Analog Simulation Training and Research Outpost Utilizing Self-sustaining Architecture: A Testbed for Moon and Mars Technology at Purdue University

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This document was created with assistance from OpenAI's ChatGPT for basic grammar and editorial assistance. The content has been reviewed and edited by John M. Peters. More information on the extent and nature of AI usage is included in the Methods or Acknowledgements sections of the document.

A proposed Earth -based analog habitat is intended to test future Moon base and Mars habitation technologies

The Analog Simulation Training and Research Outpost Utilizing Self-sustaining Architecture (ASTRO-USA) is a proposed Purdue-led Moon and Mars analog habitat concept project intended to test sustainable habitation technologies on Earth before future use in long-duration surface missions.

Development Phase	Purpose
Secondary Mini-Hab	Near-term subsystem testing for food production, sensors, controls, and biological water-processing research
Primary Habitat	Long-term high-fidelity analog target for closed-loop systems, controlled human factors, and Moon/Mars habitat design

ASTRO-USA may provide an Earth-based testbed for proving technologies needed for future Moon base and Mars habitat operations.

ASTRO-USA is proposed to address the need for an integrated closed-loop Moon and Mars analog habitat

Need	ASTRO-USA Response
Current analogs rarely integrate all major life-support systems	ASTRO-USA will combine waste, water, air, food, power, and human factors research
Closed-loop systems must be tested before deployment	The phased Secondary Mini-Hab and Primary Habitat will allow technologies to mature before full integration

The Moon base and future Mars habitats require sustainable long-term habitation systems. These technologies must be tested on Earth before future deployment.

ASTRO-USA is being designed as an analog habitat testbed to bridge the gap between current analog limitations and the integrated closed-loop systems needed for sustainable long-term Moon and Mars habitation.

Analog fidelity criteria were evaluated using enabling systems, habitat design, and human factors

Category \ Fidelity	High	Medium	Low
Enabling Systems	• Supports TRL 6+ Technologies • Food Production • Closed-Loop Life Support Systems • Pressurization	• Supports TRL 5 Technologies • Food Production	• Supports TRL 4 and below Technologies
Habitat Design	• Constructed using space-grade materials • Structural design and layout is realistic for extraterrestrial habitation	• Meets one of the two high-fidelity prerequisites	• Meets none of the high-fidelity prerequisites
Human Factors	• Full control of environmental conditions	• Partial control of environmental conditions	• No control of environmental conditions

No reviewed analog fully combines closed -loop systems, realistic habitat design, and controlled human factors

Category / Analog	Enabling Systems	Habitat Design	Human Factors
CHAPEA	Low	Medium	High
HERA	Low	Medium	Medium
Aquarius	Low	Medium	Medium
NEK	Low	Medium	Medium
HI-SEAS	Low	Medium	High
ILMAH	Medium	Medium	Medium
Biosphere 2*	Medium	Low	Medium
SAM†	High	Medium	Medium

*Biosphere 2's enabling system capability was high-fidelity in concept but medium in demonstrated operation because closure was not maintained. Its design flaws and failures bring the Habitat Design fidelity to low

† SAM is high in enabling system capability but remains limited by incomplete closure of waste, power, and air.

