Experimental Investigation of Minimum Required Cabin Sizing in Varying Gravity Levels

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With the renewed focus on near-term human exploration beyond low Earth orbit, there is a reemphasized priority on the timely and cost-effective development of human spacecraft to support the planned missions. Decreasing habitat size and mass becomes increasingly important as the exploration target gets farther away in terms of Δv, but there is still little experimental data on the impact of smaller habitats on human performance. What data exists is primarily from microgravity experience in low Earth orbit where the marginal cost of larger habitats is minimized compared to the Moon or Mars; there is no real data base on how crew performance changes in restricted volumes for microgravity, and none for operations on the Moon or Mars. The focus of this research is to develop an experimental program to study the effects of habitat size on crew performance in microgravity, and on the Moon and Mars in terms of gravity levels. This paper summarizes past research in the field, and then focuses on ongoing research in the University of Maryland Space Systems Laboratory under the support of the NASA X-Hab program to experimentally investigate the minimum effective cabin sizing and architecture for critical elements of the space architecture, including surface ascent/descent vehicles, on-orbit and surface habitats, and pressurized rovers. Through the design and development of a modular resizable habitat mockup, tests of crew operations including flight control, simulated science activities, logistics management, and medical functions are assessed as a function of cabin volume, length/diameter ratio, and horizontal vs. vertical orientation of the cylindrical pressure vessels. Tests focus on cabin volumes between 5 and 25 cubic meters, with crew sizes ranging from 2-4. Test operations were predominantly planned for the laboratory environment, but due to restrictions arising from the pandemic, testing was exclusively performed underwater, allowing the simulation of microgravity, lunar, and Mars gravity levels. While the use of the underwater simulation environment precludes long-duration studies such as those performed in analogue field sites, the ability to repeat activities in varying habitat configurations at differing gravitations provides new insight into future spacecraft cabin/habitat design.

I. Introduction

How large does a space habitat – whether for a launch and entry vehicle, lunar or Mars ascent/descent vehicle, pressurized rover, or long-term space habitat, which might be located on a low-gravity body such as Phobos, or on the lunar or Mars surface – need to be? After 60 years of human space flight, the answer is still "We don't know." In 1963, with the longest U.S. human duration in space slightly above nine hours in the lastest Mercury mission, a conference paper[1] introduced the "Celentano curves" (Figure 1), predicting the necessary cabin volume for human missions up to a year in duration. These curves came to dominate the thinking on cabin sizing for the next half century. (It is not the intention of this paper to go into the background on the Celentano curves; the definitive work in the area was by Cohen[2] in 2008, and is highly recommended.) One of the most recent NASA attempt to define habitable volume requirements, as presented in the latest revision of the Human Integration Design Handbook[3] (HIDH), is shown in Figure 2.

The Celentano curves were *predictive*, and are primarily significant in the assumption that, past a certain duration, a given cabin volume will be adequate indefinitely. Many of the later variations of these curves used a similar paradigm, differing on how long it would take to reach the asymptote, and what the numeric values of the ultimate volumes were. The HIDH curves are, instead, a series of *regressions*, fitting functions such as log-linear or logarithmic to the known data from past and current spaceflight missions as well as Earth analogues. Interestingly, the Celentano curves were developed based on three limited Earth analog studies of a week or less in duration,[4] extrapolated to a long-term steady-state prediction. On the other hand, the regression approaches such as Figure 2 are based on experience,

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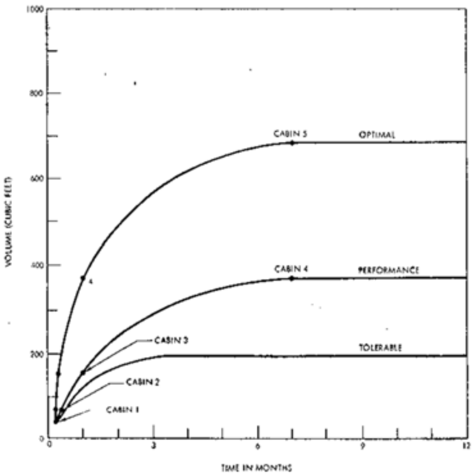

Figure 1. 1963 space habitat volume requirement predictions[1]

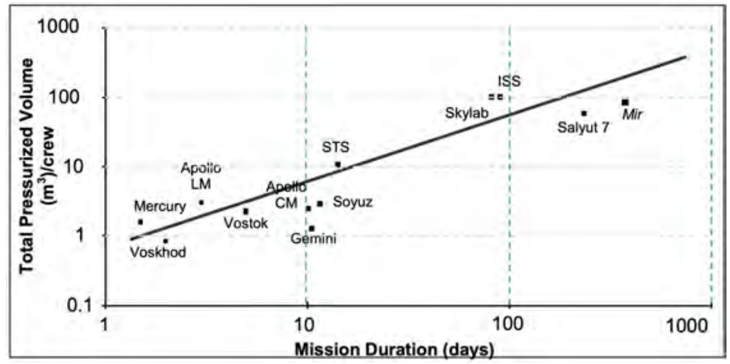

Figure 2. 2014 space habitat volume regression analysis[3]

including long-term mission in low Earth orbit. This experience indicates an exponential increase in required volume as mission duration increases, based on the volumes of Skylab, Mir, and International Space Station. What is not apparent in this regression analysis is that low Earth orbit is the "entry" level of spaceflight, so the marginal cost of adding additional habitat volume there is less than it would be anywhere else in the solar system. The key question of this study is, how much volume is truly needed for deep-space missions, where the cost of additional habitable volume may make the difference between feasibility and infeasibility (or, more precisely, affordability or non-affordability) for the program? Answering this question based on experience limited to low Earth orbit is driving the system to the larger range of sizes, which may risk program viability. On the other hand, sending humans to Mars in a spacecraft which is truly too small for long-term health and functionality is inviting disaster. This is further exacerbated by the need to start designing habitats for the surface of the Moon and Mars, when we have almost no experience in gravity levels other than Earth and orbit.

