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Mockups 101: Code and Standard Research for Space Habitat Analogues

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This paper describes the application of aerospace design methodologies to the planning, design, and construction of space habitat analogues. These habitat designs occur along a spectrum from simple Foamcore and wood construction open to the ambient environment, to steel or composite pressure vessels for human occupancy with a hypobaric atmosphere. Success in developing and operating a mockup and simulator research program often depends upon careful code and standard research aimed at compliance to protect the health and safety of construction workers, researchers, test subjects, and visitors alike.

Nomenclature

ANSI = American National Standards Institute
ASME = American Society of Mechanical Engineers
ATM = atmosphere
CERC = Controlled Environment Research Chamber
GFI = ground fault interrupt
HEDP = Human Exploration Demonstration Project
HPC = Human-Powered Centrifuge
ISS = International Space Station
PVHO = pressure vessel for human occupancy
TRL = technology readiness level

I. Introduction

Because access to space is so difficult, dangerous, and expensive, the disciplines of engineering, operations, and space architecture attempt to simulate every aspect of space habitats that they can before finalizing the design. So long as this condition holds true, there will always be a need to provide full-scale architectural simulation capabilities in which to experiment with operational procedures, develop and evaluate hardware and practice space missions with the whole crew at one time. These simulation technologies often involve sophisticated computer simulations, high fidelity engineering testbeds, and complex operational scenarios. These simulations all involve, to varying degrees, the creation of artificial environments through physical architectural.

Colin Clipson (1988) characterized mockups and analogues as *defining future worlds*. Yet, mockups and simulators that are useful beyond promotion of retail products must perform according stringent regulatory codes and technical standards. Building accurate and successful mockups and simulators for space habitats and missions can pose a substantial challenge, especially when they involve placing human subjects in a confined or closed environment. The constellation of codes and standards applicable to these analogs are complex, often confusing, sometimes contradictory, and occasionally incomprehensible. Code and Standard assessment are important for three reasons, among which the design and review processes must achieve a balance. This assessment sets limits to how the analog project may try to achieve -- but not underachieve or overachieve -- its compliance goals.

In developing the *future world* of architectural design for habitable space environments, a critical step is the design and construction of full-scale architectural mockups to simulate the designed environment. Representations, either drawn by hand or by computer-aided design (CAD), and scale models are essential steps, but the major architectural research and development step is to design and build a full-scale mockup or simulator.

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Nathan R. Prestopnik (2010, p. 167) argues that a true design science requires in equal measure theory, design, and evaluation. In his view, design science serves as the bridge between the three. This paper takes a corresponding design science (Prestopnik, 2010, p. 174) approach insofar as it connects *pure theory, technical development, and evaluation.*

A. Challenges for Research in Human-Environment Interaction

From the perspective of producing valid scientific results about architectural design, nearly all space habitat analogue studies to date have been less than successful. Insofar as the author is aware, there has yet to be one documented and published, statistically valid experimental research design in this field. The best results are still mainly anecdotal, "surveys of the experts," or experiments with vanishingly small sample sizes. Up to now, the Human Factors discipline has led what little rigorous research there is on living and working environments for space exploration. However, there have been some major shortcomings in this research. So long as the traditional Aero-Human Factors approaches dominate habitat design research, the human spaceflight community is unlikely to find the data or answers that it needs. The reasons for this problem include:

1. Human Factors scientists and engineers generally decline to recognize the human-environment interaction.
2. Aero-dominated Human Factors researchers tend to believe that a Human Factors problem occurs only over a very brief period of time, (e.g. in the last few seconds before the airplane crashes).
3. Extended mission durations are what primarily distinguish Space Human Factors from Aero Human Factors, but they are very costly and the metrics are primitive for how human performance and human-environment interaction change over long durations such as a 1000 day round trip to Mars.

In sum, human systems research for the design evaluation of space habitats must look beyond the traditional strictures of the Aero Human Factors discipline. It becomes necessary to look to other social science disciplines that can address environment interaction and long durations such as Environmental Psychology, Anthropology, and Sociology. Beyond these academic pursuits, Space Architecture through full-scale simulation needs to develop as its own design research discipline. A systematic approach to the uses, types, and degree of closure for mockups and simulators can provide a foundation for this understanding.

B. Perception and Cognition

All forms of representation are "virtual" to some degree. A freehand pencil drawing is a virtual or heuristic representation of something. Many important paradigms in architecture contain a heuristic or virtual representation of an earlier form. The distinction between representation and physical embodiment is not new; Emmanuel Kant described it succinctly in Critique of Pure Reason [1781]. Kant focused on the ways in which people see and feel phenomena.

> Perception is empirical consciousness, that is, consciousness in which there is at the same time sensation. . . .
>
> Experience is empirical knowledge, that is, knowledge which determines an object by means of perception.

Kant's distinction between perception and experience corresponds to the difference between CAD, virtual reality, and full-scale architectural simulations. People who are well trained in architectural drawing and other forms of representation are able to visualize a three-dimensional environment from a 2D architectural drawing. However, most people cannot visualize a full environment from a 2D plan or building section. Kant frames the paradox such that although someone cannot visualize 3D space from the perception of 2D drawings, the moment she or he is in a physical mockup, that person can visualize and understand it. EVERYONE HAS EMPIRICAL KNOWLEDGE and is an expert because they already know and live in physical reality. What is most important is that what people learn through experience they learn more deeply and permanently than what they learn by reading, seeing drawings, or listening to explanations. This empirical knowledge determines how people will perceive and evaluate the space habitat environment.

Kant was the consummate methodologist. This discussion follows with a focus upon methodology through categorization that defines the thresholds between different state-conditions of the environment. This methodology can span seemingly disparate systems of thought such as closure of pressure vessels, electrical safety, environmental psychology, fire safety, and technology readiness levels, among other sets of parameters.

C. Human-Scale Simulation Research

Full-scale simulation offers the unique quality that it is human–size. An observer or a test subject can go into it, see it, touch it, hear its acoustical qualities (however flawed, but different from the surrounding environment), and even smell the glue. These qualities, especially the ability to physically enter the artificial world have a verisimilitude and a persuasive power about the nature of the simulated design that is difficult to achieve in any other way, although virtual reality technology offers some inroads in this area. The choices of computer representation versus full-scale physical simulation will continue to raise such questions until there are fully functional and commercially available "holodecks."[2]

Space living and working environment analogues can provide important data to inform the design of future crewed spacecraft, habitats, and lunar and planetary bases. In architectural design research, the general objective is to learn how well an environment performs and how it may be possible to improve or remediate it, and how to design a better one the next time. It would be enormously valuable to the designers of future spacecraft to plan and conduct scientifically valid research at the existing analogues including terrestrial habitats, field exercises, simulators, and the ISS.

The human spaceflight community can begin designing advanced habitats to the Crew Productivity Figure of Merit (Cohen, Houk; 2010) to develop and apply metrics to measure the human-environment interaction. "Advanced Habitat" should mean that it is designed, built, and tested to meet rigorous evidence- and performance-based standards– NOT merely a material-spec description. The community can define and develop these standards and specifications only through scientifically valid architectural design research that closes the circle with the research purpose of mockups and simulators.

D. Caveat: The Chronological Age of Architecture, Mockups, and Simulators.

There is a perhaps natural tendency to discount past accomplishments, facilities, and historical events as "too old." However, in the profession and study of Architecture, the age of a building does not diminish its importance or relevance. In the same manner, the chronological age of a space program or mission does not diminish the effort, logic, or reasoning that went into it. The projects and artifacts from the first few decades of human spaceflight were quite remarkable and often showed a brilliance and elegance that NASA has yet to recapture. This paper presents mockup and simulator projects from these decades as well as contemporary projects. These projects and the effort that went into creating them remain equally valid and relevant.

II. Analogue Purposes and Research Design

This section describes three key aspects of why space architecture researchers build habitat analogues. These aspects constitute the purposes for mockups and simulators, the frame of reference of control versus realism, and the fundamentals of design research in these analogues.

A. The Purposes of Mockups and Simulators

The essence of architectural simulation is the creation of an artificial environment, which may serve a variety of purposes, depending upon the customer's, researchers, or designers' intentions. These purposes are not mutually exclusive, but can co-exist or overlap in the same mockup or simulator. The essential question for architectural simulation research is for what purposes full scale simulation environments or mockups will continue to be appropriate. To be meaningful, the creators must place full-scale architectural simulation mockups within a research program or systematic design inquiry. Typical mockup objectives vary by the customer, the researcher, and the designer. The researcher is central to the whole undertaking, and often is also the customer. Sometimes the researcher is also the designer. However, the designer is rarely the customer, *per se*. The following lists present some of the most common objectives.

1. *For The Customer:*
   - Create a Space Habitat demonstration and display capability to support technology development.
   - Demonstrate the rigor and fidelity of an approach.
   - Create a showcase for a space vehicle concept.
   - Prove that a crew can perform the mission-required tasks.
2. *For The Researcher*
   - Provide a Part-Task Simulator for Flight Crew and Work Station.

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[2] http://www.startrek.com/database_article/holodeck

- Provide a Full-Task Simulator for Mission Simulation.
- Create an operational environment in which to study interaction of crew and systems.
- Create an operational environment in which to study crew-to-crew interactions.

3. *For the Designer*
   - Provide a common experiential frame of reference for the engineering subsystem IPTs.
   - Provide a three dimensional, full-scale engineering integration simulator for the subsystem IPTs.
   - Implement a design research tool for habitability, human factors, and ergonomics.
   - Identify the interfaces among the subsystems and their intersection with the common constraints of the habitat or spacecraft configuration.
   - Explore how the need of the subsystems' functionality and crew operations informs the configuration.

B. Common Frame of Reference: Control versus Realism

This paper offers a common frame of reference for understanding full-scale mockups and simulators for human spacecraft. In order to forge this common framework, it distills these myriad objectives down to five key purposes.

- Concept evaluation,
- Design research,
- Engineering integration
- Operations simulation and development, and
- Crew Training.

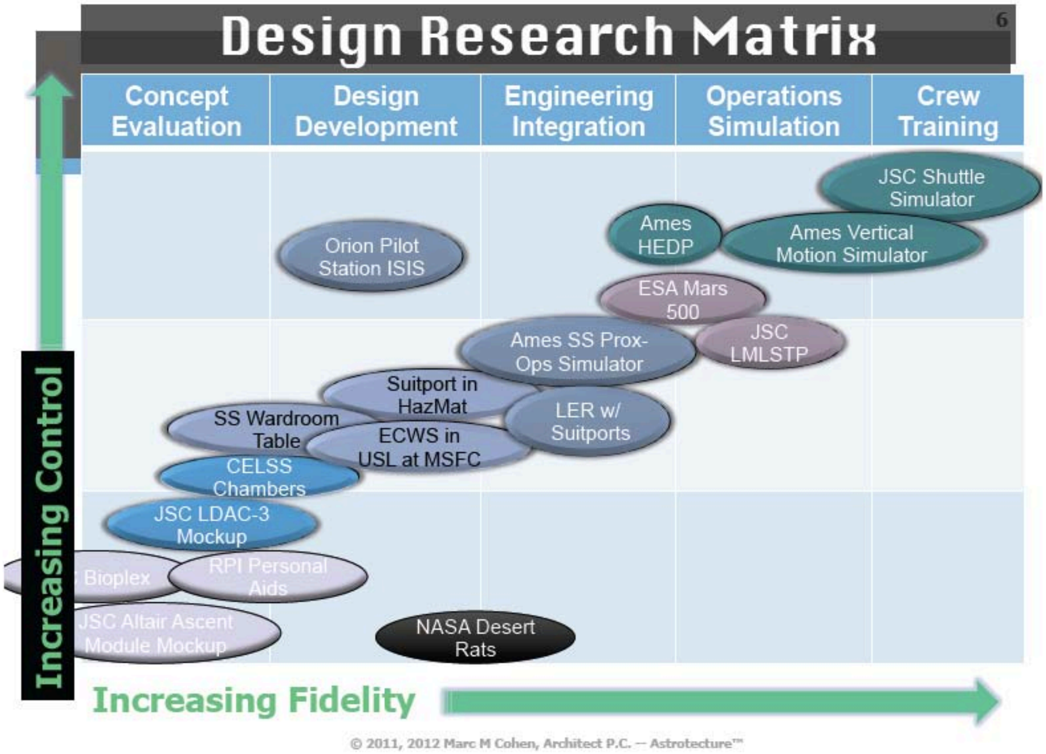

DIAGRAM 1. The Design Research Matrix for assessing control and realism across the five purposes for mockups and simulators.