Current analog gaps define ASTRO -USA's design targets

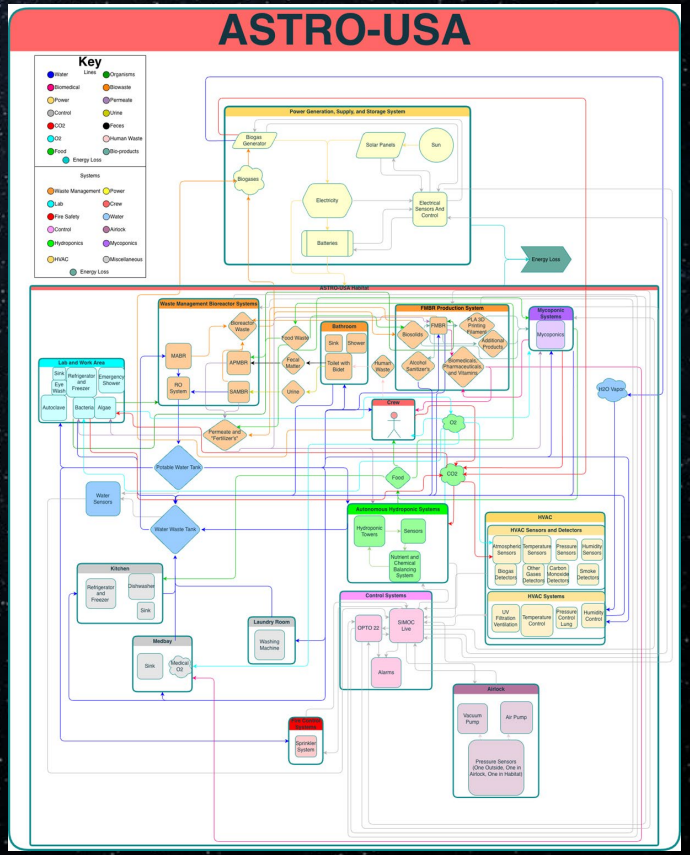
Current Analog Gaps	What This Means	ASTRO-USA Design Response
Non-flight-ready habitat structures	Many analogs use fixed buildings or layouts that do not reflect future Moon base or Mars habitat architecture.	Develop a modular habitat concept with off-world relevant design targets.
Incomplete closed-loop systems	Waste, water, food, air, and power systems are rarely integrated into one sustained habitat loop.	Connect waste, water, food, air, power, and controls into one phased testbed.
Limited food-production integration	Food production is often separate from life support and waste recovery.	Tie hydroponics and Mycoponics™ into future nutrient and waste recovery research.
Limited environmental and operational control	Many analogs simulate isolation but do not fully control habitat conditions or mission operations.	Support controlled human factors testing, mission timelines, EVA procedures, and fault response.

SAM was the strongest analog identified, but it still lacks a flight-ready structure and full closure of waste, power, and air constraints. ASTRO-USA is intended to address these gaps through phased Secondary Mini-Hab and Primary Habitat development.

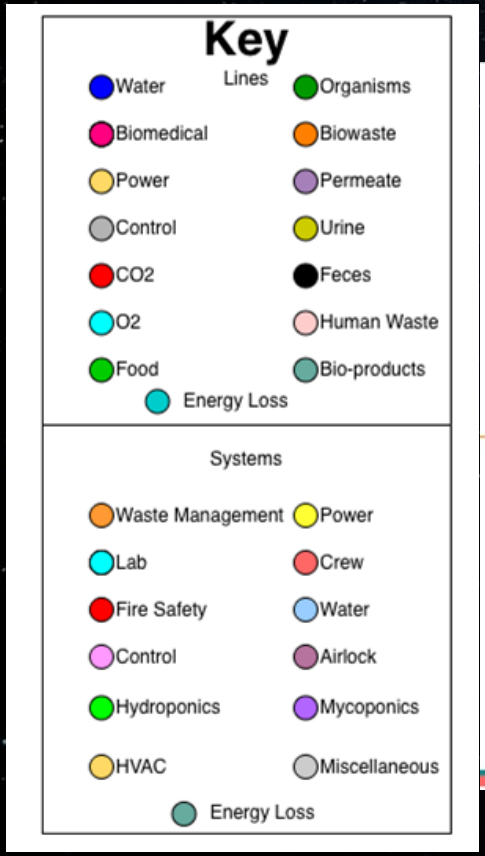
ASTRO-USA is designed to integrate closed-loop habitat systems

