42nd International Conference on Environmental Systems
15 - 19 July 2012, San Diego, California

AIAA 2012-3598

A Parametric Comparison of Microgravity and Macrogravity Habitat Design Elements

David L. Akin,*

University Of Maryland, College Park, MD, 20742, USA

With human space exploration currently in a state of flux, it is challenging to develop critical human systems, such as habitats, in the absence of a specific known destination. Systems for Earth analogue testing, such as the Habitat Demonstration Unit developed by NASA and evaluated in recent Desert RATS field tests, have been tasked with representing everything from Mars and lunar habitats to microgravity habitats for use on missions to near-Earth objects or long-duration human servicing missions. Launch vehicles are no better known than destinations at the moment, and potential habitat designs range from 4.5 meter diameters for existing expendable launch vehicles to 7-10 meter diameters for speculative future heavy-lift vehicles.

This paper attempts to take a step back from the plethora of habitat point designs under consideration, and examines human space habitats based on parametric models of size, mass, and function, with a primary goal of reaching an informed decision on the degree to which an Earth analogue habitat in full Earth gravity can meaningfully represent habitats in substantial reduced gravities (moon, Mars) or in microgravity (NEOs, cislunar space, Martian moons).

Using basic geometry and physics, this paper identifies a standard habitat element as a right circular cylinder with ellipsoidal endcaps, and assesses pressurized and habitable volumes and surface areas in various configurations. This changes based on the need to provide standing head height in macrogravity, and the equivalent head height for a neutral body posture in microgravity. This leads to differences between vertical and horizontal configurations of habitat layouts, which are extended from geometric expressions of volumes and areas to mass estimating relationships for habitat overall mass based on geometric configuration.

Simple physical models are created to understand the fundamentals of human motion in reduced gravities, such as increase in jumping capability, inadvertent free-flight due to excess energy in standard locomotion, and alternate designs for stairs, ladders, and other systems for moving between vertically stacked decks in alternate gravitational environments. This is one of the primary areas of fundamental difference between reduced gravity and microgravity, as energy requirements for climbing become meaningless in microgravity.

Finally, the paper begins the deliberation in the effectiveness of available and potential Earth analogue environments for higher fidelity assessment of habitat functionality and the development of a validated data base on reduced gravity design rules. While the U.S. space program has learned a great deal about microgravity habitat and workstation design in the last 30 years of shuttle operations, we are still at the beginning in terms of long-term life on the Moon or Mars.

Acronyms

EVA	ExtraVehicular Activity
GEO	Geostationary Orbit
ISS	International Space Station
NASA	National Aeronautics and Space Administration
NBP	Neutral Body Posture

*Director, Space Systems Laboratory. Associate Professor, Department of Aerospace Engineering. Senior Member, AIAA

NEO	Near Earth Object
SSL	Space Systems Laboratory
UMd	University of Maryland

Nomenclature

d	diameter of cylindrical section
h	deck height of habitat
k	maximum height of ellipsoidal endcaps
n	number of floors
p	heuristic exponent value for estimating volume of ellipsoids; typically $\approx$1.6
r	radius of cylindrical section
w	floor width across habitat
A	floor area of habitat
L	linear distance along exterior of habitat (perimeter) at surface level
S	surface area of habitat
V	volume of habitat
ℓ	length of cylindrical section
δ	d/h; ratio of cylindrical diameter to standard ceiling height
λ	ℓ/d; length/diameter ratio of cylindrical section
ϵ	k/r "compression" ratio of ellipsoidal endcaps

I. Introduction

Other than a general commitment to extend human presence farther into the solar system, with the concomitant requirement for long-duration habitation, there is little known about destinations. Will future space habitats be located on the Moon, Mars, at asteroids, Lagrange points, geostationary orbit, or combinations of these and other possible destinations? To what extent can a habitat designed for a planetary surface be used in microgravity, and vice versa? And how do we perform experimental ground-based investigations of habitability when we have to deal with Earth's gravity throughout the test habitats?

This paper aims to address these issues via a parametric approach, to try to model the underlying parameters of habitat design based on basic physics, geometry, and biomechanics, to understand the limitations of simulation fidelity, and to see if anything can be gleaned from past experience, both on Earth and in space to date. To this end, the paper will address the gravitational environments of Earth and the potential habitation destinations in space, and try to understand where commonalities exist, and how far they can extend. What functions have to be performed in the process of daily life in space, and how can they best be modeled if, during the development phase, they can only be performed on Earth?