DIAGRAM 1, the design research matrix, displays these five categories across the top parallel to the x-axis for increasingly fidelity. The common frame of reference spans the domain of fidelity, control, and realism. Space missions pose a special need for full-scale simulations that serve multiple purposes as the Skylab mockup did. Connors, Harrison, and Akins observe:

> Mission Simulators . . .are particularly important in space mission design because there is essentially no opportunity for a graduated series of practice efforts under true operational conditions before the mission

> takes place. Since space mission crews must be trained and highly proficient in their tasks before the flight, it is imperative that high-fidelity simulator systems be available for training on specific, individual aspects of the mission (partial simulation) and for the completely integrated "dress rehearsal" simulation of the mission [full scale simulation]. (Connors, Harrison & Akins, 1985, p. 115).

Connors, Harrison, and Akin's observation about partial and full mission simulation raises a second set of questions about full-scale simulation, on the spectrum of control versus realism. Classically, there are trade-offs between control and realism, which vary inversely in most fields of human performance research. The same condition holds for architectural research, but also correlate to the way in which an architect conducts design research as a component of professional practice. The three classic categories of research; basic, applied and field relate to architectural research on a somewhat broader scale than just full scale simulation, but still apply.

C. Fundamentals of Research Design

A research design MUST come first in formulating an analogue project. In far too many analogue projects, the participants enthusiastically undertake the task of designing and building a habitat analogue. Often they have an idea of how they will use it to act out a mission of some kind, with provisions for conducting simulated operations. However, it has been exceedingly rare that these analogonauts have a research design that enables them to produce scientifically valid, reproducible results. It is almost as rare that they ever document and publish these results in accessible, let alone peer-reviewed form. Here are the key ingredients necessary to overcome these deficiencies.

Never the less, if the researchers want to conduct scientifically valid research, they must follow the established protocols. What few analogue experiments exist in published form usually have a very low *n*, the number in the experimental sample. All too often, the would-be researcher claims the proverbial "*n=1* proof of hypothesis." How many problems are there with this *n=1* paradigm? The following discussion may seem like a recapitulation of Statistics 101, but it is necessary because many architects have never learned statistics and many engineers came away from their first statistics class having learned primarily that they should stay as far away from statistics as possible.

First, a scientist does not "prove a hypothesis." A scientist can only reject or accept the null hypothesis – that there is no treatment effect. One can reject the null hypothesis without supporting an alternate hypothesis, although that is usually in the ballpark for a statistical research design.

Second, and this is almost begging the question, an n or 1 or sometimes 2 offers no statistical power. Without statistical power, it is not even possible to apply inferential statistics that require random samples. To obtain a random sample with statistical power generally requires an n=1 to n=30, where n is the number of experimental runs for an analogue or simulator experiment. Random data is essential also to perform valid tests for significance.

The ***Alternate Hypothesis*** offers a new and different explanation for a phenomenon. It goes to the heart of the investigation: what does the experiment in the simulation do that is different and what will it achieve? How does the analogue serve to stage the experiment?

The Research Design must state clearly what is being measured and how it is measured. These protocols and procedures mean:

1) Measuring and evaluating the artificial environment and its interaction with the natural environment.
2) Measuring and evaluating human and human/machine interaction within the designed environment.
3) Measuring and evaluating human interaction with the designed environment.

Although these metrics may seem self-evident, researchers in the behavioral sciences do not always accept them. Many of these human factors and behavioral researchers are so involved in there neuroscience-based models of perception and cognition that the physical environment is irrelevant – or at best an after-thought.

Given that the researcher will want to measure these metrics and parameters, it becomes necessary to define the variables that represent them. Defining the variables means identifying the independent and dependent variables, separating them from any constants, stating expressions for their values, and calibrating the range in which to expect those values to occur.

Identifying and mitigating threats to validity poses a final gateway to meaningful results. The key point with the findings that survive these threats is how widely can the researcher generalize from the experiment to other situations. All these provisions and precautions play their role in finding significant and reproducible events.

III. Methodology

What is most important about doing the code and standard research early and thoroughly is that it makes it possible to put all the risk safety issues under control, so that it becomes possible to concentrate on producing the experience the researchers want for the test subjects or crew. Methodology plays an important role in the conception, development, construction, and operation of mockups and simulators. This section states in simplified form the methodology that underlies the Code and Standards Research in the title. For most projects, the project managers defer the chore of obtaining safety approvals for as long as possible. However, for any project that places human subjects in potentially hazardous conditions, it is vital to establish the safety paradigms and obtain the necessary reviews and approvals ***as early as possible*** in the design process. The author recalls this conversation with a project manager:

> Author: We need to secure our authorizations and permits from the Health and Safety Office before we commit to a project design.
>
> PM: Oh, we don't want to let *them* nail us down yet, not until we know what we want.
>
> Author: You don't understand! *We* need to nail them down! ***Until we nail them down, we don't have a project.***

Safety is a critical requirement both for space habitats and terrestrial architecture. The knowledge and ability to protect the public's health and safety is a fundamental requirement for a professional license in architecture in the United States and nearly every other country with such registration. Because the space environment is so much more unforgiving than the terrestrial environment, the commitment to safety through architectural design research must begin with the Earth standard as an absolute minimum and go far beyond it. Therefore, the earlier that Space Architecture researchers and designers identify all these potential safety issues and constraints, the more capable they will be to control project cost and risk, and to assure project effectiveness.

So, how should the creators of a space habitat analogue proceed? This paper is largely about methodology and how it interacts with the taxonomy of various types of mockups and simulators. The methodology involves three steps core steps:

1. Identify ALL the potential risks in relation to the relevant code and standard provisions at the outset of the project to ensure the safe and healthy operation of the analog thoughout all its development phases. Plan the project around these provisions.
2. Document everything, everything, without exception. Document what you do and do what you document.
3. Write requirements and design to the requirements. Make them all traceable. Plan to be able to refer every part of the design you documented back to a requirement and relevant safety approval.

APPENDIX A provides simple examples of the kind of diligent life safety code and standard research and documentation and its application that are necessary to create a successful project. As a caveat about this method, the Project should not go overboard in finding excessive requirements or constraints, which will drive up cost and complexity unnecessarily, especially when not needed in earlier phases and perhaps not at all in the final stage of development. Keep it as simple as possible. APPENDIX D illustrates an incremental approach to evolving electrical grounding from ground fault interrupt to explosion-proof. In much the same manner, the project should plan for the acquisition, adaptation, and reuse of equipment. It should enable the continuing use of the investment at each phase of building up the analog. It should require only minimal discarding of equipment, materials, and outfitting from one phase to the next.

E. Central Documents

To accomplish these objectives, a comprehensive evaluation and understanding of the relevant code and standard documents and requirements is essential. The five current, central documents are:

- National Fire Protection Association, (2008). NFPA 70 National Electrical Code.
- International Code Council (2012). International Building Code.
- National Fire Protection Association (2010). NFPA 99B Hypobaric Facilities. and
- ANSI-ASME PVHO-1-2012 Safety Standard for Pressure Vessels for Human Occupancy
- NASA Handbook (2004 or most recent edition). NHB:5300.9, Safety, Reliability and Quality Assurance Provisions.

IV. Degrees of Chamber Closure

The two standards that apply to the design of chambers used as pressure vessels and simulators are the ANSI/ASME PVHO-1-2012 *Pressure Vessels for Human Occupancy* and the ANSI/NFPA 99B *Hypobaric Facilities.* The key properties of simulation chambers and pressure vessels include the degree of closure, the atmospheric regime including ventilation or life support, electrical isolation and grounding, and fire protection. The PVHO presents a rating scale **A to F** that covers the range from open cardboard mockups to sealed hypobaric chambers with an artificial buffer gas. TABLE 1 presents some of these characteristics as they apply to space habitat analogues. Air circulation can be passive, through open "windows" in the shell, through a system of active ventilation, or through full life support. The atmospheric gas mix can vary from ambient air to variations in the concentration of oxygen and buffer gas. If water is present, the electrical system requires ground fault interrupt (GFI) circuits. If the concentration of oxygen is elevated, the electrical system requires high quality isolation from the building ground and explosion-proof fixtures. Fire protection requirements bring into play fireproof or fire-retardant materials, and active fire suppression system such as water sprinklers or Halon. These requirements from the applicable standards can lead to important interactions. Each of these subsystems demands careful design and integration into the experimental chamber.

TABLE 2. Overview of Environmental Chambers /Pressure Vessels for Human Occupancy

Class	Door/ Hatch	Pressure	Gas Mix	Ventilation	Electrical	Example
A	Open Door	1 ATM	Normal	Natural	Standard	JSC Altair Mockups
B	Open Door	1 ATM	Normal	Mechanical	Standard	Ames Space Station Prox-Ops Simulator
C	Closed Door	1 ATM	Normal or Life Support	Mechanical	GFI if water is present	IBMP ESA-Mars 500, Lunar Electric Rover
D	Press-Sealed	Reduced in Altitude Mode	Constant Gas Mix, Normal or Life Support	Mechanical May include air revitalization	GFI if water is present	JSC LMLSTP in 20 Foot Altitude Chamber
E	Press-Sealed	Reduced in Hypobaric Mode	Increased O2 Partial Pressure	Mechanical w/ Air revitalization	Explosion-proof w/ isolated ground/GFI	EVA Suit, Ames Controlled Environment Research Chamber (CERC)
F	Press-Sealed	Reduced in Hypobaric Mode	Increased O2 PP, Artificial Buffer Gas, Halon	Mechanical w/ Air revitalization	Explosion-proof w/ isolated ground/GFI	Ames CERC for Human Exploration Demo Project

V. Technology Readiness Levels (TRLs) for Mockups and Simulators

NASA and other agencies have adopted the taxonomic approach of classifying technology development projects by *technology readiness levels*. This system is useful for understanding where a technology or project stands in the development process. It is relevant to mockups and simulators, which can prove useful at nearly every level (except – for now – at the in-space TRLs). At each TRL, the mockup displays particular attributes. TABLE 2 explains these correlations. Nolte and Kruse (2011) warn against the proliferation of readiness levels, that is, the creation of new definitions for technology readiness to match specialized circumstances. Indeed, in the 2003-2005 period, there was an effort within NASA (Connolly, Daues, Howard, Toups) to create a new "habitation readiness scale," but this paper heeds the Nolte and Kruse warning and so adheres to NASA's established TRL scale, adjusting instead the ways and means of achieving those clearly defined levels.

The TRLs correlate *explicitly* to the mockup/simulator attributes. At a deeper level, the mockup/simulator attributes correlate i*mplicitly* to the fidelity of the analogue. *Degrees of fidelity* would be a separate discussion that is beyond the scope of the present essay.

This section presents examples of mockups and simulators that display the characteristics and properties described in TABLE 2. This series of examples is not intended to be comprehensive to show all possible types of solutions. Mohanty et al (2008) present such a wide-ranging survey. Rather, it illustrates of the level of development, refinement, and integration that occurs in analogue research. This section is organized into two parts. The first part addresses the early TRLs 1-3 that do not rise to the level of a complete "environment." The second part addresses the mid-range TRLs 4-6 that all reference a test in a "laboratory" or "relevant" environment. The higher TRLs 7-9 all involve testing or operation in the space environment, which up to this writing have never involved a habitability mockup or other analogue except insofar as Stuster (1984) suggests one space station as an analogue for a future space station.

The ESA (2008, p. 33) TRL Handbook states a *TRL philosophy* that offers a somewhat different overview:

- The first 4 levels are used to increase the level of functionality of the tool, from the mathematical formulation and through prototyping and incremental enhancement up to the level of an "alpha" version.
- The next two are used to improve the tool up to the level of a (commercial or otherwise) released product.
- The last three levels cover the deployment of the tool in a project, starting with a pilot application (an IOD) and up to a fully operational project.