So how can those first gravitational habitats be sized? And what can we better understand about cabin sizing for small, short-duration human missions either in microgravity or on planetary surfaces? There is clearly a cost for error on the high side: larger human spacecraft are both more massive and more costly, take longer to develop, and require larger launch vehicles and/or more elaborate on-orbit operations such as spacecraft assembly or refueling. Going too small has the potential for disrupting crew performance and/or mental health, with possible implications to crew safety and mission success.

II. Experimental Investigation of Minimum Crew Volumes

To address these issues, the University of Maryland proposed to the NASA 2020 Moon to Mars Exploration Systems and Habitation (M2M X-Hab) Academic Innovation Challenge program to perform an experimental investigation of small habitable volumes for short-duration missions. Although much more limited in funding than even a typical academic research endeavor ($30K), the X-Hab program does provide a focus for senior capstone design classes and enables moving a spacecraft design course into a corollary of the "design-build-fly" activity common in aircraft design courses.

The first question was how best to set up an experimental investigation of variable space habitat volumes? The proposal was based on extensive prior experience of the Space Systems Laboratory with habitat mockup design, fabrication, and testing, starting with the design of a minimum functional habitat element for lunar exploration created for a NASA Human Exploration Operations Mission Directorate contract in 2009 (Figure 3). This was a 40 m^3 habitat concept, for which a full-scale mockup was constructed for design verification and some limited day-long and multi-day simulated mission activities.[5] Lessons learned from this activity, as well as the development of an inflatable habitat element for the first NASA X-Hab program in 2010, were factored into the 2012 development of a modular habitat test facility (Figure 4), also with X-Hab funding. Although the volume was fixed by the selection of a five meter diameter, the habitat was designed with eight interchangeable wall panels to allow the easy modification of numbers and placements of hatches, windows, and other unique design elements.[6]

Figure 3. Lower-level interior view of the ECLIPSE habitat (3.6m diameter)

Figure 4. Interior view of the HAVEN habitat (5m diameter)

A. Development of a Modular Habitat Mockup

The initial objective of the 2020 X-Hab project was to investigate the functionality of habitats with interior volumes between 5 and 100 cubic meters. As shown in Figure 5, this represents a wide range in potential sizes, even ignoring design issues such as horizontal vs. vertical orientation, varying length/diameter ratio, or number of floors inside the habitat volume. Complicating the issue was the strong desire to obtain data never before available by using underwater body segment parameter ballasting to allow the test subjects to work within the same mockup hardware under microgravity, lunar, and Mars gravity conditions.[7] An initial attempt to do habitat assessment from the 2014 X-Hab program is shown in Figure 6. This used PVC pipe and common plumbing fittings to create a volumetric simulation of a two-story 5m diameter habitat, which coincidentally corresponded to the 100m^3 end condition for the planned human factors study. That study did not include the development or use of internal habitat components, which limited the functionality of the underwater portion of the research.[8]

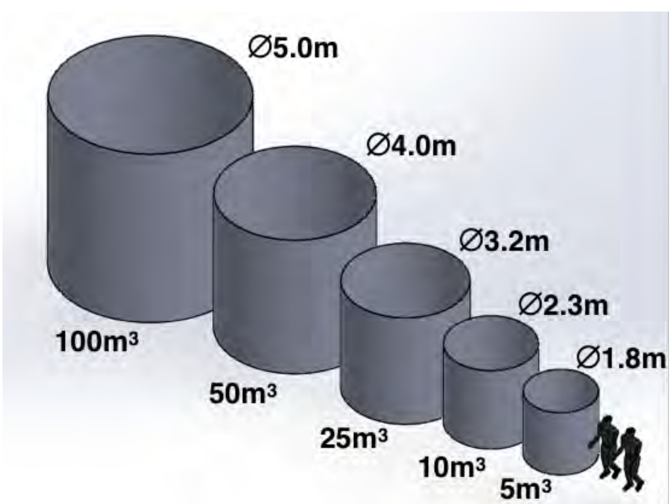

Figure 5. Visualization of habitat sizes ranging from 5m^3 to 100m^3, with length/diameter ratio kept at 1 for purposes of illustration

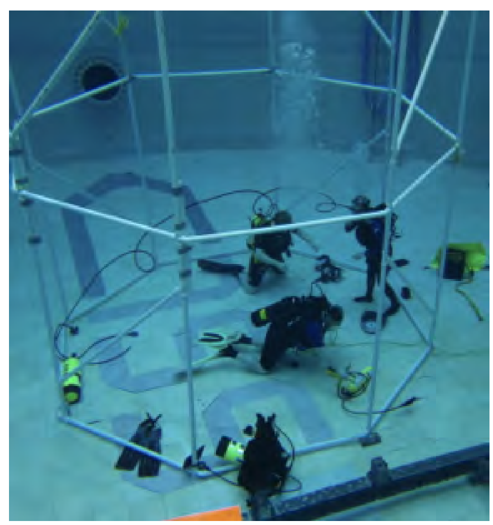

Figure 6. 5m diameter habitat volumetric simulator for neutral buoyancy testing

The 2020 X-Hab project began staffed by 20 students from the UMd ENAE 483/484 yearlong capstone course in Spacecraft Design. Initial efforts on this study were focused on the design of reconfigurable habitat mockups. Taking inspiration from the crude habitat mockup of Figure 6, the team designed a structure of aluminum engineering extrusions which would define the external shape of a cylindrical habitat up to 100m^3 in volume (Figure 7). The design incorporated sliding connections between the elements which would allow the structure to be "collapsed" to represent smaller structures, as in the 25m^3 configuration of Figure 8. A similar, smaller structure was designed to allow testing configurations between 5m^3 and 25m^3.