II. Bounding the Problem

Under NASA's current "Flexible Path" goals, future human exploration targets could include geostationary orbit (GEO), Lagrange points, near-Earth objects (NEOs) such as small asteroids, lunar orbit, the lunar surface, Mars orbit, Phobos and Deimos, and the surface of Mars. This wealth of potential destinations have widely differing gravitational environments, providing a changing target for planning human habitats that can function in many or all of the environments. Much of the current habitat planning assumes that a single habitat design, with some changes for the specific target location, can be found which will be functional in all.

The first issue is to understand what the range of potential gravitational accelerations are. This is shown in Table 1. It should be noted that the gravitation values for minor bodies within the current planning horizon are all 10^{-3}g or less, dominated by Phobos at 0.0009g; the upper end of the range cited (10^{-2}g) is associated with the largest asteroids in the main belt, such as Ceres (0.028g) and Vesta (0.022g).

This table clearly illustrates that there are two classes of destinations to consider: *macrogravity* sites where the gravitational acceleration would be readily apparent (Earth, Mars, Moon), and *microgravity* sites

Table 1. Relative gravitational accelerations of solar system exploration destinations

Environment	Gravitation (Earth=1)
Earth	1
Mars	0.38
Moon	0.16
Minor Bodies	10^{-2} – 10^{-4}
Orbit	10^{-5} – 10^{-6}

where there is no appreciable gravity, or at least a concerted effort would have to be made to discern the effect of gravity on the environment (minor bodies, orbits). We can further distinguish under the macrogravity category the difference between full Earth gravity and *partial gravity* on the Moon and Mars[a]. Thus, there are two different sets of issues at stake here: what are the fundamental differences in habitats designed for reduced gravity and microgravity, and how best to simulate each of these conditions for Earth-based development and evaluation.

III. Habitat Design Parameters

A. Size

How large a habitat must be is a highly contentious issue, with complicating factors such as crew size, mission duration, location, and environment (e.g., required radiation shielding). The simplistic answer is that space habitats should be as small as possible from the standpoint of development cost, launch mass and volume, and mission flexibility, and as large as possible from the standpoint of human factors, habitability, and psychosocial issues of mission design.

In the early days of the space program, three researchers from North American Aviation published a paper describing a set of curves as an "Index of Habitability" for long-duration space flight.[1] These curves, known as the Celentano curves after the lead author, predict that required volume reaches asymptotic limits with time. Three curves were generated in this document, for "tolerable" conditions, acceptable "performance" results, and "optimum" conditions. These curves are shown in Figure 1, along with additional added data.

While a variety of other heuristics have been proposed for predicting habitat volume requirements as a function of crew size and mission duration,[2] the Celentano curves are still used as a standard descriptor for this function. Although not presented in this form in the original source, the Celentano curves can be empirically modeled by exponential curves approaching the desired asymptotic values. Such curves are of the form

$$\frac{volume}{crew\ member} = A\left(1 - e^{-\frac{duration}{B}}\right) \tag{1}$$

where A represents the asymptotic value of volume/crew for an extended duration mission and B represents the "rise time" of the curve. The Celentano curves are adequately represented by this heuristic equation by using a value of 20 days for B, and asymptotic A values of 5, 10, and 20 m^3/crew for the "tolerable", "performance", and "optimum" limit values, respectively.

This graph also incorporates a number of data points drawn from a half century of conceptual designs for long-duration space habitats, along with a new trend line, based on the assumed form of equation (1) but with values of A and B chosen by a least squares fit to the collected data, presented in summary form in the Appendix of this paper. This curve shows some surface similarities to the Celentano "optimal" curve, with a slower exponential time constant of 35 days and an asymptotic value of 62 m^3/crew member. Some caveats on this regression analysis: with a coefficient of determination (R^2) of 0.32, the fit is too poor to make any

[a]There is an interesting challenge in coming up with a standard adjective to refer to gravitational accelerations such as those on the Moon and Mars. Common usages include "partial", "reduced", and "low" gravity; all of these can be said to be incorrect because "gravity" is the same everywhere; only the local acceleration due to gravity changes. The author asserts that, of these three options, only "partial" gravity unambiguously refers to acceleration levels less than those of Earth, but clearly greater than the microgravity levels of the minor solar system bodies. The author admits to the willful use of the technically inaccurate term "partial gravity" to prevent having to write "partial gravitational acceleration levels compared to Earth" over and over again.