A caveat about this section is that most of the TRL literature focuses upon the validation to certify that a technology has achieved a particular TRL. The following summary uses TRL to describe the whole effort to bring a technology from the earlier level to the one by which it is labeled.

TABLE 2. Technology Readiness Levels (TRLs) in Relation to Mockup Attributes

TRL	General Description	Mockup-Specific Attributes	Typical Materials	Remarks
1	Basic Principles Observed	Conceptual Design to show that X can exist with attributes Y & Z.	Foamcore, Cardboard, Sintra board	Scale models usually work as well as full-scale mockups.
2	Concept Formulation, Modeling, and Simulation	Control design variables for dimensions	Plywood, Sintra board, Wood	Architectural Experiments
3	Proof of Concept	Form, Fit, Function, Mechanical Operations	Metal, Plastic, Wood	Engineering Integration Phase
4	Component/ Subsystem Test in a ***Laboratory Environment***	Functional and Operational Research	Electronics, Mechanical Systems	Includes part task flight simulator
5	Subsystem Test in a ***Relevant Environment***	Partial Habitable Living and Working Environment Simulation	Electronics, Mechanical Systems, Atmospheric System	Includes motion-base flight simulator
6	System Test in a ***Relevant Environment***	Full Habitable Living and Working Environment Simulation	Electronics, Mechanical Systems, Hypobaric Atmosphere	Includes high fidelity mission simulator

TRL-1 Basic Principles Observed and Reported

TRL-1 is basic scientific research that the investigators can turn into an application or a concept under a research and development program. The imperative of TRL-1 is that it must suggest a path to future development. TRL-1 marks the point where scientific research begins to provide the basis for a new technology, whether it is a material, a process, a machine, or something else. Basic research and physical or computational models help to substantiate the basic principles observed. Scale models also play an important role and can be very cost-effective for representing three-dimensional relationships, but they are part of a different discussion.

1. *Altair Lunar Lander Ascent Module Basic Mockup—Chamber Class A*

Kriss Kennedy and Larry Toups at NASA-JSC designed the mockup shown in FIGURE 1. Its purpose primarily was to understand the rough volume that would become available in the Altair Ascent Module. It is made entirely of Foamcore board except for the plywood representation of the engine head in the floor. Behind the engine head is the "EVA hatch," modeled upon the Apollo Lunar Module EVA hatch.

FIGURE 1a. Exterior view of the Altair Ascent Module Mockup, showing the pilot windows. Author Photo, 2006.

FIGURE 1b. View of the Ascent Module interior with the engine head represented on the floor and the "EVA Hatch" behind it. Author Photo, 2006.

FIGURE 1c. Interior view of the flight deck/pilot stations at the pilot windows. Author Photo, 2006.

Figure 2a. Altair Sizing Mockups: Ascent Module to the left and the Airlock Module to the right. Author Photo.

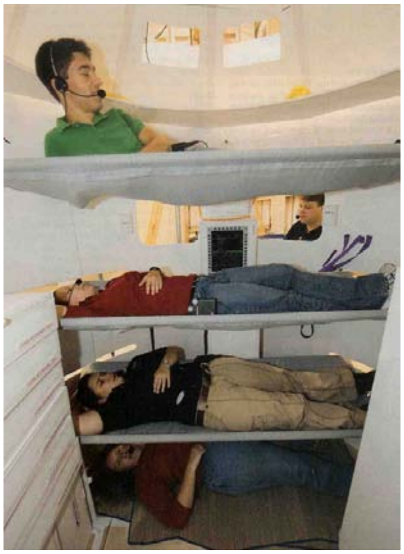

Figure 2b. Crew bunks in the Ascent Module Mockup. NASA Photo.

2. *Altair Ascent Module and Airlock Sizing Mockups—Chamber Class A*

Robert Howard at NASA-JSC oversaw the development and operation of this low fidelity simulator to understand the constraints and possibilities in cylindrical ascent modules of varying diameters. Each of the two cylinders is made of Foamcore and suspended from a wooden "A-frame." The cylindrical forms of the cabin consist of overlapping, curved sheets of Foamcore that can expand and contract over the range of likely diameters. The research staff can install Foamcore boxes to represent various outfitting and stowage, and install bunks to estimate crew living conditions. This sizing mockup is probably the most successful and useful TRL-1 apparatus of its kind that the author has found. FIGURE 2a shows the two cylinders with the bungee cords that constrained the outer diameter. FIGURE 2b shows the interior of the Ascent Module with four bunks installed in front of the pilot station/flight deck and piloting windows.

TRL-2 Concept or Application Formulation

TRL-2 is when invention begins. In the case of space habitats, TRL-2 involves the schematic design of hardware and habitat configurations. The concepts begin to use fixed dimensions and to integrate with practical pressure vessel shapes and sizes. For the mockup to succeed, it must prepare to accept all the engineering systems: architectural, electrical, fire protection, lighting, mechanical, and structural. That does not mean that the concept formulation must incorporate or represent those engineering functions and interfaces, but it must demonstrate a cognizance of them and preparation to accommodate them at higher levels of development. This characteristic becomes increasingly important when planning to meet the code and standard requirements for the crew in a potentially closed environment. Often it is possible to achieve TRL-2 for Space Habitats with drawings or scale models, but full-scale mockups carry a special power of empirical knowledge through experience.

1. Spacelab / Space Station CELSS Plant Growth Chambers—Chamber Class B

At the time of the design of these Controlled Ecological Life Support System (CELSS) chambers in 1984, the Spacelab module was flying on the Space Shuttle, and it provided the functional cross section of the module in which to integrate these research "racks." Space Station modules were still quite speculative, so the project followed the Spacelab template. The module shell conformed to the dimensions of the Spacelab module, with the floor deck at about the same height, and the hung ceiling unit coming down to the height of the Spacelab module. The project plan called for eventual integration with the electrical, data, and life support systems.

FIGURE 3. Spacelab module in use during the Shuttle Flight STS-51B. NASA Photo.

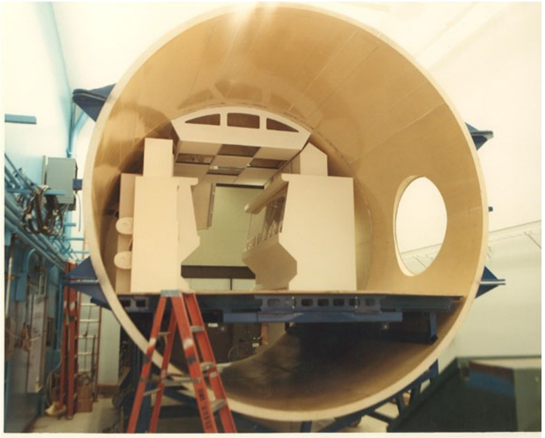

FIGURE 4. Mockups of plant growth chambers for CELSS experiments for Robert McElroy in a Spacelab-type configuration. NASA Photo.

2. TransHab Mockup—Chamber Class A

The TransHab project at NASA JSC developed a concept for a large "fat tire" inflatable toroid around a rigid Endoskeletal core (the "axle"). The architects were Constance Adams and Kriss Kennedy. Because of the difficulties in attaching equipment or outfitting to the pressure bladder of an inflatable, the architects developed a full-scale mockup in which to portray and evaluate their design concepts. FIGURE 5 shows views of the TransHab mockup, built from traditional flat and rigid materials to convey the rigid structural endoskeleton (axle) of the TransHab Concept. The TransHab mockup was a landmark of TRL-2 concept formulation because it displayed credibly how the interior of this toroid could be made useful.

The mockup represented portions of different floor deck levels with typical outfitting such as the crew sleep quarters surrounded by 10cm water tanks for radiation protection. The spatial division incorporated vertical triangle grid walls for mounting equipment in the tradition of Skylab. The galley/dining area included an oval table with foot and leg restraints. The TransHab mockup was highly successful insofar as it led to developing the complete inflatable TransHab module that NASA licensed the technology to Bigelow Aerospace for a future space hotel.

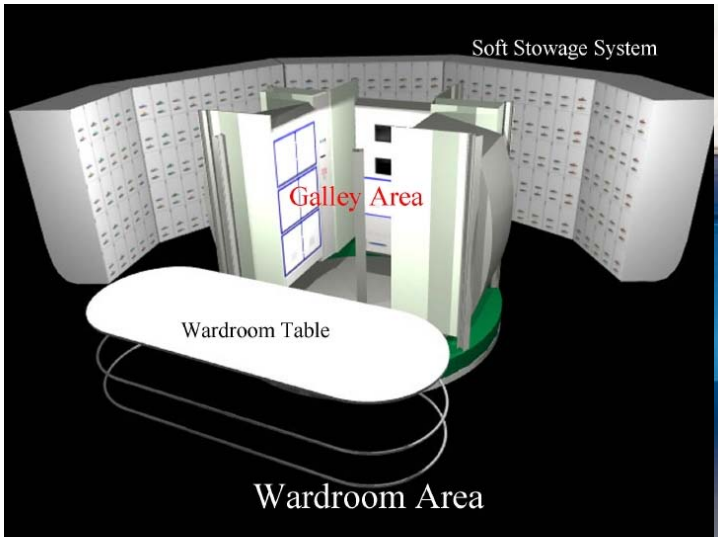

FIGURE 5a. CAD rendering of the galley and wardroom area, showing the wardroom table with leg and foot restraints. Lockheed/NASA rendering.

FIGURE 5b. Constance Adams in front of the Endoskeletal core of the TransHab Mockup.

TRL-3 Proof of Concept

The TRL-3 Proof of Concept means demonstrating one or more critical functions or characteristics of the new technology. In Space Architecture, Proof of Concept requires a full-scale, physical representation, although it may not require a complete habitat environment. This human-scale mockup must make it possible for the crew or human subjects to operate the critical functions.

FIGURE 6a. The author and Christopher R. Miller demonstrating the Space Station Wardroom Table in its compacted configuration. NASA Photo. 1991.

FIGURE 6b. Close-up view of the Space Station Wardroom Table in fully unfolded and deployed configuration. NASA Photo. 1991.

1. Space Station Wardroom Table—Chamber Class Not Applicable

The Space Station Wardroom Table was a joint project between the Southern California Institute of Architecture (SCI-Arc) and NASA Ames Research Center. Prof. David Nixon was the principal investigator on the NASA cooperative agreement, and the co-inventors were Jan Kaplicky of Future Systems, London, and the author. The team achieved Proof of Concept by demonstrating that crewmembers could use the table to support a variety of tasks and deployed its several segments to accommodate a variety of crew activities.

2. Suitport in the HazMat Vehicle—Chamber Class C for the Vehicle, Suitport, and Suit

The Suitport is a concept for rapid suit donning and doffing, egress from a space cabin atmosphere and ingress back into it, while conserving atmosphere, electrical power, cooling, and crew time. It also offers potential advantages for contaminant control, particularly to prevent the intrusion into the crew cabin of contaminants such as dust or hazardous chemicals, with the assistance of air conditioning over-pressure. The Proof of Concept for the Suitport occurred by building two Suitport mockups into the aft bulkhead of an armored personnel carrier called the HazMat Vehicle.[3] Validating the Suitport at TRL-3 involved demonstrating the crewmember could don the suit through the Suitport, egress the Suitport in the bulkhead, and return to the Suitport, doff the suit and reenter the cabin.

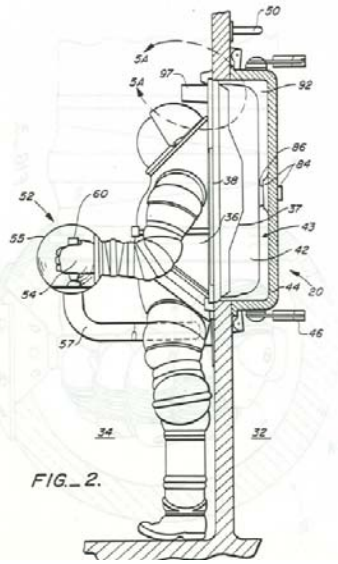

FIGURE 7a. Cross-Section through the Suitport. US Patent 4,842,224.