Figure 7. Adjustable habitat shell concept at 100m^3

Figure 8. Adjustable habitat shell concept at 25m^3

At this point, a number of issues with this approach were recognized. Even with the standard engineering extrusions and simple sliding interfaces, reconfiguring the shell pieces would require a number of people and some significant time to prevent the elements from binding. Due to the size of the structure in its larger configurations, a number of the actuations would have to be done on ladders to access the sliding mechanisms. It was unclear how much force would be required to move the components, or to what extent the structural elements would have to be supported against gravity. Indeed, even with the structure locked into a particular configuration, there was concern that the structure would need reinforcements to support its shape against its own weight, to say nothing of any internal outfitting. The structure would be usable in both the laboratory and the underwater environment of the UMd Neutral Buoyancy Research Facility (NBRF), but the fixed length of the elements of the structure would result in struts cantilevered out in various directions, as seen in Figure 8, which could be a hazard to divers underwater. There was some consideration of building dedicated structures at each test point, but there is insufficient room in the NBRF to store test hardware of that size and in those numbers.

Despite all of these unresolved problems, the solution came from the other lesson from past underwater habitat studies: the envelope of the pressure hull does not interact with the test subjects in any significant way, because the activities to be simulated almost exclusively deal with the systems internal to the habitat, rather than the pressure vessel itself. The key realization was that making the internal outfitting modular, rather than the pressure hull itself, would produce a more useful simulation of the habitable volume – indeed, it would be unnecessary for this level of testing to have an external representation of the pressure vessel at all, as the modular internal equipment would define the habitable space for the test subjects.

III. Modular Rack Architecture

The first step in creating a modular, highly reconfigurable representation of a crew cabin was to define a standard equipment rack, similar in concept to the International Standard Payload Rack (ISPR) modules used throughout the International Space Station. Since the upcoming lunar Gateway station had announced that it would use a different (but similar) standard than the ISPR but has not published specifications, the UMd team defined a similar standard that would be easy to reproduce with engineering prototyping materials such as 80/20™. The rack was designed to be approximately one meter in width, two meters in height, and 1/2 meter deep. Each rack was outfitted with casters to simplify reconfiguration and to allow minimal storage volume when not in use. By adopting the use of this standard, any arbitrary vehicle or habitat shape could have its interior habitable space defined by the appropriate construct of racks, as illustrated in Figure 10.

Twelve rack shells were initially fabricated. These were designed to be attached to each other in a number of configurations, as illustrated in Figure 11, representing cylindrical habitats which are both vertically oriented (circular sections) and horizontally oriented. The use of a single layer of modules simplified the test set-up considerably, but

Figure 9. Shell of standard rack module

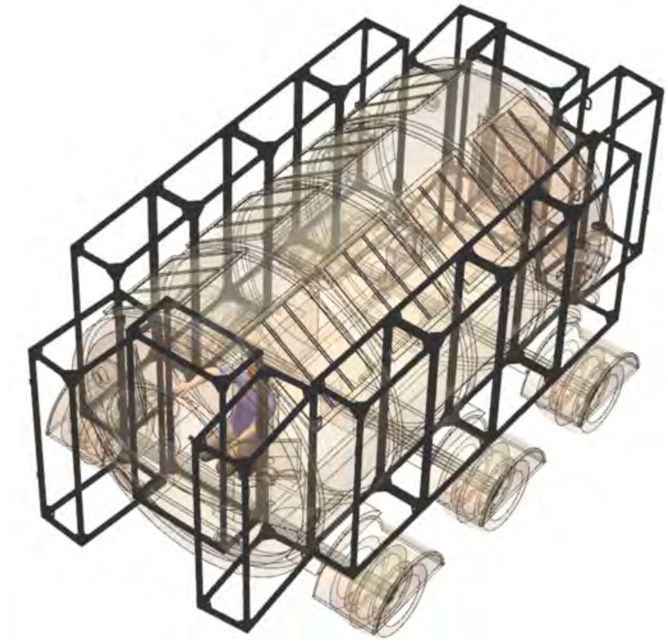

Figure 10. Notional pressurized rover cabin approximated by modular racks

limited the range of volumes tested to between 5-25 m^3 for this series of tests. The floor inside the racks serves as the floor of the habitat mockup, whether in the laboratory or the neutral buoyancy facility; the top of the habitat is left open for clear lines of sight for cameras, motion capture systems, safety monitors, and direct ascent when used underwater.

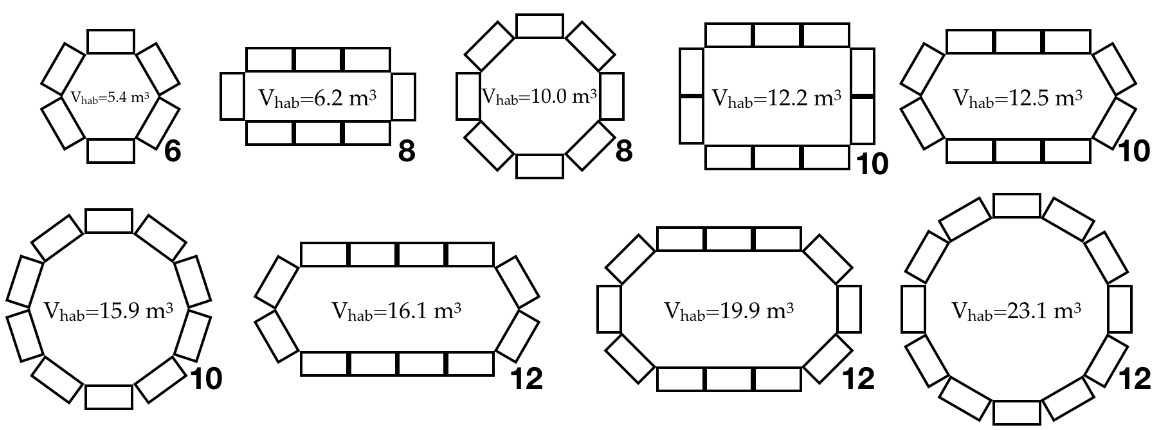

Figure 11. Variation in internal volume based on configuration of rack modules, shown as top views. Numbers in bold refer to number of racks in each configuration.