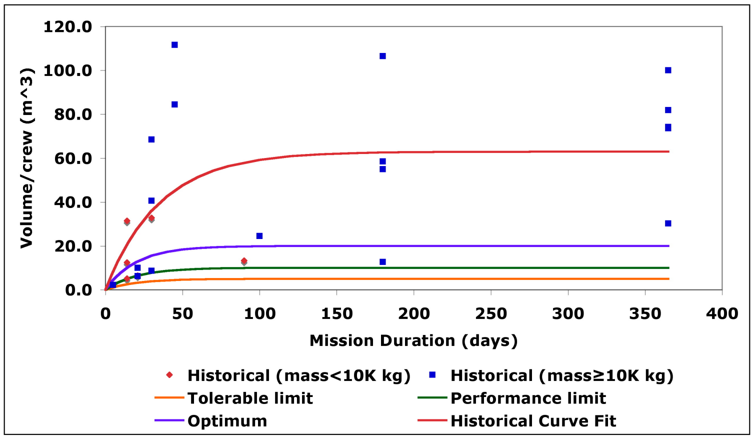

Figure 1. Habitat Volume vs Mission Duration

sweeping conclusions as to the universal applicability of this curve. Also, this curve is based exclusively on lunar surface habitats, so it is unknown how the trend will relate to microgravity habitats. This is an area for further research in the near future. However, this trend does indicate that the median asymptotic value for volume per crew member is more than three times that predicted by the most generous of the Celentano curves. In comparison, recent design guidance from the NASA habitat development program to schools involved in the 2012 X-Hab program is to design for a minimum of 42 m^3/person – twice the maximum Celentano value, if still significantly below values for ISS and Skylab.

B. Shape and Orientation

The first function of any habitat is to restrain the atmospheric gases and pressure to keep the crew alive. As such, it is first and foremost a pressure hull, and will fall within the general practices for pressure hull design. In general, the most mass-efficient pressure shape would be a sphere. Since another design constraint is to launch the habitat into space, an additional geometric constraint will be fixed by the diameter of the launch vehicle payload fairing; this tends to make all habitat designs turn out to be roughly cylindrical, with hemispherical or ellipsoidal endcaps to prevent stress concentrations in those areas.

It should be pointed out that, with the current interest in inflatable structures, another geometric shape which could be considered is a torus. This is a typical inflatable shape when the central core is composed of rigid structure, and a toroidal inflatable envelope is attached to either end of the core. The number of potential toroidal geometric shapes precludes its direct incorporation into this analysis; instead, it will be noted that most toroidal shapes are similar to low length/diameter cylinders with highly ellipsoidal endcaps, so that case will be assumed to subsume toroidal configurations here.

It is therefore assumed for this analysis that the pressure hull is a right circular cylinder of diameter d and length ℓ, with ellipsoidal endcaps of maximum height k. Simple analytic geometry provides the equations for volume V and surface area S of the cylindrical component as

$$V_{cyl} = \frac{\pi}{4} d^2 \ell \tag{2}$$

$$S_{cyl} = \pi d \ell \tag{3}$$

For the axisymmetric oblate ellipsoidal endcaps, the internal volume of both endcaps is defined as

$$V_{end} = \frac{4}{3} \pi r^2 k \tag{4}$$

which, it should be noted, produces the standard equation for the volume of a sphere when $k = r$. Given a desire to define the nature of the ellipsoidal endcap in terms of the ratio between radius r and height k, where a "4:1" ellipsoid has a value of r equal to 4 times k, we can define the reciprocal ratio

$$\epsilon \equiv \frac{k}{r} = \frac{2k}{d} \tag{5}$$

and rewrite equation (4) in terms of ϵ and d to find

$$V_{end} = \frac{\pi}{6} d^3 \epsilon \tag{6}$$

The surface area of an ellipsoid is complicated to compute exactly; in this analysis, the approximation of

$$S_{end} = 4\pi \left(\frac{a^p b^p + b^p c^p + c^p a^p}{3} \right)^{\frac{1}{p}} \tag{7}$$

is used; a, b, and c are the semi-principal axes of the ellipsoid, and an accurate estimate is generally obtained for p=1.6. Since this is an axisymmetric oblate ellipsoid, we can substitute

$$a = b = r = \frac{d}{2} \text{ and } c = k = \frac{d\epsilon}{2} \tag{8}$$

to find the final estimate of the surface area for the two ellipsoidal endcaps

$$S_{end} = \pi d^2 \left(\frac{1 + 2\epsilon^p}{3} \right)^{\frac{1}{p}} \tag{9}$$

As a check, substituting $\epsilon = 1$ correctly produces $4\pi r^2$ as the surface area of a sphere.