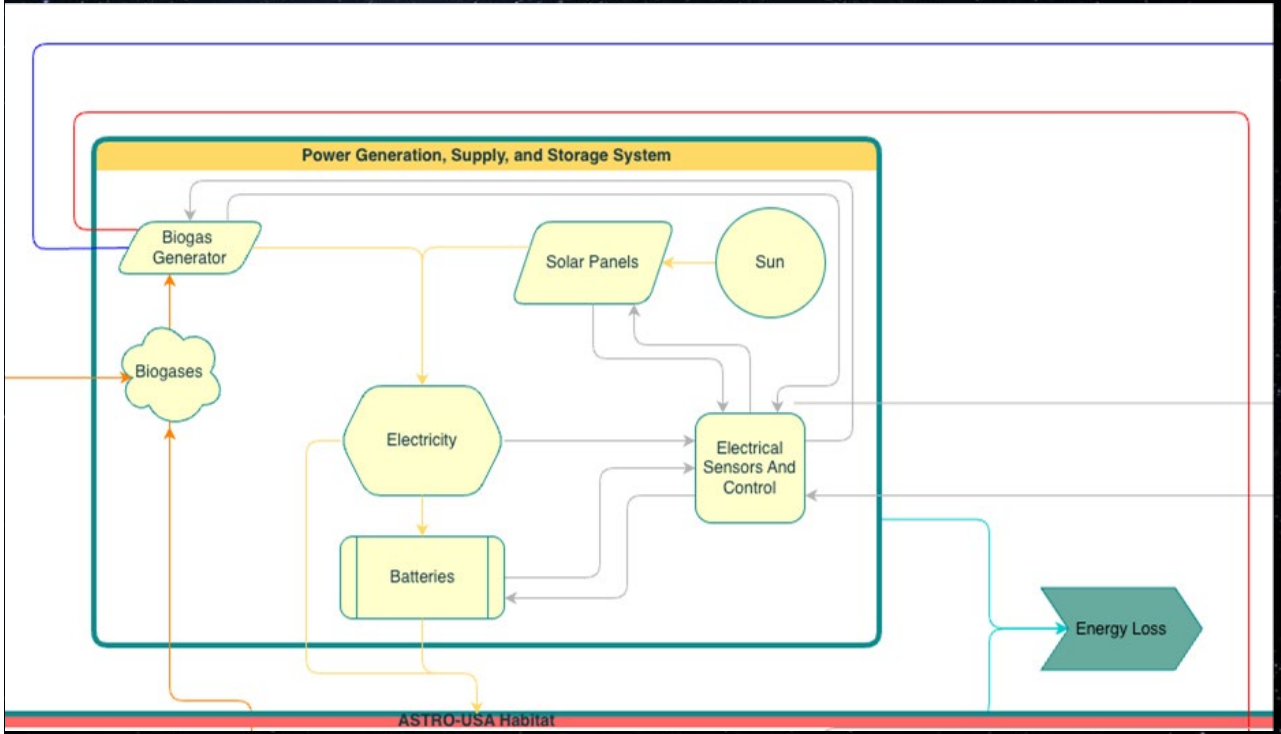
This flowchart shows the full ASTRO-USA concept as one integrated habitat system rather than separate standalone subsystems.

- Connects waste, water, food, air, power, crew systems, and controls.
- Routes human waste and graywater through bioreactors and reverse osmosis.
- Produces potable water, fertilizer, biogas, and food-production inputs.
- Uses Scalable, Interactive Model of an Off-World Community (SIMOC) Live and Opto 22 for monitoring, automation, and fault response.