FIGURE 7b. The Ames Hazmat Vehicle with two Suitports in the aft bulkhead. Jerry James demonstrates the Suitport-compatible backpack on the HazMat suit. NASA Photo.

TRL-4 Validation in a Laboratory Environment

TRL-4 constitutes a Component / Breadboard Validation in a Laboratory Environment. The laboratory environment can take a number of different forms. It can consist of a laboratory benchtop, a simulation in an environmental chamber, or a naturalistic test in a "field laboratory," among many other options.

1. Space Station Proximity Operations Simulator – Chamber Class B to C

The Space Station Proximity Operations Simulator was a project to build and operate a simulator that would be capable of world-class research in orbital operations. It offered the capability to "fly" spacecraft in a virtual out the window environment, to simulate rendezvous and docking, and navigational maneuvers. The Prox Ops included the first voice recognition/voice synthesis display in a space simulator, a 3D color "God's eye" navigation display, and video display of scale model operation of spacecraft. The operator could select a spacecraft in the three-screen out the window display and fly it using the standard Shuttle side-arm controller. The Prox Ops Simulator appears in FIGURES 8 and 9. Richard Haines managed the project to achieve TRL-4 by validating component and breadboard operation within several "integrated mission simulations" and by supporting research that was published in more than 20 peer-reviewed articles.

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[3] Philip Culbertson, Jr. was the industrial designer who produced this Suitport demonstrator/mockup.

FIGURE 8. Space Station Proximity Operations Simulator at NASA Ames. Richard Haines sits at the controls. NASA Photo.

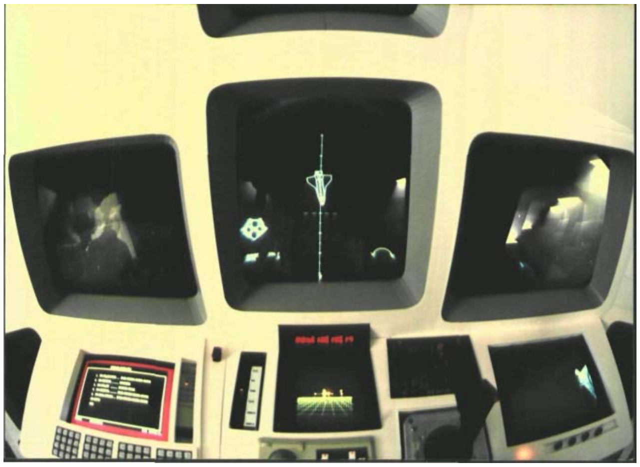

FIGURE 9. Close-up view of the Space Station Prox Ops Simulator Controls and displays. NASA Photo.

2. Lunar Electric Rover Test at Desert RATS with Suitports—Chamber Class C to D

Perhaps the most widely known field laboratory test involved the NASA Lunar Electric Rover (LER), which includes two Suitports, mounted in the "rear" driver positions. Michael Gernhardt, the Astronaut Office representative for Exploration EVA is leading this project. The LER team has conducted field tests at the NASA Desert Research and Technology Studies (RATS)[4] field exercises for several years as shown in FIGURE 10, and have made progress in improving the mechanisms and reducing the parts count by half.[5] On January 20, 2009, the LER served as the NASA float in President Obama's inaugural parade in FIGURE 11.

FIGURE 10. Lunar Electric Rover at the 2010 Desert RATS field test in the Arizona desert. NASA Photo.

FIGURE 11. Two astronauts driving the Lunar Electric Rover while situated in the Suitports as the NASA float in President Obama's inauguration parade. Courtesy of News 8.

3. ISIS Lab – Orion Control and Display Simulator – Chamber Class Not Applicable

The Orion Control and Display Simulator in the Intelligent Spacecraft Integrated Systems Lab (ISIS) follows the traditional concept of a laboratory more closely than the other examples. Robert McCann and Brent Beutter developed several crew station simulators for the ISIS Lab.[6] FIGURES 12 and 13 show two aspects of the Orion pilot station. FIGURE 12 shows the ergonomic crew couch and FIGURE 13 shows a detail of the piloting and

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[4] http://www.nasa.gov/exploration/analogs/desertrats/index.html

[5] Personal conversation with Mike Gernhardt, May 2012.

[6] http://www.nasa.gov/centers/ames/research/technology-onepagers/human_factors_ISHM.html

navigation display. ISIS showed its worth and achieved validation along the way by solving the extreme vibration problem for the Orion when mounted on top of the ill-conceived Ares-1 "stick." The vibration would have been so high that it was impossible for the crew to read more than a few digits or characters at any time. The ISIS team solved the problem by tuning a strobe light to the vibration frequencies, enabling the crew to see the letters and numbers "blinking" in the same place the whole time, even though everything was shaking wildly.

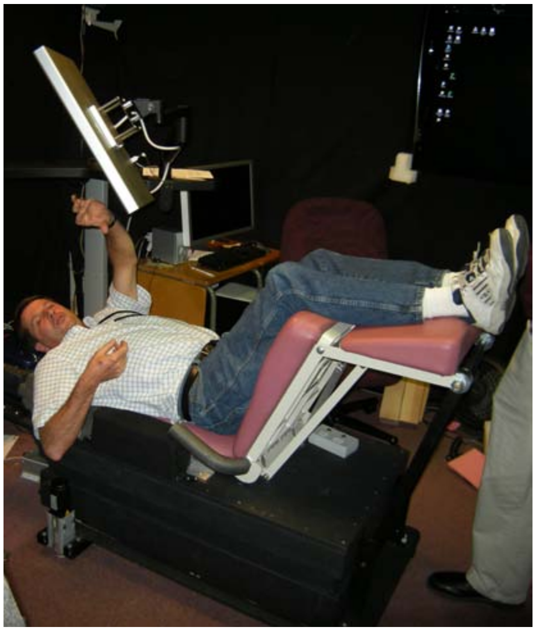

FIGURE 12. Intelligent Spacecraft Integrated Systems Lab, NASA Ames. Brent Beutter demonstrates the crew couch and pilot display positions. Author Photo.

FIGURE 13. Intelligent Spacecraft Integrated Systems Lab, NASA Ames. Robert McCann explains the pilot display screens, icons, and procedures. Author Photo.

4. Habitat Demonstration Unit/Deep Space Habitat—Chamber Class C.

The Habitat Demonstration Unit (HDU) served as a part of the 2011 Desert RATS. It is a generic habitat intended to simulate a deep space habitat in zero-G or on a lunar, planetary, or small body surface. In 2012, NASA JSC conducted TRL-4 tests in a highbay laboratory environment in Houston. These tests involved the following components, breadboards, and subsystems[7]:

1. Autonomous Mission Ops
2. "Intelligent" Habitat System Management Software
3. iHab Digital Double (D^2) Augmented Reality
4. Common Avionics Architecture Hab Computing
5. Common Displays & Controls
6. Advancements in Human Interfaces for Spacecraft
7. Advanced Caution and Warning System (ACAWS)
8. Failure Consequence Assessment System (FCAS)
9. HDU Core Computing, Wireless Communication and RFID
10. Communications Service Assembly (CSA)
11. Standards-based Modular Instrumentation System: Wireless Sensor Nodes
12. Power Generation and PM&D Systems
13. Current Sensor Implementation
14. iPad Induction Charging System
15. Radiation Environment Monitor detector (REM)
16. Fourier Transform Infrared Spectrometer (FTIR)
17. Avionics integrated Flat Surface Damage Detection system (FSDDS)

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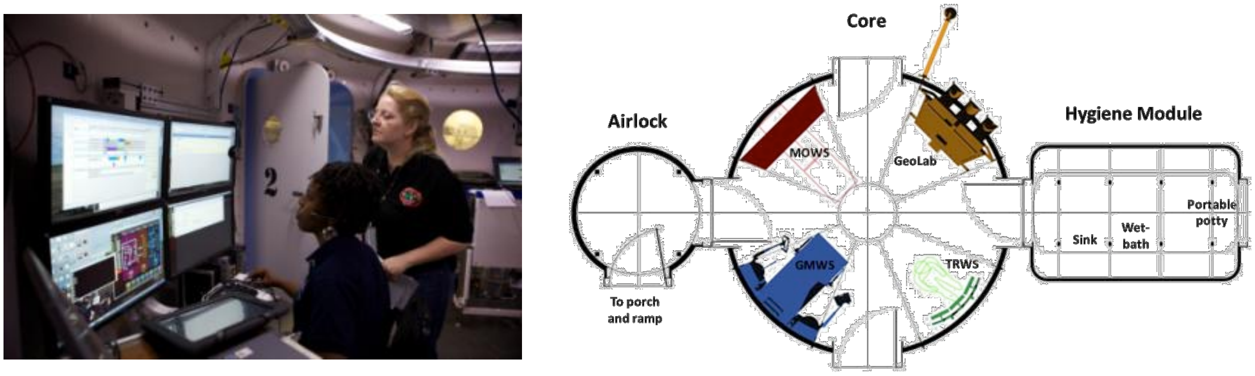
[7] Personal communication, Kriss J. Kennedy

    a. Stand-alone multi-panels,
    b. Flat Surface Damage Detection system (FSDDS)
18. Avionics integrated MMOD Hab impact monitoring system
19. Wireless Comm & RFID
20. RFID Temperature Sensors
21. Evolved Structures (ES) & Attachment H
22. Smart Rail Multi-functional Structure (SRMS)
23. Smart Palettes for Crew Quarters (SPCQ)
24. Telerobotic / IVA Workstation
25. Geo-Science Lab Glovebox/Workstation
26. General Maintenance/EVA Workstation
27. Medical Ops/Life Science Workstation
28. Food Production: Atrium concept
29. LED Lighting: Solid State Lighting Assembly
30. Inflatable X-Loft (X-Hab Challenge)
31. Habitability / Habitation: Advanced Crew Systems
32. Hygiene - Logistics Module
33. Logistics-to-Living Cargo Transfer Bags
34. Radiation Protection Technologies
35. Operational Demonstration of Cargo Transfer Bags to deployable blankets for Radiation Protection and ECLS water purification demo
36. X-Hab Challenge: 4 Universities
37. Material Handling

View of Upper Level Galley **View of Upper Level Exercise Station** **HDU-DSH Upper Level Plan**



View of HDU-DSH lower level. **FIGURE HDU-DSH Lower Level Plan**

FIGURE 14. 2012 Activities at the Habitat Demonstration Unit – Deep Space Habitat (HDU-DSH) in the Research and Technology Studies at Johnson Space Center. All images courtesy of Kriss Kennedy.

TRL-4/5 Transition from Validation in a Laboratory Environment to a Relevant Environment

The ESA-Russian collaboration on the EuroMars105 and EuroMars500 simulation experiments mark a pivotal transition from testing in a *laboratory* environment to testing in a *relevant* environment. FIGURE 15 illustrates the constituent modules of the simulator configuration at the Institute for Biomedical Problems (IBMP) in Moscow, where the simulations occurred.[8] These chambers are Class C since the protocol involves closing and sealing the hatches, then supporting the crew with mechanical ventilation and potentially with life support. In many of the photos, the crew wears tank-top type shirts, suggesting that it is very warm inside the habitat. FIGURE 16 shows some of the crew and activities.

The EuroMars objective was to simulate the long duration mission for a crew voyaging to Mars. The first experimental run of 105 days was a kind of a shakedown cruise. The second run took 520 days, which would replicate the crew time on the surface of Mars during a conjunction class mission. The IBMP simulator is largely a laboratory for a wide range of observations and experiments. Despite the purpose of simulating a space habitat in which non-flammable materials would be all pervasive, the IBMP chose to outfit their simulator with a wood paneled interior. This choice of materials to create a warm and home-like environment seems contradictory with the whole purpose, but perhaps it reflects a lingering social-realist aesthetic in which people bring their complete material and environmental conditions of their society with them.