We can now write explicit relations for the total volume and surface area of the habitat pressure hulls:

$$V_{tot} = \frac{\pi}{4} d^2 \ell + \frac{\pi}{6} d^3 \epsilon \tag{10}$$

$$S_{tot} = \pi d \ell + \pi d^2 \left(\frac{1 + 2\epsilon^p}{3} \right)^{\frac{1}{p}} \tag{11}$$

A further parametric enhancement of this geometric model can be obtained by defining the length/diameter ratio for the cylindrical section of the habitat

$$\lambda \equiv \frac{\ell}{d} \tag{12}$$

The total volume and area equations can now be written in terms of nondimensional parameters

$$V_{tot} = \pi d^3 \left(\frac{\lambda}{4} + \frac{\epsilon}{6} \right) \tag{13}$$

$$S_{tot} = \pi d^2 \left[\lambda + \left(\frac{1 + 2\epsilon^p}{3} \right)^{\frac{1}{p}} \right] \tag{14}$$

With this analytical understanding of habitat volume and area, any of a number of heuristic mass estimating equations can be used to produce initial estimates for habitat mass. For example, some manipulation of data in Heineman[3] produces a heuristic mass estimation for the complete habitat (including internal systems) of

$$m\langle \text{kg} \rangle = 460 (V \langle \text{m}^3 \rangle)^{0.76} \tag{15}$$

Combining (15) for mass estimation with (13) for volume as a function of shape results in

$$m\langle \text{kg} \rangle = 460 \left[\pi (d\langle \text{m} \rangle)^3 \left(\frac{\lambda}{4} + \frac{\epsilon}{6} \right) \right]^{0.76} \tag{16}$$

This allows a parametric examination of the effect of design parameters, such as demonstrated in Figure 2 showing the effects of λ, ϵ, and diameter d. As might be expected, increasing λ $(= \ell/d)$ has much more impact on habitat mass than changing the shape of the ellipsoidal endcaps, which has limited effect on the mass or volume.

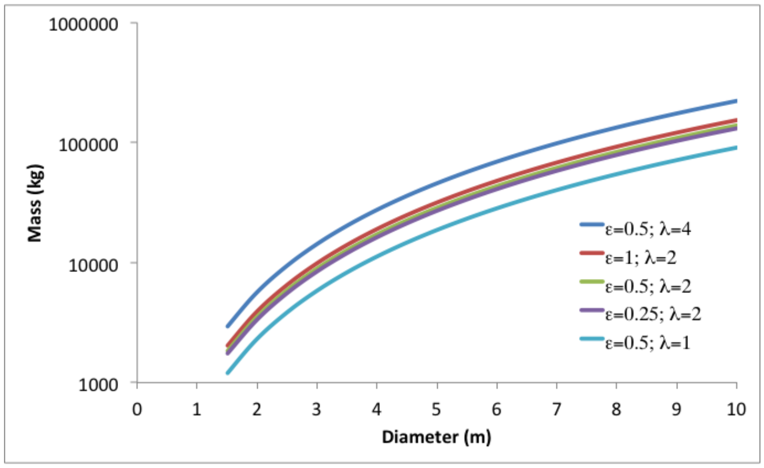

Figure 2. Effect of geometric configuration parameters on habitat mass

C. Habitable Area and Volume

One of the critical differences between macrogravity and microgravity habitats is the relative importance of area and volume. In architecture on Earth, habitat size is generally given in terms of area. A house will be a certain number of square feet; the ceiling is presumed to be high enough, and if some rooms have cathedral ceilings, they add to the volume (and cost) of the house, but not to the available living area. On the other hand, in microgravity the entire volume could be accessible for various living functions, and area becomes the less meaningful figure of merit.

In the previous section, the volume analyzed was *pressurized volume*: the total volume within the pressure hull. In this section, we will seek to define the portion of the pressurized volume actually accessible to the inhabitants, or the *habitable volume*. which eliminates volumes filled with equipment, stowage, or just by its size or shape inconvenient for human occupancy. As a rough rule of thumb, in many designs habitable volume is on the order of half of the pressurized volume.

One of the investigations of Skylab was to examine interior layout, in particular multiple orientations within compartments. The Apollo Telescope Mount section of Skylab had multiple work stations, each with its own orientation vector which varied widely across the module. In comparison, the living quarters on the lowest level of the Orbital Workshop had a single enforced vertical orientation throughout. The Skylab astronauts strongly preferred the singular orientation, and eight of the nine crew strongly criticized the variable orientations of the ATM.[4] Since that time, it has been standard practice to design orbital modules, including habitats, with a single enforced direction for standard orientation.