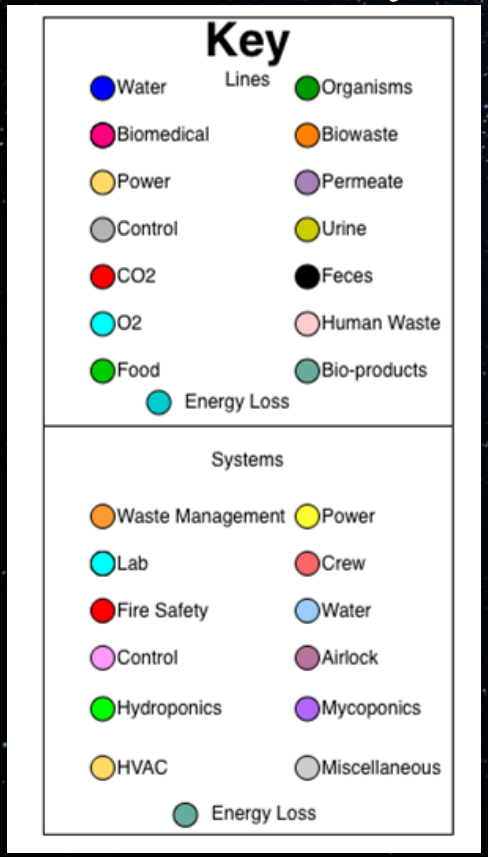


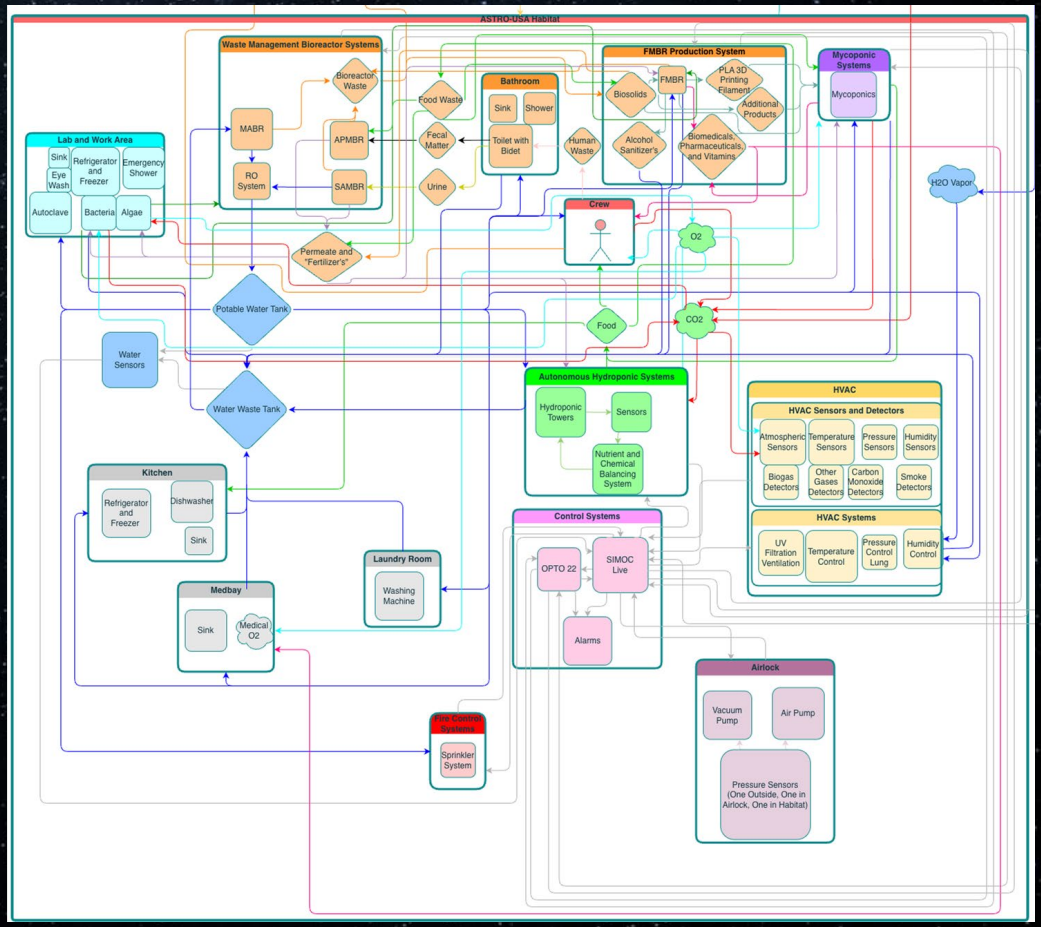
Solar and biogas power support habitat energy needs





Waste, water, food, air, and control loops connect the full habitat system





The Secondary Mini -Hab provides near-term subsystem testing while the primary habitat is the high-fidelity target

Category	Secondary Mini-Hab	Primary Habitat
Purpose	Near-term prototype for phased system testing	Long-term high-fidelity Moon/Mars analog
Enabling Systems Fidelity	Medium	High
Habitat Design Fidelity	Low	High
Human Factors Fidelity	Medium	High
Focus	Food production, sensors, solar power, early human factors	Closed-loop waste, water, air, food, power, and crew systems
Mission Scale	Crew of 6 for two weeks	Sustained long-duration analog missions
Role in ASTRO-USA	Tests systems before full integration	Final integrated habitat testbed