What makes the EuroMars Simulations in the IBMP facility a "relevant environment" is the long-duration isolation and confinement that will be the *sine qua non* of a human mission to Mars. In addition, the closed atmosphere and life support aspect of the simulation offers another potential kind of subsystem test and validation. ESA has release a substantial amount of documentation and photographs of the simulations. However, the Space Community is still waiting for peer reviewed or refereed papers that present the research results.

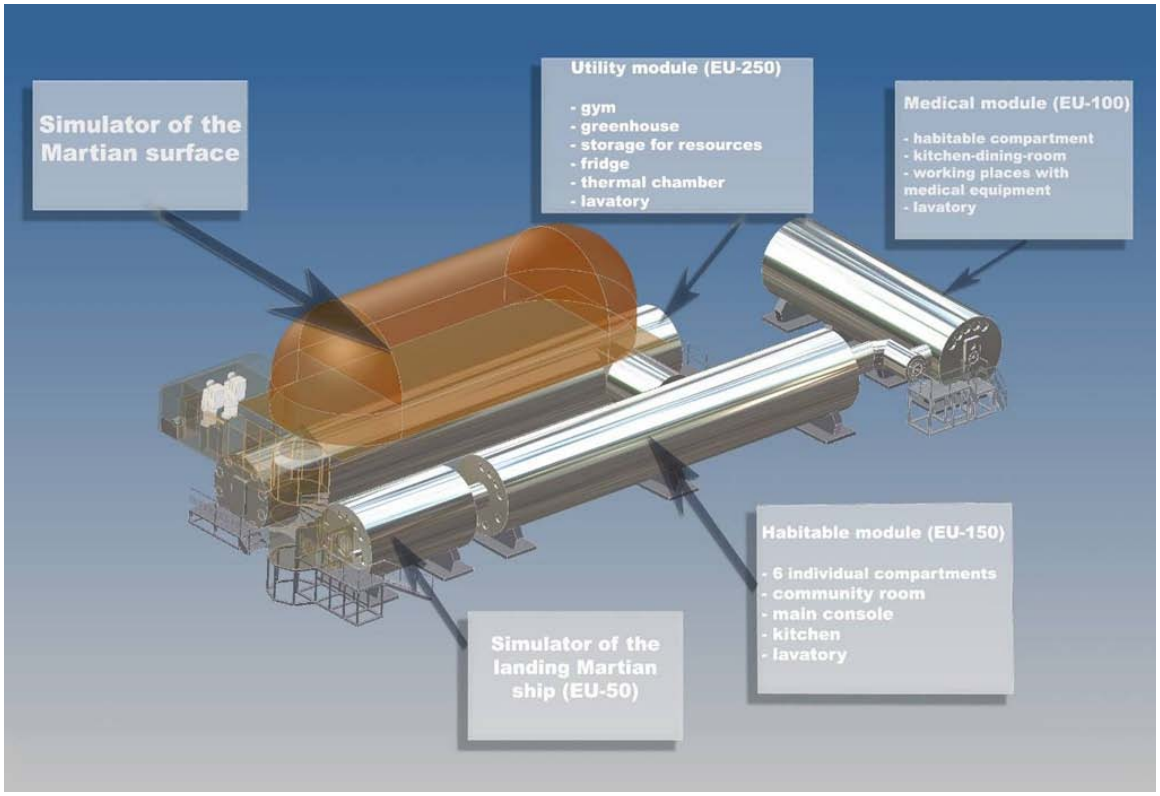


FIGURE 15. Isometric view of the EuroMars 500 Simulator configuration at the Institute for Biomedical Problems (IBMP), Moscow. Courtesy of ESA.

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[8] http://www.esa.int/esaMI/Mars500/SEM7W9XX3RF_0.html

FIGURE 16a. Crew of the EuroMars 105 simulation in the habitat. Courtesy of IBMP.

FIGURE 16b. A EuroMars 105 crewmember serving as a subject in a biomedical experiment. Courtesy of IBMP.

TRL-5 Component / Breadboard Validation in a Relevant Environment

TRL-5 initiates the technology maturation phase of testing in a relevant environment, which means some aspect of the space environment. What constitutes a relevant environment can vary widely. For life support systems, a relevant environment may mean an environmental or pressure chamber in which the gas mix is controlled and varied for an experiment; it may involve human subjects in that chamber. For a spacecraft, it may mean subjecting components or subsystems to vibration on a shake table or a thermal/vacuum test in which the radiant temperature varies from hot to cold. The possibilities are almost endless for what testing in which attribute of environment will be vital to achieve TRL-5 validation for each critical function.

FIGURE 17. Vertical Motion Simulator, NASA Ames. The cab sits on a three-degree of freedom motion base that provides roll, pitch, and yaw. This motion base is on a bridge track with 12m lateral motions. The bridge affords 24m of vertical motion. NASA Photo.

FIGURE 18. Vertical Motion Simulator cab configured as the Altair flight deck and pilot station. James Berry, Northrop Grumman Chief Engineer for Exploration stands at the controls. Author Photo.

1. Ames Vertical Motion Simulator (VMS)—Chamber Class C

The Vertical Motion Simulator is a state of the art facility that with offers the largest vertical range of travel of any flight simulator in the world. Researchers use the VMS to experiment with a wide range of aircraft, particularly rotorcraft. The Shuttle pilots trained for landing on the VMS. FIGURE 17 shows a typical VMS cab mounted on the motion base. The VMS operates with about five to six cabs that the staff can configure to represent a variety of cockpits. FIGURE 18 shows the basic configuration for the Altair lunar lander ascent module. This cab achieved TRL-5 validation on the lunar lander flight algorithms for the controls and operations.

2. Neutral Buoyancy Testing – Chamber Class E for the Suit—Not Applicable for the Water Tank

Neutral buoyancy testing enjoys the status of the "gold standard" of relevant environment testing for space hardware.[9] Because it offers the opportunity to put crew and hardware in an environment that can simulate zero gravity, researchers and engineers test a wide range of equipment including airlocks, docking systems, habitation outfitting, space suits, tools, and even the walking gait on a treadmill. The NASA Human Integration Design Handbook (2010) states that neutral buoyancy testing has been used successfully for IVA foot, handhold, and waist restraints (p. 63, 70), and EVA suit design and range of motion testing (p. 957). FIGURES 19 and 20 show examples of neutral buoyancy testing for both EVA construction and habitability at the University of Maryland Space Studies Lab's Neutral Buoyancy facility.

FIGURE 19. Sleep quarters accessibility test in the University of Maryland Neutral Buoyancy Facility. Courtesy of Prof. Dave Akin.

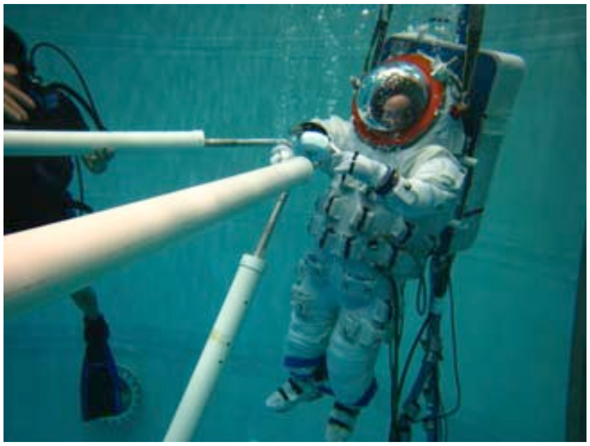

FIGURE 20. EVA truss assembly experiment in the University of Maryland Neutral Buoyancy Facility. Courtesy of Prof. Dave Akin.

3. TransHab Prototype in Thermal-Vacuum Test—Chamber Class D

The thermal-vacuum test is the flagship TRL-5 test of nearly all spacecraft components and subsystems, and even applies to complete spacecraft or modules. This test was conducted in the large thermal-vacuum chamber at Johnson Space Center. The test involved inflating the TransHab to full size, without any people in it, and then subjecting it to space environmental exposure, a relevant environment. The test protocol was to evacuate the air from the chamber down to a vacuum, then expose the TransHab module to extremes of heat and cold. FIGURE 21 a TransHab prototype undergoing testing in the thermal vacuum chamber.

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[9] Personal conversation with Prof. Ted Krueger, Rensselaer Polytechnic Institute, Rensselaer NY, May 2005.

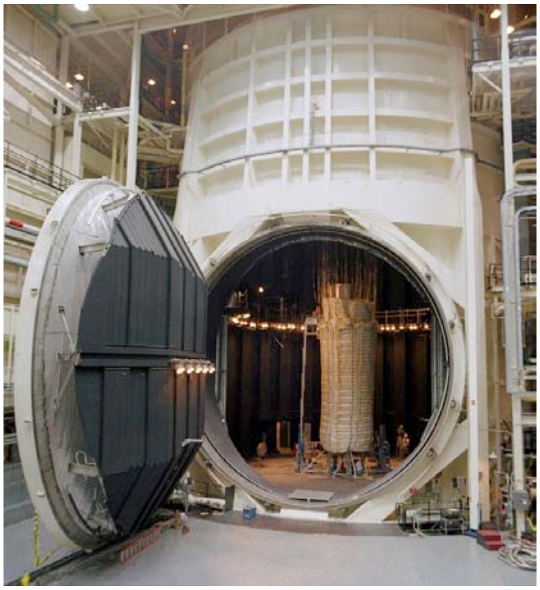

FIGURE 21a. The TransHab Shell Development Unit 3 with MMOD layer before inflation in the thermal-vacuum "Chamber A" at NASA Johnson Space Center. December 1999. NASA Photo.

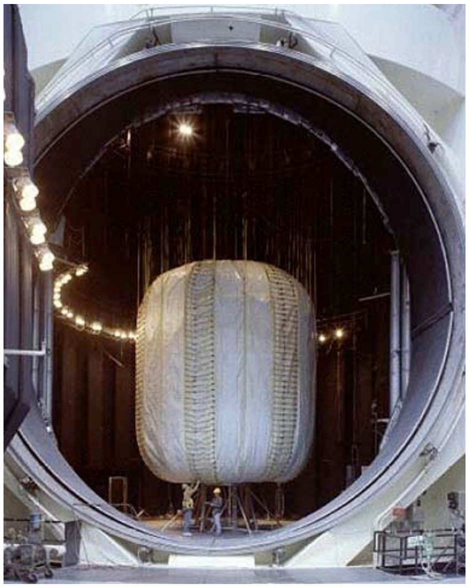

FIGURE 21b. TransHab Shell Development Unit (SDU) 3 fully inflated in the thermal-vacuum "Chamber A" at NASA Johnson Space Center, Dec 1999-Jan 2000. Courtesy of Synthesis-International.

TRL-6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

1. Human Exploration Demonstration Project (HEDP)—Chamber Class C, D, E, and potentially F.

There are few examples of Space Habitat mockup or simulator projects that go all the way to TRL-6. What few system demonstrations in a relevant environment did occur provided little available published documentation (e.g., the 1971 McDonnell-Douglas 90-Day Life Support Test, and the 1997 JSC 91-Day Lunar-Mars Life Support Test Project. The HEDP stands as a rare case study insofar as it is well documented and may have been the only serious attempt to achieve a full TRL-6 Space Habitation validation capability.

The HEDP example in this section (Cohen, 2002) was a project to make a multidisciplinary simulation of "a day in the life of a planetary habitat." The context involved the renovation and renewal of the S-18 Altitude Chamber to simulate crewed space missions. The irony of this plan was that when NASA built the S-18 and the nearby 50-G Centrifuge in the Building 243 rotunda, their purpose was to simulate the human mission to Mars that NASA expected to launch by 1985. FIGURE 19 shows the S-18 chamber when it was new. The sphere to the right of the horizontal airlock cylinder was a pressurizable capsule. After spending six months in the S-18, the Mars crew would enter the capsule to be transferred to the 50-G Centrifuge to simulate Mars atmospheric entry and landing.