That decision actually minimizes the difference between macrogravity and microgravity habitats. If all compartments have fixed orientations, they can be designed with a designated floor and ceiling, with a calculable floor area. The relationship between area and volume will be fixed by the standard ceiling height, discussed below, but frequently similar to Earth-based design norms. The primary difference between macro- and microgravity becomes the flexibility in choosing the designated vertical orientation direction; when in a gravity field, the internal orientation must line up with the gravitational vector. This means that a choice must be made between a vertical orientation (axis of symmetry aligned with the gravity vector) or horizontal orientation (axis of symmetry aligned with the local horizontal surface.)

Regardless of gravity levels, humans tend to operate upright, and require what is known on Earth as “standing head height”. Although neutral body posture (NBP) in microgravity is not as tall as a human standing erect, the difference is minor in terms of required ceiling heights. In a vertically oriented cylinder, the humans are standing parallel to the axial direction of the cylinder, and the walls are vertically straight. Thus, the entire cross-sectional area of the cylinder is potentially habitable floor area, multiplied by the number of floors; the entire cylindrical length times the cross-sectional area is all potential habitable volume. (While it is possible that some of the volume interior to the ellipsoidal endcaps could also be made habitable, for geometric simplicity this portion of the pressurized volume will not be considered habitable, and will be reserved for equipment, stowage, and so forth.)

Working with these assumptions, the habitable area of a vertical configuration pressure hull is the cross-sectional area

$$A_{xsec} = \frac{\pi}{4} d^2 \tag{17}$$

multiplied times the number of floors, defined as n. The habitable volume is then simply the habitable area times the floor height h[b]. Since there is little reason to extend the cylinder length beyond that required for the number of living levels, an assumption is made for vertical orientation habitats that the cylindrical length is fixed by $\ell = nh$. Formally, the equations for a vertical geometry habitat, normalized by habitat diameter, become

$$\frac{A_{tot,V}}{d^2} = \frac{\pi n}{4} + \pi \left(\frac{1 + 2\epsilon^p}{3} \right)^{\frac{1}{p}} \tag{18}$$

$$\frac{V_{tot,V}}{d^3} = \frac{\pi}{4\delta} n + \frac{\pi}{6} \epsilon \tag{19}$$

$$\frac{A_{hab,V}}{d^2} = \frac{\pi}{4} n \tag{20}$$

$$\frac{V_{hab,V}}{d^3} = \frac{\pi}{4\delta} n \tag{21}$$

For a horizontally oriented cylinder, the occupants stand perpendicular to the cylindrical axis. As illustrated in Figure 3, this means that the potentially habitable volume in a horizontal cylinder is the inscribed rectangle of height equal to the desired ceiling height h and width sufficient to span the circular cross-section of the cylinder. The circular arc regions on the four sides of the inscribed rectangle are pressurized, and could be used for bunks, storage, life support equipment, etc., but for the purposes of this analysis the focus is on volume in which the crew can stand and walk upright. Unlike the vertical orientation assumptions, the ellipsoidal endcaps are also assumed to be potentially habitable in horizontal configurations. Thus, any level on a horizontally oriented habitat would consist of a rectangular center section and elliptical end sections conformal to the ellipsoidal end caps of the pressurized cylinder. Using the variable definitions above, the area and volume of such a living level can be calculated by

$$A_{level} = w\ell + \epsilon\pi \frac{w^2}{4} \tag{22}$$

$$V_{level} = w\ell h + \epsilon\pi h \frac{w^2}{4} \tag{23}$$

As shown in Figure 3, the definition of "habitable space" is fixed by the assumption of a constant value for desired standing headroom. A standard 8 ft headroom, with some structure between levels as discussed above, corresponds to a floor-ceiling height of 2.5 m. Using this value, the horizontal orientation cannot become a multifloor arrangement until some point after the diameter exceeds 5 m, high enough for two full standing head heights.

