external rack enclosure while maintaining standardized, individually isolatable interfaces inside the habitat - reinforces this: any single subsystem can be replaced by an experimental demonstrator without depressurizing the habitat or disrupting the remaining subsystems.

HUMANS development is organized around staged review and readiness gates that separate design maturity, integration completion, and operational authorization. This includes formal readiness at the facility level following integrated verification activities (TRR, SVR, ORR), rather than treating acceptance as a set of disconnected subsystem checkouts.

For an analog intended as research infrastructure, the core verification product is not only "system works," but "system behavior is reproducible under controlled scenarios." That requires: (i) configuration baselines; (ii) explicit operating modes and allowable transitions; (iii) calibrated instrumentation with traceable data products; and (iv) documented scenario definitions (crew loads, timelines, boundary services availability) that condition each test's pass/fail criteria.

The planned integration logic prioritizes qualification of the pressurized structure and pressure integrity, followed by commissioning of the critical systems (power distribution, command and data handling, fire detection and suppression, communications, thermal and humidity control, atmosphere control and supply), and only then integration of the ECLSS core functions (atmosphere revitalization, water recovery and management, waste management, crew systems) and integrated end-to-end testing leading to operational readiness. An explicit schedule buffer (M35-M40, with M40+ available for deferred items) is included to absorb commissioning delays, particularly for advanced subsystems, without moving the Phase 1 operational milestone.

This sequencing is what makes the phased campaign plan credible: it establishes a stable, safety-qualified platform early, then treats loop closure and experimental technologies as controlled increments, each justified by scenario-conditioned verification evidence rather than by implicit assumptions.

VI. Integrated model-based workflow for configuration-controlled analysis (MOSAiC)

HUMANS is supported by an integrated model-based workflow (MOSAiC [16] [17]) intended to prevent “digital thread fragmentation”, where system architecture is captured in MBSE artifacts while analyses and simulations evolve as disconnected work products that drift in assumptions and parameters. The core premise is that architecture, operational modes, scenarios, and quantitative assessments must be treated as inseparable elements of a unified design

and validation process, especially for tightly coupled life-support loops where design errors propagate across interfaces and across stages [32].

MOSAiC defines a structured relationship between requirements, configurations, scenarios, and operating modes, such that each verification claim is tied to a specific configuration and a specific operational context. The facility is described not as a single static system but as a set of controlled configurations, each with declared technology content, interface states, setpoints, and allowable mode transitions.

In practice, the HUMANS architectural model defines the functional and physical architecture and allocates requirements to rack-level subsystems, with each requirement linked to a declared verification method (test, analysis, inspection, or demonstration). As an example, the requirement that CO_2 partial pressure shall not exceed a specific threshold during continuous habitation is allocated in the architectural model to the Atmosphere Revitalization Subsystem (ARS), with the declared verification method being analysis supported by test. In Phase 1, where open-loop scrubbing will be active, this requirement will be verified against a CO_2 accumulation simulation run under a scenario assuming four HMS-equivalent crew members at nominal metabolic load for a 72-hour campaign. The simulation will draw its parameters (cabin volume, leakage rate, scrubber capacity, HMS duty cycle) directly from the Phase 1 configuration instance in MOSAiC, not from a standalone spreadsheet. When the Phase 2 configuration will be declared, with all units commissioned and active, the same requirement will be re-evaluated: the simulation will be regenerated against the updated configuration parameters, and the verification claim will be reissued and bound to the Phase 2 snapshot. Any difference in predicted CO_2 margin between Phase 1 and Phase 2 will be therefore interpretable as a direct consequence of the declared configuration delta, not as an artefact of parameter drift between independently maintained analysis files. This is precisely the discipline that makes HUMANS usable as research infrastructure rather than as a one-off demonstrator.

Operating modes are defined within the same model as configuration states, specifying which subsystems are active, which flows are enabled, which setpoints apply, and which mode transitions are permitted. Scenarios consist of time-ordered sequences of mode transitions and boundary condition assumptions – crew presence, HMS duty cycles, external interface availability – and drive quantitative analyses. New interfaces, setpoints, and mode transitions are declared in the model, and updated analyses are regenerated and bound to that configuration instance, preserving traceability and making campaign-to-campaign comparisons interpretable as technology effects rather than artefacts of undocumented changes.

As HUMANS evolves through phased campaigns with progressive insertion of experimental or bioregenerative elements, MOSAiC provides the mechanism for maintaining a stable baseline while accepting controlled changes. Each campaign is treated as a configuration snapshot with its own verification scope – what must hold (constraints), under what conditions (scenario), and under what operational definitions (modes). This supports readiness authorization and post-campaign interpretation, as deviations can be traced to specific configuration or operational changes rather than attributed to undocumented facility evolution.

VII. Discussion: facility differentiators, research envelope, and limitations

HUMANS addresses a persistent gap in analog development: life-support technology and human-in-the-loop operations are typically studied either in isolation or in facilities where ECLSS is not a research variable. The distinguishing characteristic of HUMANS is that it is designed to make configuration-controlled, system-level testing routine – including mode transitions and contingency handling that are generally excluded from subsystem demonstrations.

Several integration challenges are anticipated as HUMANS progresses through its campaign phases. One of the most sensitive architectural dependencies is the coupling between water recovery and humidity condensate from the thermal control function: whether a given water recovery unit meets its targets depends not only on its own performance but on condensate flow rates, which are shaped by crew metabolic loads, temperature gradients, and HMS duty cycles. This dependency can only be resolved by exercising the full coupled system under representative operating profiles. Similarly, the transition from open-loop CO_2 scrubbing to a Sabatier-based atmosphere revitalization loop requires not only technical readiness but operational readiness: the supervision system must handle Sabatier outlet products (methane, water) as new inputs to the water and waste loops, and the mode transition must be demonstrated as a controlled, reversible operation. Characterizing these procedural and control requirements in an integrated facility – rather than in simulation – is one of the primary research objectives of the Phase 1 to Phase 2 progression.