The HEDP strategy was to test multiple subsystems together over a relatively short time of one to two days in a confined environment. The four disciplines were Human Factors, Information Science, Life Science, and Life Support. The Human Factors Research Division provided habitability outfitting on the upper deck shown in FIGURES 21 and 22, including the ship ladder to the lower level, plus a virtual reality system with capability to operate a rover in a remote building. The Information Science Division provided the rover on a Mars landscape in the other building for the crew subjects to operate. Information Science provided also the data system that afforded the central system integration to HEDP. The Life Science Division provided the Human Powered Centrifuge (HPC) and the biomedical monitoring for the HPC subjects and potentially other crew. The Advanced Life Support Division provided the renovation and outfitting of the S-18 Altitude Chamber as a hypobaric chamber to serve as the Controlled Environment Research Chamber. The Advanced Life Support Division committed also to provide a "plug and play," externally mounted life support system that they called a "life support microscope." The HEDP accomplished its first major milestone of subsystem validation of all the elements except the life support microscope. However, NASA politics and management attention spans being what they are, no funding was available for the next phase of two years.

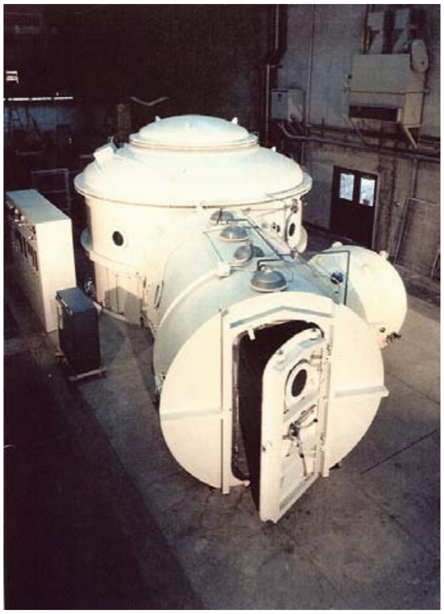

FIGURE 21. The S-18 Altitude Chamber circa 1965 when it was completed to simulate a human mission to Mars and other scenarios. NASA photo.

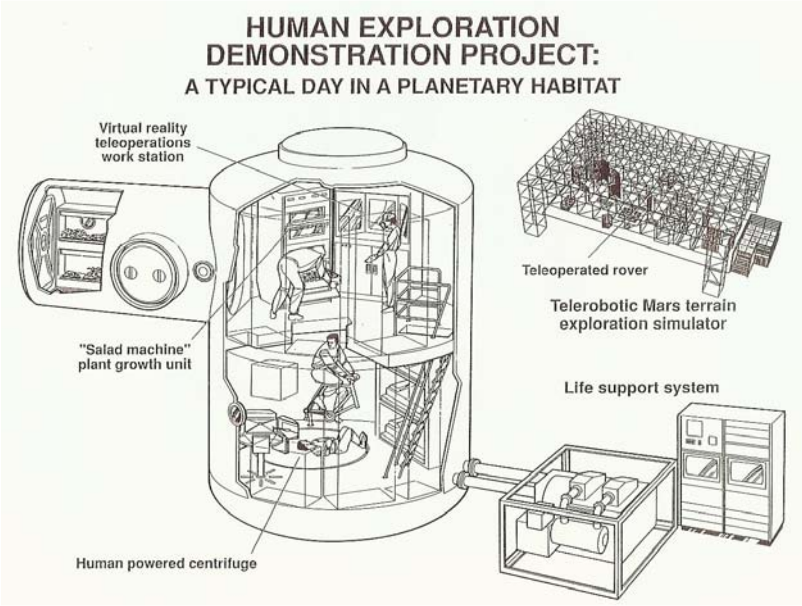

FIGURE 22. Concept rendering for the Human Exploration Demonstration Project emphasizing the multi-disciplinary nature of the short-term simulation. Drawing credit: Niche Wallace for NASA.

FIGURE 21. Upper level of the S-18 Altitude Chamber during renovation to serve as the Controlled Environment Research Chamber (CERC). NASA Photo.

FIGURE 22. Interior of the CERC upper level with outfitting installed. NASA Photo.

FIGURE 23. Lower level of the CERC showing the ship-ladder and the Human-Powered Centrifuge. NASA Photo.

FIGURE 24. Lower Level of the CERC with the Human Powered Centrifuge in operation. NASA Photo.

VI. The Method of Code and Standard Research

The preceding sections all address methodology -- the study of methods -- and its implications This section presents the method of code and standard research itself, explicating in detail how to conduct and apply code and standard research for a space habitat analogue. The author developed this method while serving as the Project Architect and Configuration Control Manager for the Human Exploration Demonstration Project (HEDP). HEDP involved the redesign and renovation of a ground-based Class D Altitude Chamber to serve as a Class E to F hypobaric chamber called the Controlled Environment Research Chamber (CERC) at NASA Ames Research Center.

The constellation of codes and standards applicable to closed habitat analogs are usually complex, often confusing, occasionally incomprehensible, and ***always contradictory***. First it is necessary to understand the difference between codes and standards:

* A code is largely preventative; it tells you what you cannot do, particularly the standard of care below which you cannot go. Codes become most formidable when there are few if any alternatives to the initial or preferred solution. Codes are regulatory; there is not much choice about complying with them.

* A standard is largely prescriptive; tells you what you must do to stay above the standard of care. Standards typically open the door to a variety of potential solutions. . Standards are typically products of professional or technical societies that document the “best practices” needed to sustain the professional standard of care.

Second, it is essential to determine which codes or standards rule for each technical and operational concern. To help the HEDP participants better understand the criteria that apply to the Project throughout the development phases, the author prepared the following narrative. This overview covers several key points: the rationale or philosophy, the specific steps, and ways to interpret code and standard compliance. The success of HEDP and the follow-on phases in this arena would depend upon obtaining not just safety approvals -- but the right approvals -- for the appropriate occupancies, operations, and uses.

A. Instructions

Code and Standard assessment is important for three reasons, among which the design and review processes must achieve a balance. This assessment sets limits to how the Project may try to achieve -- but not underachieve or overachieve -- its compliance goals.

1) It is essential to identify all the relevant provisions to ensure the safe operation of the CERC for HEDP and beyond.
2) Although certain measures are not absolutely necessary for HEDP as Faze A, it would be wasteful to make an inferior temporary installation if it must be torn out and discarded before going to Phase 2.
3) The Project should not go overboard in finding excessive requirements or constraints, which although ultimately necessary for Phase B, incur a penalty unless delayed until the HEDP Phase A is complete.

While conducting its survey of Code and Standard applicability and compliance, the Configuration Control Management Office developed this method for analyzing codes and standards and extracting the relevant provisions. This approach is markedly different than typical system engineering that is largely preventative – it is primarily a methodology to prevent error. This method is mainly pro-active, telling participants how to do the job rather than imposing gateways that filter out errors and omissions in performing the job.

1. Prepare the Schematic Design

Prepare a schematic design or operational procedure for how the Project will occupy and use a particular area or aspect of the facilities. Develop confidence that this preliminary design or procedure will meet the project's needs without unacceptable compromises to performance or hazards to the occupants. It is often valuable to develop several alternative schematic designs in parallel, provided that they all meet the same requirements.

2. Do The Code and Standard Research

Do careful code and standard research to find the provisions that will support and constrain the preliminary design. This step demands a huge amount of read of extremely dry and boring material. If none of the participants enjoy reading, they should find a different vocation. Seek the code and standard provisions that allow the greatest latitude in occupancy and utilization, with the least recourse to waivers or exceptions. Always try to go into the permit and authorization process "completely legal," without the need for waivers of requirements or variances to prevailing practice. This precept can be very challenging to accomplish – and it may seem to contradict technical goals of a project -- but aiming for compliance from the beginning can greatly expedite the whole review process and avoid antagonizing the reviewing authorities. Assume that once the Project begins the process of safety and man-rating reviews, that the reviewers will place additional constraints upon the facilities for particular operations

2.1. Identify the code and standard issues in relation to the relevant or responsible disciplines. TABLE 3 shows the assignment of these responsibilities to architecture and engineering disciplines for the Human Exploration Demonstration Project in renovating the S-18 Altitude Chamber to become the CERC.

2.2. Identify the code and standard issues in relation to each of the main project tasks. TABLE 4 shows the connection between these responsibilities and the eight HEDP tasks. This connection was important to determine which tasks were responsible for funding each of the remediations or other actions to comply with codes or standards.

3. Handle Each Issue on Its Own Merits

Treat each issue, constraint, or provision upon its own basis or merits, independently as possible from all the other issues. This separation of issues is vital to understanding the original and individual risks before jumping to the interaction of risks. It is easy to confound code and standard provisions together because of the expectation that ultimately the Human Research Review Board and the Human-Rating Review Board will look at all the compliances together. It is especially important to avoid "horse-trading," that is, making deals such that if one party will allow A, the other will allow B, and so on. This kind of wheeler dealing can compromise the main, long-range objectives to achieve short-term convenience. The only way to make confident and reliable progress is to address each item on its own merits, without distraction or political pettifoggery.

4. Provide Detailed Explication

Compose a detailed explication of the applicable Code and Standard provisions to explain how the Project will meet these requirements. It is valuable to furnish the participant's understanding of how the Project will meet the codes and standards to the other members of the Project and to the Safety Office. TABLES 3, 4, and 5 present examples of such an explication.

5. Prepare Documentation

Prepare the appropriate documentation for Safety or Engineering approval, as appropriate. Generally, it will be necessary to seek special approvals where waivers, exceptions, or critical applications apply. In these cases, the

Configuration Control Manager may prepare a Safety Finding or other action document, to garner and advance a consensus position on the pertinent issue.

B. The Tables

These three tables to provide a top level view of the major applicable codes and standards. The Table of Occupancy Definitions describes how each of the major code authorities treats the capability and the constraints to occupy and use the CERC for HEDP and follow-on activities. The Matrix of Codes and Standards Applicable by Discipline explains which architectural and engineering discipline is responsible for particular issues of code and standard compliance. The Matrix of Codes and Standards Applicable by Project Task traces the responsibility to the research task that needs the capability that compliance will assure.

TABLE 3, the Occupancy Definitions. Summarize how to interpret how each of the relevant codes and standards treats the CERC during each phase. These interpretations may have profound implications for how many people may occupy the CERC, under what environmental conditions, and what they may do there. The critical aspect of this table is that the future plans for the CERC as a Class E or F Chamber under NFPA 99B will create a much more constrained environment than HEDP requires. However, because the Life Support Division, that is funding most of the CERC renovation wants to make these improvements only once and do it right the first time, they are rebuilding the Chamber in one pass to serve all phases of use. This approach will not impose any penalties upon HEDP if we apply it judiciously, and it may help HEDP obtain safety approvals that might otherwise be difficult to justify.

TABLE 4, the Matrix of Codes and Standards as Applicable by Discipline provides a guide to which codes and standards apply to each discipline. Conversely, it shows the authorities of which each discipline must be cognizant. Complexity and potential contradiction arises from the fact that at least two codes or standards apply to each discipline. These contradictions become particularly thorny in attempting to reconcile NFPA 70, the National Electrical Code with NFPA 99B, the standard for Hypobaric Facilities, with different nuances to electrical protection against sparking or arcing in an oxygen enriched or medical environment. This table provides the entry into code and standard research, but it does not correspond to the actual project tasks and to ask the task managers to pursue them by discipline rather than task would pose an excessive burden.

TABLE 5, the Matrix of Codes and Standards Applicable by Project Task, summarizes the conclusion of this codes and standards research. It indicates precisely which codes and standards should concern each of the task managers. Since many of the tasks are multi-disciplinary to the degree that they involve several design and engineering disciplines, Table 4 offers a substantial simplification.