The UMd team, in collaboration with the NASA X-Hab reviewers, identified nine categories of habitat activities to be simulated in testing, with the need for specialized equipment mounted in the racks:

- Medical (first aid, monitoring of incapacitated patient)
- General workstation (habitat systems monitoring and control)
- Food preparation and eating as a group activity
- Cargo transfer bag (CTB) stowage, access, and organization
- ECLSS system maintenance and repair

- Glove box operations
- Suitport ingress/egress
- Suit maintenance
- Airlock operations

Designs were created and materials ordered to fabricate the necessary components for specialized racks for these test operations. The team developed a series of detailed test procedures for each category of tests, demonstrated data collection techniques, and produced an overall test plan summarized in Figure 12. A primary lesson reinforced from much prior experience at the Space Systems Laboratory is that underwater test time is much more restricted than laboratory testing, due to the greater operational overhead and the need for a larger test support crew, all of whom have to be qualified as divers in the NBRF. For this reason, the test plan started with extensive laboratory testing of the individual simulation scenarios, without attempting to run through the entire test matrix. After the completion of this sequence of tests, a select subset of tests would be performed underwater at microgravity, lunar, and Mars gravity conditions. With these single-task results, the team would assess the available test time, and come up with a downselect to specific habitat configurations and team sizes for a second round of laboratory testing, which would incorporate issues such as habitat configurations and number of test subjects while running through a number of the test tasks as a simulation of several hours of habitat operations. Finally, a further downselect would occur to determine how best to use the available underwater test time to validate the laboratory results and to explore the effect of different gravitational environments on the crew's performance across the various habitat sizes and configurations. At the point where the team was ready to begin testing (March 2020), the University of Maryland was shut down due to the COVID-19 pandemic; all students were sent home, and all classes went 100% online for the rest of the Spring 2020 term. All experimental research activities were shut down.

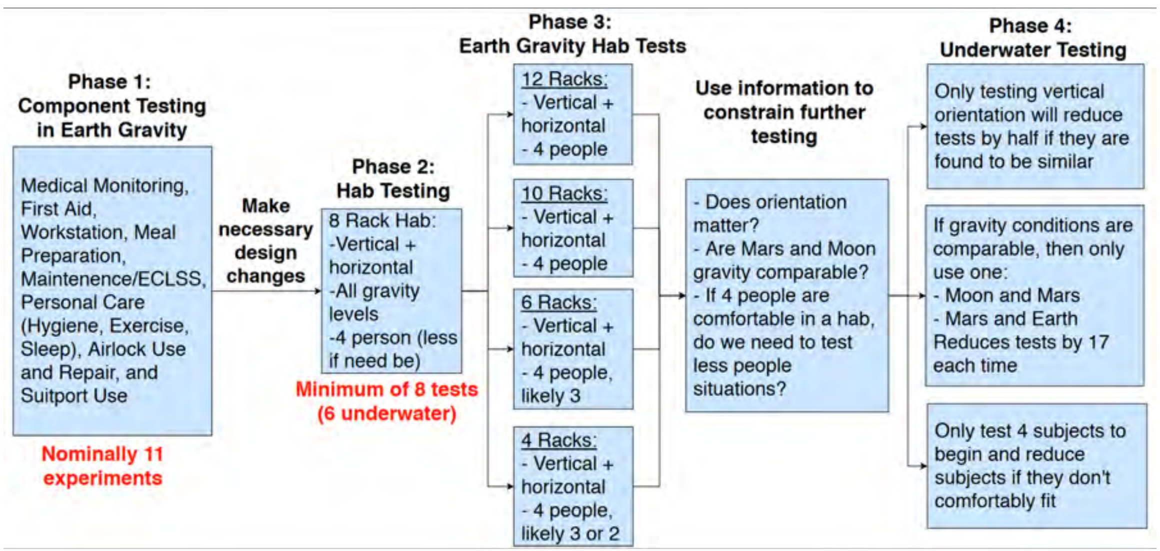

Figure 12. Original test plan for study of habitat sizing, based on both laboratory and underwater simulations

IV. Response to COVID Restrictions

Since the planned experiments could not take place, the final portion of the ENAE 484 design class (and the 2020 X-Hab project) switched to examining the implications of habitat size and gravity conditions based on analysis. The team performed the detailed design of six habitat configurations: 20m^3, 40m^3, and 80m^3 habitats for microgravity (Figures 13-15) and planetary surfaces (Figures 16-18).

The conversion to flight habitat design accomplished the pedagogical goals of the senior capstone design class, as well as providing a "reverse flow" from modular rack designs to actual outfitting of habitat interiors. The teams found from their detailed design activities that the life support and crew outfitting masses were largely invariant with habitat volume, so the 80 m^3 habitats were only 30-35% more massive overall than the 20 m^3 habitats. Although the