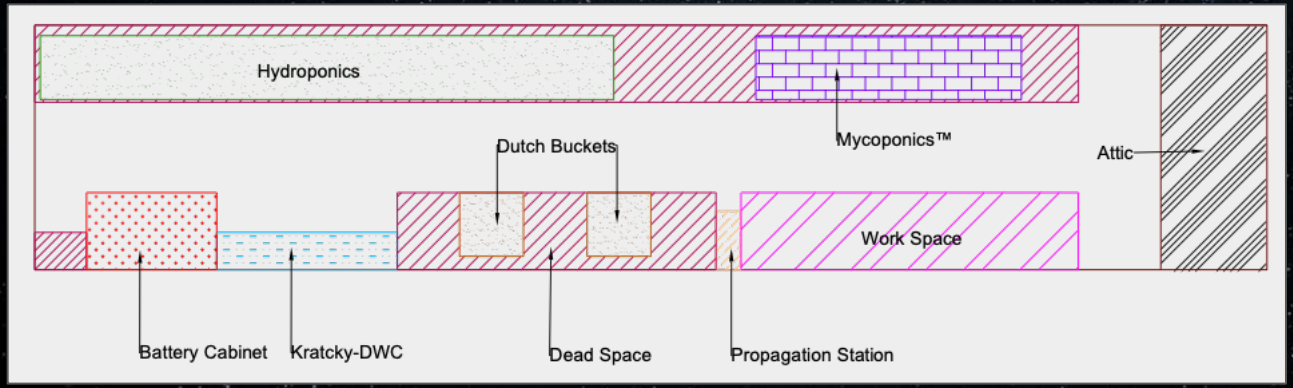
Secondary Mini -Hab starts ASTRO-USA development with food production, sensors, power, and early human factors

Category	Mini-Hab Implementation
Main Purpose	Medium-fidelity prototype for testing ASTRO-USA subsystems before full habitat integration
First Module	Food Production Module
Mission Support Goal	Support a crew of 6 for a two-week mission
Core Systems	Hydroponics, Mycoponics™, sensors, solar power, and environmental monitoring
Research Focus	Plant growth, crop selection, food production, and early human factors research
Future Integration	Waste and nutrient recovery systems will connect into the food production loop

The Mini-Hab is the lower-cost first step toward ASTRO-USA. It does not replicate the final habitat structure, but it allows food production, sensors, power, and closed-loop subsystems to be tested before they are scaled into the primary habitat.

The Food Production Module organizes support systems, hydroponics, propagation, Mycoponics™, and workspaces

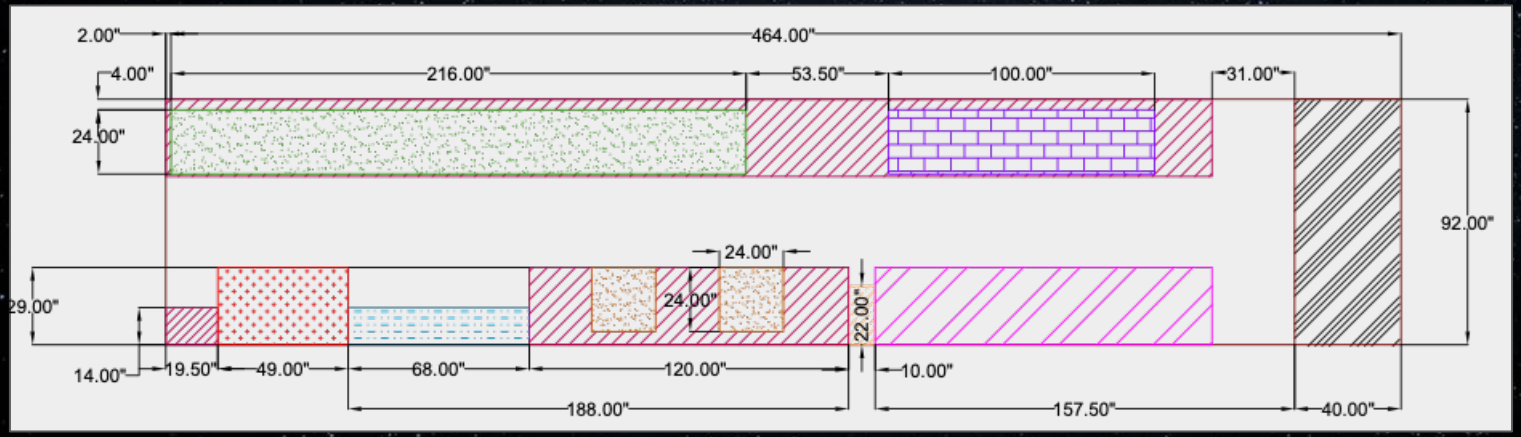
- Hydroponics: primary crop-production area
- Propagation: seedling growth and early plant development
- Mycoponics™: fungal growth and biological research
- Battery Cabinet: power storage and support infrastructure



This layout shows the functional organization of the Food Production Module, including hydroponics, Mycoponics™, propagation, Kratky-DWC, Dutch buckets, workspace, battery storage, and attic space.