TABLE 3a. Occupancy Definitions for the Controlled Environment Research Chamber

Authority	**Key Points of Application**	**Phase 1 – 2 Years and First Demonstration**	**Phase 2 – 2 Years and Full Data System Integration**	**Phase 3 – 2 Years and Integrated Operations**
American Society of Mechanical Engineers *ANSI-ASME PVHO-1-1987* *Safety Standard for Pressure Vessels for Human Occupancy (1987)*	Viewports, nozzles, windows, penetrations, pressure piping & pressure vessel shells	ALL PROVISIONS APPLY	ALL PROVISIONS APPLY	ALL PROVISIONS APPLY
International Conference of Building Officials (ICBO) *Uniform Building Code* *(1991)*	Part III Requirements Based on Occupancy. Fire separation, egress, and safety provisions.	701. Group B, “Business Occupancies” Division 2, 3. Laboratories and Vocational shops.	701. Group B, “Business Occupancies” Division 2, 3. Laboratories and Vocational shops, and/or 4. Medical Gas Systems.	901. Group H, “Hazardous Occupancies,” Div. 2.... which present a moderate explosion hazard or a hazard from accelerated burning, including: 4. Flammable or oxidizing gases.
NFPA 70 *National Electrical Code, (1990)*	General provisions plus: Article 500–Hazardous (Classified) Locations Stringent explosion-proof electrical installation requirements. Article 517–Medical Facilities	**No special hazards apply, but, Article 517 may apply for special medical usage.	**No special hazard at 1 ATM. Article 517 may apply. If in high-altitude mode: perhaps closest to 500-5 (b) Class 1, Div. 2 (2) location in which ignitable concentrations of gases or vapors are normally prevented through positive mechanical ventilation, and which might become hazardous through failure or abnormal operation of the ventilating equipment.	500-5 (b) Class 1, Division 2 (1) location in which ... flammable gases ... are used, but ... will normally be confined within closed containers or closed systems from which they can escape only in case of accidental rupture or breakdown of such containers or systems, or in case of abnormal operation of equipment.

** Designed and installed for Class 1, Division 2 (1) except for the interim use of non-explosion proof computers, lights, or other equipment.

TABLE 3b. Occupancy Definitions for the Controlled Environment Research Chamber

Authority	**Key Points of Application**	**Phase 1 – 2 Years and First Demonstration**	**Phase 2 – 2 Years and Full Data System Integration**	**Phase 3 – 2 Years and Integrated Operations**
ANSI - NFPA 99B *Hypobaric Facilities, (1990)*	1-5.2 Classification of Chambers - Occupancy. atmospheres, installation & ops	*Class D — Human-rated, air atmosphere not oxygen-enriched, operate with door open. Install all new power & grounding to meet req's of 99B.	*Class D — Human-rated, air atmosphere not oxygen-enriched, operate with door closed. Possible to operate in high altitude mode.	Class E — Human-rated, oxygen- enriched atmosphere OR Class F— Human-rated, oxygen enriched atmosphere with an artificial buffer gas.
NFPA 101 Code for Safety to Life in Buildings and Structures (1991)	5-2.8, Fire Escape Stair to connect the lower level to the upper level.	Table 5-2.8.4 A, Fire Escape Stair "Serving 10 or fewer occupants."	Table 5-2.8.4 A, Fire Escape Stair "Serving 10 or fewer occupants."	Table 5-2.8.4 A, Fire Escape Stair "Serving 10 or fewer occupants."
NASA-Ames Research Center *Chlorofluorocarbon (CFC) and Halon Phase-out Plan (April 3, 1992)*	Priorities for Critical Applications (page 6)	Include Life Safety in the CERC as a priority critical application, using Halon 1301.	Critical application, using Halon 1301 or an appropriate substitute.	Critical application, using Halon 1301 or an appropriate substitute.
NASA Policy on Use of Chlorofluorocarbon (CFC) and Halon Compounds (Interim) *NXG June 26, 1990*	3. (a) identify critical versus discretionary uses by NASA (c) Prioritize the use of projected supplies and reserves for critical applications until substitutes become available.	Lower level of the chamber constitutes a potentially critical application for a closed vessel.	With the door closed, both the upper and lower levels of the chamber constitute a potentially critical application for a closed vessel.	Oxygen-enriched environment constitutes an absolutely critical application.
NASA Handbook *NHB 5300.9 July, 1991* *Safety, Reliability and Quality Assurance Provisions*	Project Risk Classification & Requirements Selection 201 a (2)	Class 3 Low Risk	Class 2 Medium Risk	Class 1 High Risk

* Designed & Rehabbed for Class E & F but operated as Class D until all electrical and fire–rated separation requirements are met.

TABLE 4. Matrix of Codes and Standards as Applicable by Discipline.

Code or Standard Authority	Architectural	Structural	Mechanical	Electrical	Human Factors	Fire Safety
ANSI / ASME PVHO-1-1987 *Pressure Vessels*		●	●			
AMM 1760-1 *Man-Rating of Simulators*			●	●	●	
NASA Std. 3000 *Man-Systems Integration*	●				●	
ICBO UBC *Building Code*	●	●			●	●
NFPA 12A *Halon*			●			●
NFPA 13 *Sprinkler Systems*			●			●
NFPA 70 NEC 1990 *Electrical Code*				●		●
NFPA 72E *Fire Detectors*				●		●
NFPA 77 *Static Electricity*				●		●
ANSI / NFPA 99B *Hypobaric Facilities*	●		●	●	●	●
NFPA 101 *Life Safety*	●					●
Ames CFC Phase-out Plan 1992			●			●
NASA Policy on CFC & Halon Compounds 1990			●			●
NASA NHB 1700.1 *Safety Manual*			●	●		●
NASA NHB 5300.9 *SR&QA for OAET Centers*	●	●	●	●	●	●

C. Summary of Codes, Standards, and NASA Handbooks

CODES: NFPA 70 National Electrical Code, 1990 and the Uniform Building Code, 1991 are codes to which the Project must conform in all possible respects. Normally, there would be no appeal from these codes in private or commercial practice for hazardous facilities, and local code authorities would require strict conformance. The NEC is particularly stringent, and there are unlikely to be any waivers from it. However, the UBC is somewhat more open to interpretation, so that when it is impracticable to conform to the letter of a provision and a non-hazardous alternative solution appears adequate, it should be possible to obtain a case-specific waiver from the Ames local code authority in the System Engineering Division.

STANDARDS: NFPA 99B Hypobaric Facilities, 1990, and ANSI-ASME PVHO-1-1987 Safety Standard for Pressure Vessels for Human Occupancy are standards that provide technical guidance on building, operating and maintaining the CERC. Generally, these kinds of standards allocate local interpretation and decision making to the local authorities having jurisdiction, as happens with NFPA 99B. ASME PVHO-1-1987 is rather less flexible because of its high degree of specificity and close referencing of the ASME Boiler and Pressure Vessel Code.

However, this local latitude in NFPA 99B may be particularly helpful in sorting out the electrical power service, grounding and isolation requirements.

NASA HANDBOOK: NHB: 5300.9, July 1991 Safety, Reliability and Quality Assurance Provisions for OAET Centers, is more of management guidance than a technical standard. It "provides the top level SR&QA policy and procedural basis for all non-space flight projects/operations at Ames" (cover memo from Dale Compton, 12/5/91). The definition that it provides of most immediate relevance is the classification of risk, based on a combination of a point formula and judgment. This NHB provides the review process for a wide range of SR&QA concerns and issues. While most of these final responsibilities fall under the aegis of the safety offices, it will be important for all participants in HEDP to be aware of these SR&QA requirements and to work towards a successful and hopefully painless review.

This analysis provides the basis for a comparative assessment of the relevant sections of the Codes, Standards, and NHBs that will affect HEDP and CERC operations over several phases of development. The Table of Occupancy Definitions explicates the several overlapping code authorities and how they may define the CERC occupancy and specific uses. The detailed review of these materials will prove valuable for presentation to the Human-Rating Review Board and Human Experiments Board.

VII. Conclusion

Full Scale mockups come into play when it is time to progress beyond drawings (whether those drawings are hand sketches or fully rendered 3D CAD) and scale models. Mockups are useful because most people encounter difficulty visualizing a 3D environment from a 2D drawing, no matter how realistic it may be. However, all people can understand an environment much better by experiencing it directly from the mockup or simulator. Full-scale mockups are especially helpful to enable blind or visually impaired people to understand a space habitat design.

TRL-1 Full-scale "soft mockups" can be cost effective to achieve TRL-1 Basic Principles Observed. However, it is important not to over-invest in mockup fidelity, materials, and finishes to attain this cost-effectiveness.

TRL-2 modeling and simulation afford the opportunity to experiment in human-scale with the architectural parameters to achieve TRL-2 Concept Formulation. TRL-2 is when invention begins so that it becomes possible to experiment with innovative and novel designs for space habitats.

TRL-3 is the suitable phase for engineering integration for form, fit, and function of components and subsystems. This integration of the parts enables a full scale TRL-3 Proof of Concept for one or more critical functions.

TRL-4 validation in a laboratory environment is appropriate for nearly all part-task simulators and some full mission simulators. Part-task research is generally more affordable and manageable, and may make the best investment of time and resources. Part-task simulations with very clear objectives and limits are often the most productive and meaningful uses of human-scale analogues. TRL-4 introduces the requirement for scientific validation of the technology or design concept and to achieve it, the researchers must posit a rigorous approach based upon figures of merit and their metrics.

TRL-5 validation in a relevant environment demands a physically immersive system. TRL-5 component/breadboard/subsystem testing can become very expensive and requires careful research design and data recording to obtain useful results. Safety oversight becomes paramount in nearly all cases.

TRL-6 Subsystem/system demonstration for space habitats generally requires a high level of system integration, safety monitoring, and oversight of operations. For human exploration missions, it almost invariably involves a hypobaric atmosphere either in the spacesuit, the habitat, or both. Operating a TRL-6 system test would be much like operating a spacecraft on the ground. Establishing criteria to evaluate the success of such a TRL-6 demonstration is a challenge that the researchers must approach in a realistic manner. In fact, it may be wisest to turn over the operation of a TRL-6 demonstration to an impartial and disinterested third party so as not to contaminate the results with potential conflict of interest or experimenter bias.

Code and Standard Research and Application is vital at every step on the TRL ladder for Space Habitat Analogues. Only by grasping all the architectural, engineering, health, and safety issues at the outset of the project can the Space Architect enjoy true freedom to investigate space habitat design at human-scale.

Table 5: Matrix of Codes and Standards as Applicable by Project Task.

CODE OR STANDARD AUTHORITY	Data System	Tele-Robotics	Habitation	Virtual Environment	CERC	Life Support	HPC	Biomedical Monitoring
ANSI / ASME PVHO-1-1987 *Pressure Vessels*					●			
AMM 1760-1 *Man-Rating of Simulators*							●	
NASA Std. 3000 *Man-Systems Integration*			●					
ICBO UBC *Building Code*					●			
NFPA 12A *Halon*			●		●			
NFPA 13 *Sprinkler Systems*			●		●			
NFPA 70 NEC 1990 *Electrical Code*	●	●	●	●	●	●	●	●
NFPA 72E *Fire Detectors*					●			
NFPA 77 *Static Electricity*				●	●		●	●
ANSI / NFPA 99B *Hypobaric Facilities*					●	●		
NFPA 101 Life *Safety*			●		●			
Ames CFC Phase-out Plan 1992			●		●			
NASA Policy on CFC & Halon Compounds 1990			●		●			
NASA NHB 1700.1 *Safety Manual*			●		●			
NASA NHB 5300.9 *SR&QA for OAET Centers*	●	●	●	●	●	●	●	●
NASA STD-2100-91 *Software Documentation Standard*	●	●		●				●

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IX. Appendix

This Appendix presents a few selected documents from the HEDP office of the Configuration Control Manager, who was effectively the Project Architect. They address examples of some of the key issues in Code and Standard research that required the project to obtain system safety and engineering approvals. A crucial aspect of these documents is that they are as brief and concise as possible. Brevity here is more than a virtue. It is a pragmatic response to the algorithm of bureaucratic process that the time to process increases as the square of the page count (i.e. if it takes one month to approve a one page finding, it takes four months to approve two pages).

Appendix A addresses the thorny issue of fire egress from the lower level by a single stair ladder. The approved ship ladder appears in FIGURES 21 and 23.

Appendix B addresses the fire suppression systems proposed for the CERC, notably the water fire sprinklers and a Halon system. The approved Halon system appears in FIGURE 23 as the thin vertical pipe with the red emergency switch cover.

Appendix C is the successful request for authorization to acquire and install Halon gas for the Halon System.