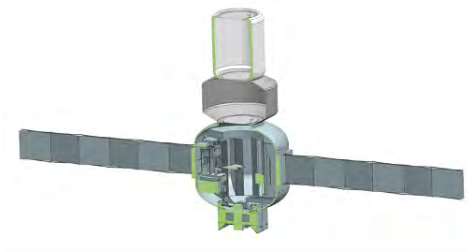

Figure 13. 20m^3 microgravity habitat design

Figure 14. 40m^3 microgravity habitat design

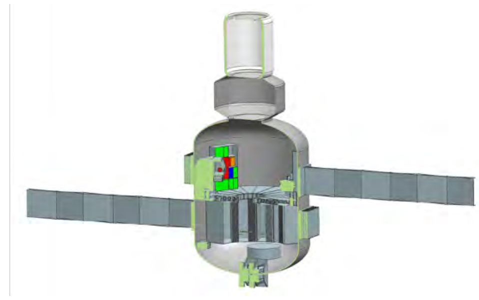

Figure 15. 80m^3 microgravity habitat design

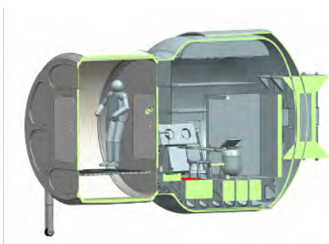

Figure 16. 20m^3 surface habitat design

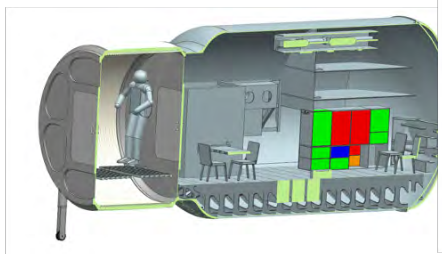

Figure 17. 40m^3 surface habitat design

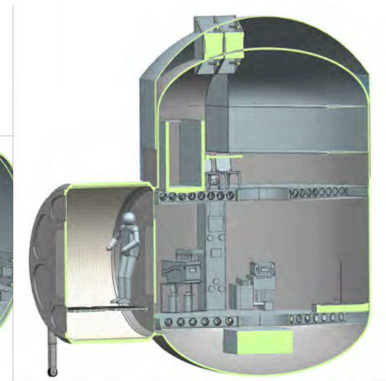

Figure 18. 80m^3 surface habitat design

two smaller surface habitats proved to work better with a horizontal orientation, rather than the vertical orientation preferred to the largest surface habitat and all of the microgravity habitats, the mass penalty for a surface habitat was only 5-10% compared to the corresponding microgravity habitat.[9]

V. Resumption of Experimental Activities

With the assumption (proved later to be naive) that the pandemic would pass in a few months, the University of Maryland proposed a follow-on activity for the 2021 X-Hab solicitation to complete the experimental portion of the previous year. By the start of the 2020/2021 academic year, research activities on campus had resumed with fairly significant limitations, but it quickly became clear that the extensive laboratory simulations, predicated on putting multiple test subjects in small habitats for extended periods of time, would not be feasible until the pandemic was completely over. This meant that the experimental data collection would have to be exclusively performed underwater. Unlike having 2-4 people in the close confines of a habitat mockup on the surface, underwater each person has their own independent air supply with no danger of virus transmission. However, as noted above, underwater tests are much more demanding of support personnel, which has its own implications in a time of restricted access to laboratories.

VI. Results to Date

Prior to starting testing of the modular habitat configurations, the Space Systems Laboratory had to evolve modified dive operations in conjunction with the University of Maryland Diving Safety Officer to incorporate requirements of the UMd COVID response policies. This included such items as maintaining adequate distancing between divers and support personnel while entering and leaving the water, and minimizing the interval between wearing a COVID face mask and breathing compressed air underwater. X-Hab test operations resumed under the new procedures on Dec. 11, 2020. Testing has been further complicated by the inability to train new divers during COVID restrictions. This means, for example, that the Space Systems Laboratory is currently limited to two divers certified for full-face mask diving, required for serving as a test subject. Testing is still underway at the time of writing. The goal, at least in terms of the X-Hab 2021 period of performance, is to at minimum attain qualitative assessments of all of the planned test conditions and simulation activities by the end of the Spring 2021 semester.

Test subjects nominally use full-face masks with communications gear, with flexible umbilicals to the surface comm unit. The face masks are attached to the standard scuba bottles via a 30-ft “hookah” hose, which is routed together with their comm umbilical. The scuba tanks are secured outside the habitat mockup and the subjects enter and leave the test volume from the top, allowing a direct ascent to the surface in the event of a contingency. Each test subject requires a dedicated safety diver. Special safety diver assignments are required when the test subjects are ballasted to represent their weight on the lunar or Mars surface.

A. Habitat Configurations

Tests have incorporated vertical habitat configurations formed by six-, eight-, ten-, and twelve-rack units, as shown in Figure 19. Tests for horizontal habitat layouts were all performed with three-rack straight segments separated by one 90^o rack, two racks at 60^o, and three racks at 45^o angles, as shown in Figure 20. The available internal volumes of each of these test configurations are noted in the figure captions, and correspond to the values noted in Figure 11. To more accurately represent the limitations of the interior volume, plastic corrugated panels were attached to all racks which do not incorporate other test items, such as CTB shelving units or deployable table segments.

Figure 19. Underwater testing of vertical habitat configurations formed by (L. to R.) 6-, 8-, 10-, and 12-rack units. Internal volumes are 5.4 m^3, 10.0 m^3, 15.9 m^3, and 23.1 m^3, respectively.

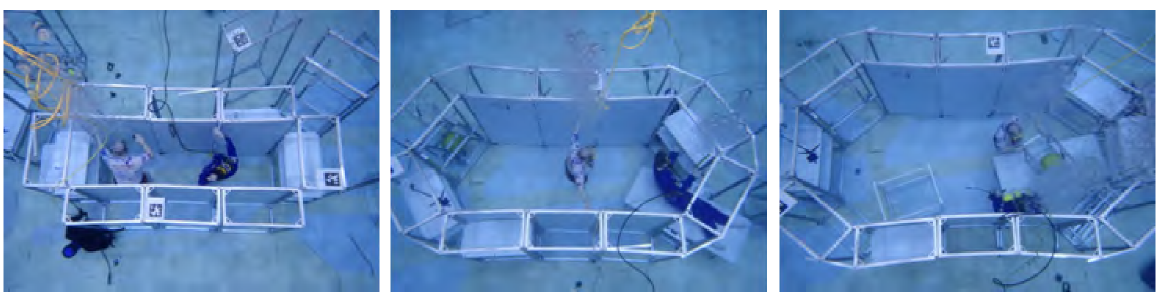

Figure 20. Underwater testing of horizontal habitat configurations formed by (L. to R.) 8-, 10-, and 12-rack units. Internal volumes are 6.2 m^3, 12.5 m^3, and 19.9 m^3, respectively.