The Food Production Module layout defines the first physical Mini-Hab test space

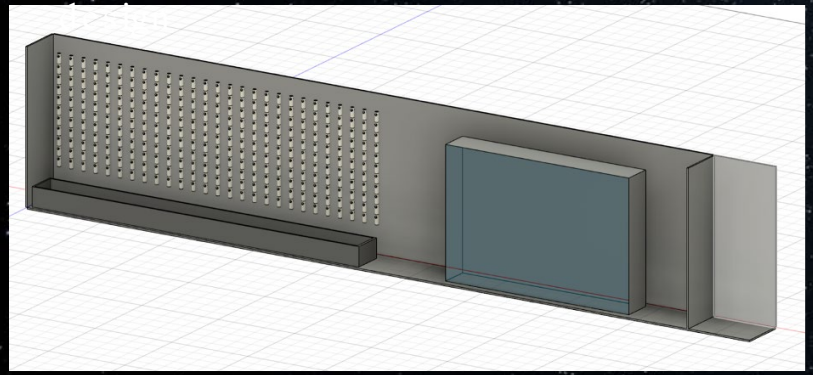
- 464 in × 92 in module footprint
- Hydroponics and Mycoponics™ zones
- Workspace and support equipment
- Battery and utility areas

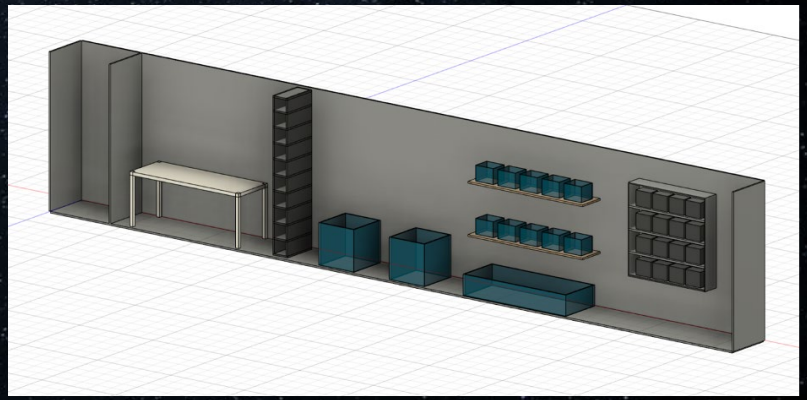


The Food Production Module is the first physical Mini-Hab module. This dimensioned layout defines the usable footprint and shows how major food-production and support systems fit inside the container.

The container setup provides a practical testbed for early Mini-Hab subsystem development

- Low-cost test environment
- Builds early operational experience
- Supports food-production research
- Provides data for primary habitat

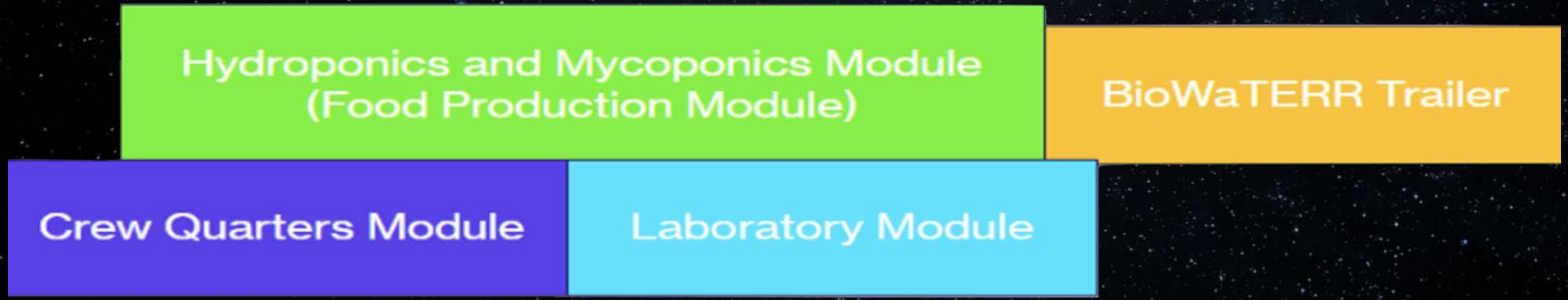




The container setup represents the first implementation step for the Mini-Hab. Its purpose is not high-fidelity habitat structure, but practical subsystem testing for food production, sensors, power, and early closed-loop operations.