Appendix D is an analysis of the electrical grounding and isolation problem, leading to the request to hire an expert electrical engineer with specialized power-engineering experience. This request was successful, and the project retained Henry Landsman, a "silver fox," who recommended a three-step solution. The first step was to isolate the CERC power from the CERC panel box throughout the CERC. The second step was to isolate the entire circuit leading to the CERC from the building main breaker panel. The third step to achieve a Class E chamber, would be to install a separate building breaker panel and isolate it all the way back to the transformer.

Appendix A

HEDP
Human Exploration Demonstration Project

July 9, 1992

SAFETY FINDING: Fire Escape Stair from the Lower Level of the CERC

In the renovated Controlled Environment Research Chamber (CERC) located in Building N239A, the stair connecting the lower level to the upper level shall be a ***fire escape stair as*** defined by NFPA 101 Code for Safety to Life from Fire in Buildings and Structures (1991), Section 5-2.8, to be designed as follows:

The fire escape stair design shall conform to the details in Table 5-2.8.4 A, ***"Serving 10 or fewer occupants."*** This stair shall have a maximum riser height of 12 in. and a minimum tread of 6 in. for a maximum slope of approximately 63.5°. The stair, handrails, and guardrails shall be fabricated entirely of aluminum. The stair design shall exceed the minimum design requirements as follows: The clear width shall be 24" between the handrails and the treads shall be a solid non-skid surface.

Constraints:
The design of the stairwell opening shall protect against objects falling from the upper level to the lower level. During tours and CERC operations, the use of the stair as an observation gallery shall not be permitted.

Waiver:
This finding waives the dual-egress requirement of clause 5-2.8.1.4 so that this fire escape stair may serve as the sole egress from the lower level.

For HEDP:	For Health and System Safety (DQ):
Prepared by Marc M. Cohen, DS, Configuration Control Manager	Daniel K. Kaiser, Boeing Aerospace, Fire Safety Consultant
Concurrence, Christopher Miller, FL, Habitability Manager	Kenneth P. Zander, Institutional Safety, Office of Safety, Health and Medical Svces
Concurrence, Edwin Force, SA, Life Support Division Representative and CERC Manager	Laura W. Doty, Chief, Office of System Safety
Concurrence, Edward Chevers, FI, HEDP Project Manager	Clifford N. Burrous, Chief, Office of Safety, Reliability and Quality Assurance

Appendix B

HEDP
Human Exploration Demonstration Project

August 12, 1992

SAFETY FINDING #2: Fire Suppression System for the CERC

The Fire Suppression System in the Controlled Environment Research Chamber (CERC) in Building 239A shall consist of both an automatic sprinkler system and a Halon 1301 system to provide redundant protection. Fire protection in the areas proximate to the CERC shall be automatic sprinklers. All fire suppression systems shall conform to the NASA Safety Manual, NHB 1700.1, Vol. 9 “Fire Protection,” and the codes and standards referenced therein.

Automatic Sprinkler Systems:
The primary protection of all electronic equipment areas shall be automatic sprinkler systems in accordance with NHB 1700.1, Vol 9. Appendix E, Section 702-4. The sprinkler system in the CERC and in the pit area around the CERC shall be a wet pipe system. The sprinkler system protecting the *essential electronic equipment* (as defined in Appendix E, Section 103) in the Life Support Control Room in N239A shall be a dry pipe / preaction system. All sprinklers shall conform to NFPA 13, Installation of Sprinkler Systems.

Halon 1301 Fire Extinguishing Agent System:
The CERC qualifies as a *critical application* for life safety as defined in the “NASA Policy on Use of CFC and Halon Compounds” (NXG, June 26, 1990) 3(a) and (c) because of its planned use as an oxygen-enriched environment. As a critical application, it is necessary to install a halon 1301 system now, while the renovation of the CERC is underway. This halon system shall conform to NFPA 12A, Halogenated Fire Extinguishing Agent Systems - Halon 1301, with a surrogate gas for performance testing to minimize the release of halon. When a satisfactory substitute becomes available, it will replace the halon 1301.

For HEDP:	For Health and System Safety DQ:
Prepared by Marc M. Cohen, DS, Configuration Control Manager	Daniel K. Kaiser, Boeing Aerospace, Fire Safety Consultant
Concurrence, Christopher Miller, FL, Habitability Manager	Kenneth P. Zander, Institutional Safety, Office of Safety, Health and Medical Svces
Concurrence, Edwin Force, SA, Life Support Division Representative and CERC Manager	Laura W. Doty, Chief, Office of System Safety
Concurrence, Edward Chevers, FI, HEDP Project Manager	Clifford N. Burrous, Chief, Office of Safety, Reliability and Quality Assurance

Appendix C

HEDP
Human Exploration Demonstration Project

August 12, 1992

Justification for Installing a Halon 1301 System For Fire Suppression in the CERC.

The Controlled Environment Research Chamber (CERC) in Building 239A is being renovated to serve as a simulated lunar or planetary habitat as a major component of the Human Exploration Demonstration Project (HEDP), and for longer-term use as a life support experimental research facility. HEDP is a high priority project, with strong support from the Ames Center Director, who is providing a major portion of the funding from the Director's Discretionary Fund. The HEDP occupancy and use of the CERC will involve research and demonstration activities on both the upper (entry) level and in the lower level. The primary fire suppression system will be a wet pipe, automated sprinkler system, designed, and installed according to NFPA 13, Installation of Sprinkler Systems.

A long-term goal of the CERC renovation is to provide a Class E Hypobaric Chamber, as defined in NFPA 99B, Hypobaric Facilities (1990), for a *human-rated, oxygen-enriched atmosphere.* A sprinkler system is not sufficient to protect against the risk of fire in an oxygen-enriched atmosphere -- in which *the atmosphere itself may ignite.* ***Halon*** is the only extinguishing agent available and proven to meet this need. The halon system will enhance the margin of safety during all other CERC operations -- with or without the door closed -- or when people may need to evacuate from the lower level.

Therefore, we request approval to install a Halon 1301 system, in conformance with NFPA 12A, Halogenated Fire Extinguishing Agent Systems - Halon 1301 (1989). We request permission to install the halon system *at this time because* the project is making all the mechanical, structural and electrical modifications to the CERC in FY 92 & 93, and the tight geometries will make future installation difficult. HEDP has the budget now, and halon systems are still available at reasonable prices. The direct protection of human life should qualify this halon installation as a *critical application* as defined by "NASA Policy on Use of CFC and Halon Compounds (Interim)" NXG June 26, 1990, 3. (a) And (c).

We are aware of the damage to the earth's ozone layer caused by CFCs and Halons, and will take every step possible to prevent or minimize the inadvertent release of halon. All performance tests will use an environmentally safe surrogate gas. As soon as an acceptable substitute for halon becomes available, we pledge to replace the halon with it.

Prepared by Marc M. Cohen, DS,
Configuration Control Manager

Concurrence, Edwin Force, SA,
Life Support Division Representative and CERC Manager

Concurrence, Christopher Miller, FL,
Habitability Manager

Concurrence, Edward Chevers, FI,
HEDP Project Manager

Appendix D

HEDP

Human Exploration Demonstration Project

CCM Note #3: Electrical Power Grounding and Isolation for the CERC

Marc M. Cohen MS 240-10 x40068 March 4, 1992

Summary:

The electrical power requirements of the various divisions for the Controlled Environment Research Chamber (CERC) are not entirely compatible and may pose constraints with significant cost and complexity implications. SA Division is providing 110v ungrounded service in conformance with the NFPA requirements for hypobaric atmospheres. FI and probably FL will almost certainly require grounded power for their computer systems, and they would prefer conditioned, grounded power. Providing an isolated ground in the CERC is potentially expensive. This draft Note outlines 3 possible design strategies to provide an isolated grounding system that may meet the requirements.

Constraints:

Speaking very generally, the NFPA standards that govern hypobaric environments affect the electrical service in two ways; the grounding requirements and the materials used to achieve isolation and distribution. First, the electrical devices must be explosion-proof to prevent ignition of materials or the atmosphere itself in an environment with an elevated partial pressure of oxygen. Generally, the explosion proofing involves not connecting the electrical service to building ground, which in its simplest form means an ungrounded power service such as SA Division proposes to provide in the CERC. However, it may be possible - in fact it should be possible to provide a high quality isolated ground on the receptacle side of an isolation transformer for the CERC. Second, the materials typically used to achieve isolation also come into question in a hypobaric atmosphere. The plastic junction boxes and conduits that usually make isolated or conditioned power easy to install in modern buildings such as N262 and N269 will not be allowable in the CERC because of the problems of toxicity, outgassing and smoke produced.

Precedents:

There are a number of precedents at Ames for multiple power services combining isolated ground and conventional grounded or ungrounded power systems that offer possible exemplars of solutions. These exemplars include the 40x80 Wind Tunnel, the U-2Cs and the U-2 aircraft support building. In addition, the Space Shuttle Orbiter operates with a reduced cabin pressure in preparation for EVA in which the partial pressure of oxygen is elevated. The 40x80 Wind Tunnel Control Room uses a high quality copper bar ground that is isolated 5 Mega Ohms from building ground for a computer access floor that is mounted on an older wood floor. The U-2Cs used three flavors of power, if I recall correctly, 18v, 400hz DC aircraft power, 28v ungrounded camera power and 28v grounded censor power, which are also distributed in the U-2 Aircraft Support Building. On the Orbiter, a great variety of different fans, pumps and computing devices and other electro-mechanical devices are in use that continue to operate in the reduced pressure atmosphere, I believe. So it should be possible to find a design solution for the power system in the CERC. The real issues are cost, complexity, and time to install the optimal or preferred system.

Three General Design Strategies:

I will outline three general design strategies for providing an isolated grounded power supply in the CERC. These three possible approaches are not intended as complete solutions but rather as an attempt to bind the problem and to indicate some of the pros, cons, and trade-offs.

1. Isolate the entire CERC System:

In this strategy, we would isolate the entire CERC structure and all the associated pumps and compressors. There would be a major isolation transformer providing power to the entire system and several secondary isolation transformers for the pumps and compressors, the lights and for the computer-conditioned power. This approach would probably provide the simplest situation inside the CERC itself, although the scale of the isolated system might replicate building ground itself and thus be self-defeating.

2. Build an isolated floor and stair structure inside the CERC:
In this strategy, the floors and possibly the floor structures would be removed and remounted on ceramic isolators to create an isolated core. Equipment and racks would stand directly on the floor, without contact with the CERC walls, which would remain at building ground. It might be desirable to provide surface isolation to the CERC walls in the form of a Nomex curtain. The ungrounded light system would be wall mounted and remain separate.

3. Local Point and Surface Contact Isolation
In this strategy, the emphasis is upon providing isolating surface treatment and isolated equipment mounts from the floors and walls. Probably the best material to provide both the floor and wall equipment mount isolation is ceramics. A ceramic tile floor applied directly to the floor plate would provide an opportunity to introduce color. Nomex cloth on the walls would help prevent humans from becoming ground fault circuits.

Preliminary Recommendation:
None of the above strategies are particularly appetizing. There are real cost and perhaps operational penalties associated with any of the potential options. Therefore, HEDP Project Management should retain the services of an expert electrical power engineer who can understand the range of issues that I attempt to illuminate in this draft note. We should also collect and review carefully the power service requirements of each of the divisions to determine exactly what level of service is required and how best to provide it.

Alternate Electrical Isolation Strategies

Power Isolation Strategy	**Pros**	**Cons**
1. Isolate the entire CERC System	Create the simplest isolation regime.	Incur potentially enormous expense.
	Least chance of a ground fault or sneak circuit.	Seismic and structural mods may make this option unfeasible.
2. Build a new isolated floor and stair structure inside the CERC.	Create an isolate floor, rack, and equipment ensemble.	Cost of removing and remounting the internal equipment ensemble.
	Ground fault and sneak circuits will be easy to detect and identify.	Greater but still moderate complexity.
3. Isolate the point of contact and surface finish.	Lowest cost.	Greatest complexity.
	Least disruption of CERC construction and operations.	Greatest risk of a possible hard to trace fault or sneak circuit.
		Difficult details at stairs, railings, and floor hatch and other places.