While the goal is to test all of these configurations at microgravity, lunar, and martian gravity levels, the subjective evaluations to date from mostly microgravity evaluations have been interesting. Although the smallest of the horizontal configurations is 15% larger than the corresponding vertical configuration, the hexagonal vertical space was much easier to work in, as the 1 m spacing between the parallel surfaces in the horizontal unit was too constricting for most activities, including the two test subjects passing each other comfortably. At the other end, the widest horizontal configuration was preferred by the test subjects (at least in microgravity), as the subjects were never out of reach of a handrail or other grasp point for mobility, as opposed to the larger 12-rack vertical configuration in which a majority of internal volume is out of reach of handrails or other mobility aids.

B. Rear-Entry Suit Operations

By special request from the NASA technical monitor, the dive tests are assessing the impact of habitat volumetric restrictions on ingressing and egressing spacesuits incorporating rear-entry hatches. To represent this, the MX-2 pressure suit developed at the University of Maryland was repurposed to allow underwater ingress and egress. The rear hatch with all of the pressurization hardware was removed, and the soft goods arms were replaced with AX-5 style hard-suit arms to more accurately represent the effect of entering and exiting a fully pressurized suit. It was felt that the soft goods forming the lower torso assembly would be adequate without incurring the delay to design and fabricate a similar hard-suit lower torso assembly.

In tests to date, the MX-2 suit test item in its standard donning station was placed in the center of an eight-rack vertical habitat configuration for the tests. While there are plans to relocate the suit to an equivalent donning station built into one of the racks and representing a suitport, there are several concepts of future operations where rear-entry suits would be donned inside the habitable volume, which is represented by the current configuration. Figure 21 shows a test subject ingressing the suit simulator. In this image, a piece of corrugated plastic sheet has been attached to the top of the donning stand, representing a notional ceiling for the habitat and limiting the ability of the test subject to enter the suit from "above".

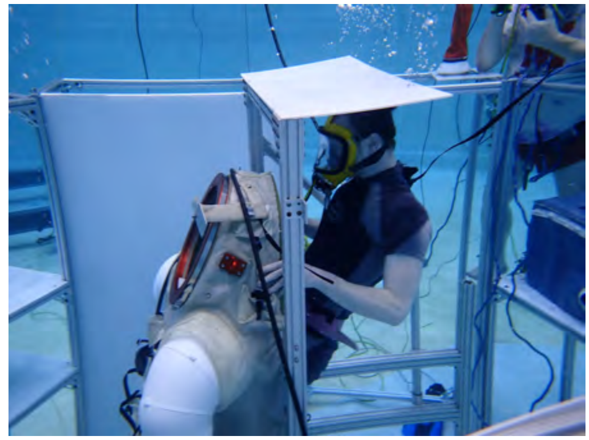

Figure 21. Rear-entry EVA suit ingress internal to habitat. The white sheet at the top of the donning rack represents the ceiling of the habitable volume.

Suitport tests to date have only been performed in microgravity simulations. In this mode, subjects did not encounter any difficulty in ingressing or egressing the suit. Initial tests were performed to assess functionality and safety of the suit entry procedure, and subjects were observed to float above the entry hatch and drop "down" into the suit legs. In subsequent testing with simulated ceiling constraints, the subjects had no difficulty in approaching the hatch from the rear and "sitting" in the hatch for entry, much as is done in 1-g ingress and egress. These tests will be repeated with the subjects ballasted to lunar and Mars gravity levels, as suit operations may be performed more easily under gravity with a greater free volume above the suit entry hatch.

C. Effects of Gravity Levels

The primary advantage of underwater testing (beyond maintaining pandemic restrictions) is the ability to simulate the gravitation environments of the Moon and Mars, or any other planetary body. Body segment parametric data is used to determine the proper ballast to replicate the apparent weight in the desired environment: for this project, the lunar (1.6 m/sec^2) and martian (3.8 m/sec^2) surfaces. By distributing the ballast weights proportionally around the body (Figure 22), rather than as a lump sum in a backpack, the masses are both more comfortable for the test subject and produce a more realistic dynamic system, in that the crew's center of gravity is essentially unaltered, and the leg segment dynamics are more accurate for planetary activities than when the subject is in a suspension harness for weight offset.[10] Weights are placed on the front and back of the torso, on the lateral surfaces of the thighs, and on the ankles for the lower leg ballast. The weights of the head and neck are lumped in with the torso weights, as are the arm weights, which are not separately ballasted because the required weights are only 1-2 kg and weights tend to restrict arm dexterity.

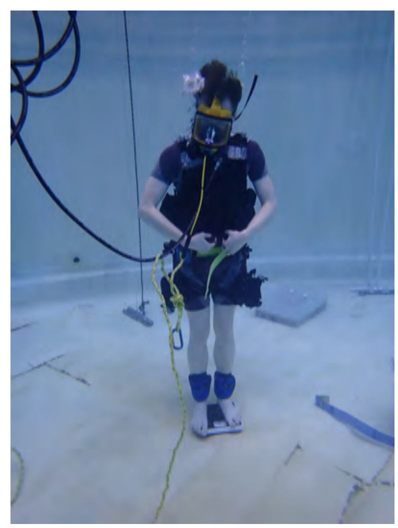

Figure 22. Test subject ballasted to lunar conditions.

Test subjects ballasted appropriately reported no problems maneuvering in the underwater environment at lunar or Mars weight, and had an easier time in some activities compared to microgravity, such as a simulated repair of an equipment module (Figure 23) since even lunar gravity was sufficient to maintain body positioning. A number of available chairs and stools (Figure 24) were placed in the habitat mockup to assess utility. As expected, none of them were particularly beneficial to the subject in microgravity, but even at lunar weight the test subject felt comfortable sitting in a standard chair.