Compared to HERA (148.6 m^3, three-story layout, behavioral focus) and Yuegong-1 (approximately 160 m^3 including plant growth modules, fixed bioregenerative architecture), HUMANS occupies a distinct design space: a smaller pressurized volume of approximately 77 m^3 optimized for ECLSS integration density and configuration

control rather than long-duration behavioral habitability. HUMANS is not designed to replicate the living conditions of a multi-month exploration mission, but to provide a controlled integration environment for systematic characterization of architecture and operations trade-offs across evolving configurations.

The phased campaign structure supports three classes of research of increasing complexity: operations and contingency handling on a stable baseline; technology insertion studies in which a bounded subsystem set changes under controlled conditions; and progressive closure exploration in which architecture and operations are jointly adjusted within declared scenarios. The MVH configuration ensures early operational readiness is maintained throughout this progression.

An important class of facility outputs concerns transient behavior and operational margins: startup and shutdown dynamics, mode switching sequences, fault isolation and recovery timelines, and the crew time and procedural complexity required to maintain loop closure under realistic mission schedules.

The evidence generated at HUMANS has value beyond the analog itself: architectural choices that appear feasible in isolation – a particular CO_2 removal technology, a water recovery strategy, a contingency procedure – often reveal unexpected dependencies, margin violations, or operational costs only when exercised within an integrated, time-pressured system. Identifying and resolving these issues at analog scale, where configurations can be changed and campaigns repeated, is substantially less costly than encountering them during flight system development or during operations.

HUMANS is designed around modular integration and controlled interfaces, with a workflow that ties evidence generation to declared configurations and scenarios. Rigorous campaign-to-campaign comparisons require consistent enforcement of three baselines: the installed and connected configuration, the assumed demands and boundary services, and the active operating modes with their permitted transitions. Without this discipline, observed differences between campaigns will reflect undocumented facility drift rather than the effects of the technology under study.

HUMANS is an interior, terrestrial facility; reduced gravity, radiation, and vacuum are not replicated. Results should therefore be interpreted as architecture and operations evidence under controlled boundary conditions, not as direct validation of space environmental performance. The facility's value lies in integration realism and operational control, not in environmental fidelity to off-Earth conditions.

Two additional operational limitations are worth noting. First, crew ingress and egress will temporarily disturb the internal atmosphere – oxygen fraction and total pressure – and the recovery dynamics of these transients must be characterized during early Phase 1 operations. Managing them without compromising ongoing experiments or the safety envelope is a practical challenge not captured in steady-state analyses. Second, the HMS reproduces crew metabolic loads (CO_2 production, O_2 consumption, water vapour, heat release) but not the variability and cognitive load of a real crew. HMS-enabled campaigns provide ECLSS system performance data; crewed campaigns add the procedural and human-systems integration dimensions the HMS cannot replicate. This distinction must be preserved in the interpretation and reporting of campaign results.

Hypobaric high-O_2 operation increases relevance for certain mission concepts but also restricts permissible materials, maintenance actions, and fault responses. Experimental flexibility can be maintained only if design-for-test considerations and safety constraints are managed together from the outset.

A preliminary budget estimation has been developed as part of the Phase A/B design activities. The total investment for HUMANS is of the order of a few million euros across all development phases, placing the facility in the range of mid-scale European academic research infrastructure; this level of expenditure is consistent with similarly capable pressurized laboratory facilities developed within the European space research ecosystem. A detailed cost breakdown is available upon request but is not reported here given the project's ongoing procurement process.

By combining phased evolution, controlled interfaces, and configuration-conditioned evidence, HUMANS is designed to characterize how different mission archetypes shift the feasible operating envelope of integrated life support. The facility does not aim to emulate any specific mission, but to enable systematic study of architecture and operations trade-offs that typically remain hidden until late-stage integration.

VIII. Conclusion

HUMANS is being developed as an interior, reconfigurable analog habitat centered on an $8\,\text{m} \times Ø3.5\,\text{m}$ pressurized core (approximately $77\,\text{m}^3$ total, approximately $70\,\text{m}^3$ habitable) within a $500\,\text{m}^2$ facility, designed for hypobaric operation down to 0.56 atm (8.2 psia) with 34% O_2. The facility scope includes an operations control segment and controlled interfaces to external laboratories and ISRU emulators, so that boundary services and resource exchanges are defined and reproducible rather than assumed.

HUMANS will evolve through phased campaigns, beginning with short human-in-the-loop operations and progressing to extended campaigns with incremental introduction of higher-closure and bioregenerative functions.

The MVH configuration allows the facility to begin generating operational and integration evidence before full loop closure is achieved, accommodating the asynchronous maturation of individual subsystems.

The HUMANS architecture and campaign concept are supported by MOSAiC, a model-based workflow that maintains consistency between requirements, configurations, scenarios, operating modes, and quantitative analyses as the facility evolves. Configuration control is what makes HUMANS usable as research infrastructure: it allows campaign-to-campaign comparisons to be interpreted as technology effects and verification claims to be stated against explicit operational contexts.

As a long-term European infrastructure, HUMANS is positioned to enable systematic exploration of architecture and operations trade-offs for tightly coupled life-support systems, with particular emphasis on reconfigurability, safe mode transitions, and repeatable evidence generation under controlled boundary conditions.

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