Future Mini -Hab development will expand toward laboratory, BioWaTERR, crew quarters, and missions

- Food Production Module: hydroponics and Mycoponics™
- Laboratory Module: bioreactor testing and BSL-2 research
- BioWaTERR Trailer: potential wastewater and nutrient recovery integration
- Crew Quarters Module: habitation required for first full Mini-Hab analog mission



Future Mini-Hab development will expand from the Food Production Module into a testbed with crew quarters, laboratory space, and the BioWaTERR trailer for waste, water, and nutrient-loop research.

BioWaTERR Reference: ICES-2026-290

The primary ASTRO-USA habitat is the long-term high-fidelity closed-loop analog target

Design Area	Primary Habitat Design Target
Enabling Systems	Integrated closed-loop waste, water, air, food, power, and crew-support systems
Habitat Design	Modular cylindrical and spherical habitat sections using off-world relevant structural materials
Human Factors	Fully controlled internal environment for lighting, atmosphere, temperature, noise, circadian studies, and mission scenarios
Controls and Monitoring	SIMOC Live and Opto 22 for real-time data, automation, alarms, and fault response
End Goal	High-fidelity Moon/Mars habitat analog for Moon base relevant technology maturation

The primary habitat is the long-term ASTRO-USA goal: a high-fidelity analog that is intended to integrate habitat design, human factors, and enabling systems into one closed-loop testbed.

ASTRO-USA may support Moon and Mars habitation objectives

Exploration Need	ASTRO-USA Contribution	Why It Matters
Sustainable lunar habitation	Intended to test closed-loop waste, water, food, air, and power systems	Reduces dependence on resupply for long-duration missions
Technology maturation	May provide an Earth-based testbed for integrated habitat subsystems	Allows systems to be tested before deployment to the Moon or Mars
Crew health and performance	Intended to enable controlled lighting, atmosphere, temperature, noise, and mission scenarios	Supports human factors research for future surface habitats
Modular habitat architecture	Intended to develop a scalable habitat concept with off-world relevant design targets	Supports future expansion of lunar and Martian base infrastructure
Phased development	Will use the Mini-Hab to test subsystems before primary habitat integration	Lowers risk before building the full high-fidelity analog

ASTRO-USA may support the Moon base and Mars habitat architecture by maturing sustainable habitation systems needed for long-term crewed operations on the Moon and Mars.

Future work moves from Mini -Hab operations to full primary habitat integration

Phase	Development Focus	Target Outcome
Year 1	Complete Food Production Module	Hydroponics, sensors, solar power, and early environmental monitoring operations
Year 2	Develop Laboratory Module	Begin bioreactor testing, waste processing, nutrient recovery, and Mycoponics™ integration
Year 3	Develop Crew Quarters Module, fully integrate BioWaTERR, or a similar module, and operate full Mini-Hab	Conduct first full Mini-Hab analog mission and collect system performance data
Primary Habitat Phase 1	Complete primary habitat structure	Build modular high-fidelity habitat shell for long-duration mission simulation
Primary Habitat Phase 2	Integrate closed-loop systems and controls	Prepare primary ASTRO-USA for its first high-fidelity analog mission

Future work will use Mini-Hab mission data to improve closed-loop performance, human factors studies, EVA procedures, and the final primary ASTRO-USA habitat design.

ASTRO-USA is intended to provide a phased path toward a high-fidelity closed-loop habitat analog

Key Takeaways	Summary
Current analogs have full integrated capabilities limitations	Existing facilities provide useful research value, but none fully integrate high-fidelity habitat design, human factors, and enabling systems in one closed-loop architecture.
ASTRO-USA addresses this gap	ASTRO-USA is being designed as a modular, controlled, closed-loop habitat testbed for Moon and Mars technology development.
The Mini-Hab enables phased testing	The secondary Mini-Hab will allow food production, bioreactors, sensors, power, and crew operations to be tested before full primary habitat integration.
The primary habitat is the long-term target	The final ASTRO-USA habitat will provide a high-fidelity analog for long-duration mission research and technology maturation.

ASTRO-USA is intended to provide a phased path from near-term subsystem testing to a high-fidelity closed-loop analog habitat for future Moon and Mars missions.

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