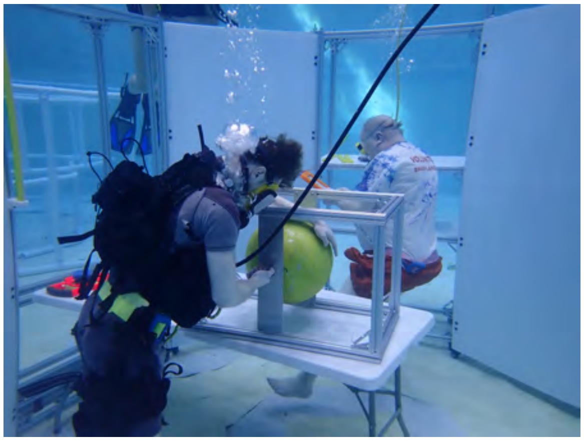

Figure 23. Simulated work on a habitat equipment module at lunar weight

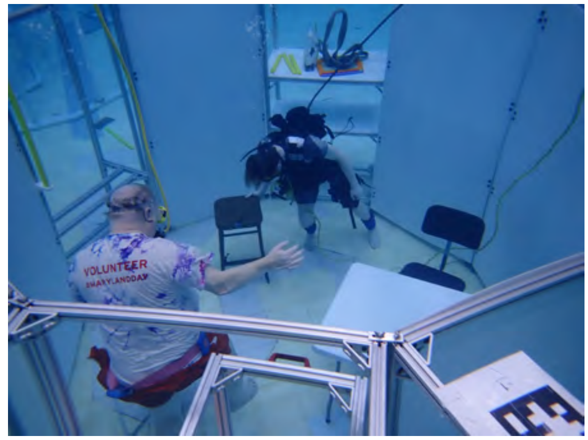

Figure 24. Testing seating for test subjects at different gravity levels

D. Effects of Crew Size

To date, all test operations have been performed with two test subjects, defined as divers ballasted properly for the test case (microgravity, Moon, or Mars) and using hookahs for breathing to eliminate the inertial and hydrodynamic effects of a body-mounted air supply. Ideally all test subjects would wear a full-face mask allowing two-way audio communication, but on several tests only one full-face mask has been available and the second test subject has worn a standard face mask and second-stage regulator with a hookah connection to a remote air tank. Limited testing has been done with support divers or full-scale human mannequins inside the habitat volume with the test subjects; in this case they replicated the constraints of two additional (inactive) crew members. As this test is to examine the effects of cabin size on crew functionality, the active test subjects are commanded by a surface test conductor to each perform a series of translations followed by simple tasks such as reporting a numerical parameter on a surface-mounted card. Video cameras monitor performance time and interferences between the test subjects, inactive test subjects, and/or fixed equipment such as the table or other furnishings.

E. Cargo Transfer Bag Retrieval, Manipulation, and Stowage

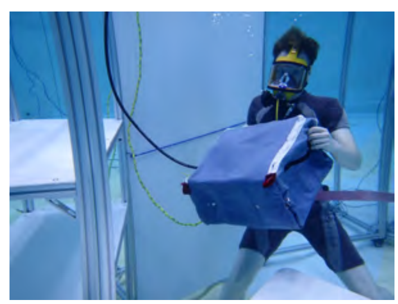

Figure 25. Test subject manipulating single-sized CTB

Much of the crew work in a space habitat is involved with logistics, from unloading an arriving logistics module to stowing the packages to random access and restowage to sorting for disposal. Currently, this has been modularized through the use of cargo transfer bags (CTBs), standard soft goods packaging for hardware in various sizes which are stowed throughout International Space Station. One of the standard tasks developed for this test series is the manipulation of CTBs for stowage, retrieval, and repackaging. Figure 25 shows a single-sized CTB which has been outfitted for underwater testing by the addition of an internal framework made of PVC pipe. This allows the CTB to hold its shape in neutral buoyancy, or the addition of ballast masses on the internal structure to give the CTB the appropriate weight for its simulated cargo and the gravitational environment under test. The small stock of CTBs at the NBRF currently are high fidelity in regards to the flight units; plans are in development for simpler designs which replicate the size and shape, but can be mass-produced to increase the inventory of CTBs (and implement different sizes) to allow more complex logistics simulations.

F. Multipurpose Table Size Investigation

Most habitat designs incorporate some horizontal surfaces, whether dedicated or general-purpose. This could vary from a small workstation internal to a rack, to a short table adequate for working on a life support module (Figure 26), to a table large enough for use as a medical examination and treatment center (Figure 27) or to work on a full spacesuit pressure garment. A commercial plastic table was incorporated into a specialized rack for testing the use of a table internal to the habitats, and to assess the impact of this unit in decreasing available movement spaces for the crew.

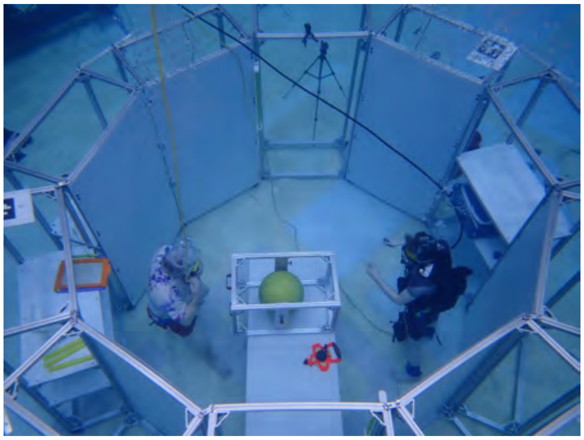

Figure 26. Simulated work on a habitat equipment module at lunar weight

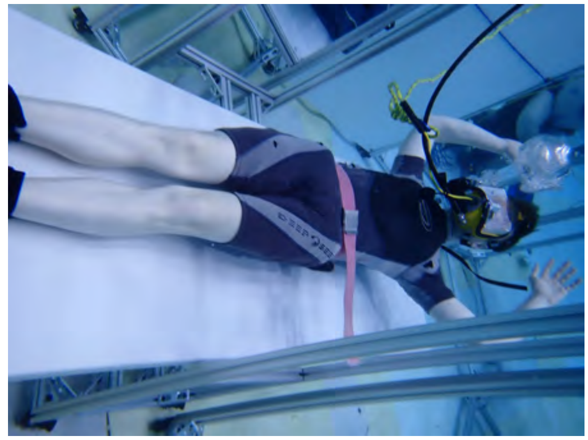

Figure 27. Testing table use as a medical examination table in microgravity

Initial tests of the table impact on habitat design consisted of having the standard 30x60 inch table inserted into the habitat interior by different depths and assessing its use for various applications. It was found that the full-length table subdivided the interior of the habitat for the 8-rack configuration, and even as a medical treatment table it was best placed to have as much of the table as feasible inside the rack structure itself. Shorter medical tables were tested and were preferable if the subject could be treated in a sitting position, or if their lower legs could dangle over the edge of the table.

Generic flat table surfaces were found to be useful when as short as 0.5 m, although larger components or more tools and associated parts would be facilitated by longer tables or orienting table components across adjacent rack modules. Smaller habitats may be prime candidates for variable length table structures, although the difficulty in any horizontal surface is generally clearing it off enough to put it away.

G. Rack Submodule Manipulation

One of the significant tasks repeated frequently on International Space Station is repairing systems internal to racks, particularly true of ISS life support equipment. This can take place internal to the rack, attached but pulled out of the rack on sliding supports, or removed entirely for repair in a different location. To represent this situation with appropriate weight for any gravitational situation, the UMd team developed a variable ballast repair module. As shown in Figure 28, this structure is built around a spherical rigid metal tank in its center. Manual valves are attached at each end of the tank, which may be opened to allow water into the tank at depth, and when equalized to vent air from the top. In this way variable amounts of water can be added to the tank to make the overall module neutrally buoyant or whatever weight is appropriate for the system simulated and the gravitational environment of interest. The fact that the tank is spherical means the weight of the contained water is always centered at the center of the tank, so rotating the module does not create any noticeable shift in balance or apparent center of gravity. As shown in Figure 29, this element was used at different simulated gravity conditions to determine how the test subjects' ability to manipulate such a large element and translate with it around the habitat was affected.

With the concept validated, it is planned to properly "install" the variable-weight module into a rack, and to outfit the interior with simulated wiring, electrical connectors, fluid tubing and connections, and physical units representing components to be removed and replaced. This will allow higher fidelity simulations of ISS servicing and maintenance tasks, performed repeatedly at different gravity levels and in different habitat sizes, configurations, and layouts.

VII. Future Plans

As stated previously, the research currently stands as a work in progress, slowed significantly by the restrictions of the pandemic. We plan for this to be an ongoing research project, separated for planning purposes between near-term (to the end of the 2020/2021 academic year) and beyond.

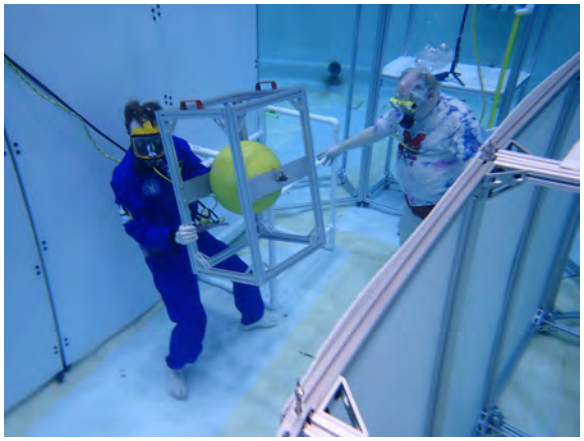

Figure 28. Handling variable-weight test module in microgravity conditions

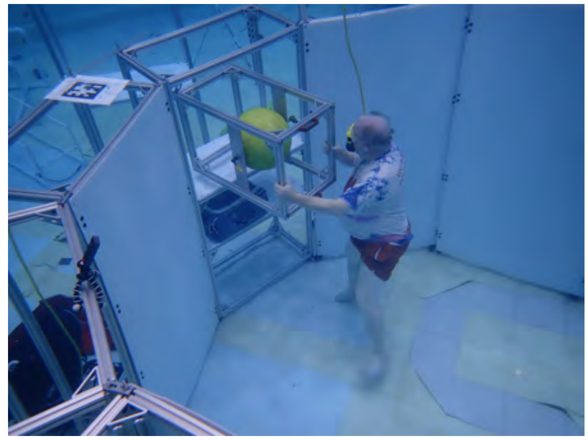

Figure 29. Inserting variable-weight test module into rack structure

A. Near-Term Plans

It is clear that pandemic mitigation policies will prevent any laboratory testing throughout the spring (and most probably summer) of 2021. For the remainder of the current academic year and X-Hab project, the UMd team will continue to investigate habitability of various modular configurations underwater, taking advantage of the environment to examine more carefully the role of gravitation in the performance of representative tasks. This will focus on two-person tests until additional test subjects can be trained and qualified, which may also be outside the remaining duration due to COVID precautions. In the meantime, we have investigated alternatives, including the use of mannequins to replicate the presence of additional (static) crew to expand testing in the interim. Tests will be more scripted and thereby more repeatable, and AprilTag visual fiducials[11] will be used to track the motion of crew and components handled within the habitat volume.

B. Longer-Range Plans

The team would like to continue this series of experiments when COVID restrictions are lifted, This would include a return to the original test plan with an emphasis on laboratory testing, supplemented by underwater correlation at various gravity levels. Laboratory testing would allow longer duration tests, which would allow sequences of activities that more accurately replicate a significant portion of a crew day on a space habitat. We plan to create additional rack modules, to allow the development of laboratory-only units which have active components allowing higher fidelity in crew interactions with simulated habitat hardware. In parallel, we plan to develop underwater rack units with some limited experimental functionality, taking advantage of waterproof switches and buttons and graphic display units in sealed boxes to protect electronics while submerged. Ultimately, the goal is to have a stable, long-term research program in space habitat design and evaluation, incorporating both underwater test facilities and refurbished existing SSL habitat mockups. Incorporating the modular rack concept in these habitats will increase the ability to revise habitat internal designs quickly and effectively. With increased fidelity and more extended test programs, it should be possible to obtain data-based guidelines for crew habitable volumes prior to the development of artificial-gravity space stations or the arrival of human crews at the Moon or Mars.

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