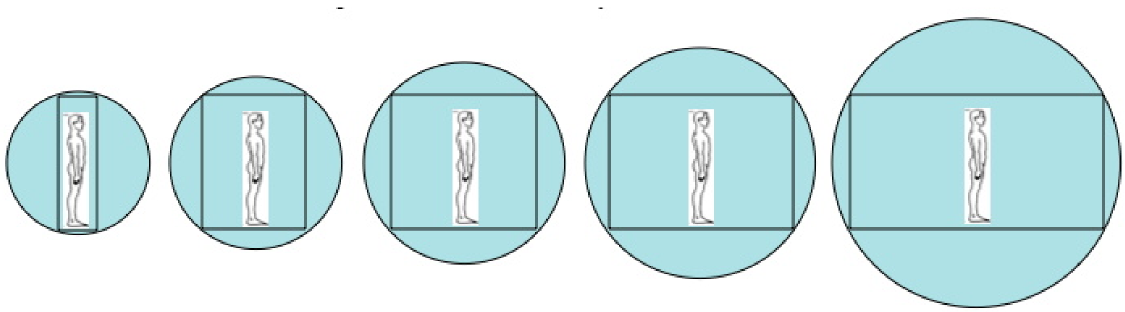

Figure 3. Concept of "habitable space" internal to a horizontal cylinder of varying diameters

[b]It should be noted that the height of a habitable level includes the structural thickness of the structure separating it from the next level; h is herefore the distance between floors, which will be somewhat greater than the floor-ceiling height

The internal parameters for the horizontal orientation are defined in Figure 4. However, the equations relating floor area and volume must take into account the number of floor levels in the cylinder. As discussed above, only the larger diameters can accommodate multiple internal levels, and an approximate floor-floor height of 2.5 m means that a 10 m diameter habitat (the largest payload fairing size under active discussion) would limit the maximum possible number of living levels in the horizontal configuration to four. Conceptual visualizations of these are shown in Figures 5 through 8. It should be noted that these interior levels are arranged symmetrically with regard to the horizontal plane of symmetry of the pressurized shell; it can be shown that this produces the maximum possible interior volume and floor area.

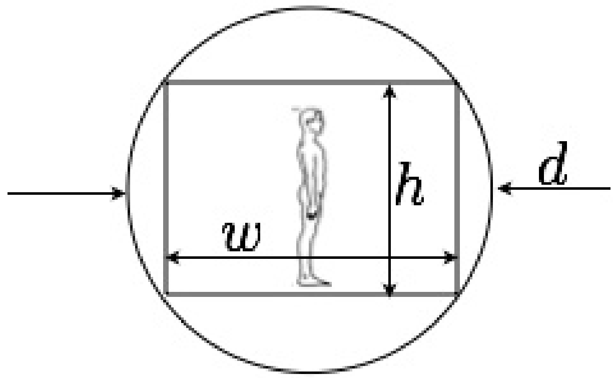

Figure 4. Definition of Parameters for Habitable Volume/Area Analysis

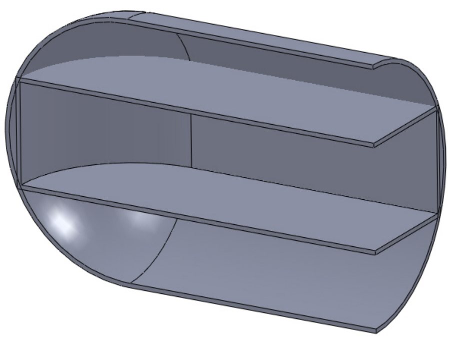

Figure 5. Single living level in horizontal habitat

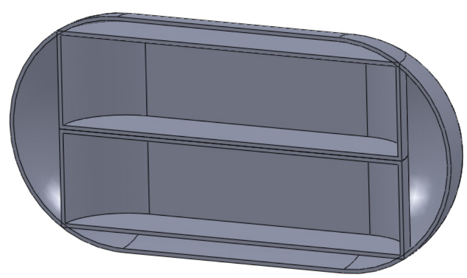

Figure 6. Two living levels in horizontal habitat

The summary equations for a horizontal habitat orientation are listed below. For the purposes of parametric examination, the areas and volumes are normalized by the diameter of the habitat, allowing the use of nondimensional design parameters throughout the equations.

$$\frac{A_{tot,H}}{d^2} = \pi\lambda + \pi\left(\frac{1+2\epsilon^p}{3}\right)^{\frac{1}{p}} \tag{24}$$

$$\frac{V_{tot,H}}{d^3} = \frac{\pi}{4}\lambda + \frac{\pi}{6}\epsilon \tag{25}$$

Single living level (Figure 5):

$$\frac{w}{d} = \sqrt{1-\left(\frac{1}{\delta}\right)^2} \tag{26}$$

$$\frac{A_{hab,H}}{d^2} = \lambda\sqrt{1-\left(\frac{1}{\delta}\right)^2} + \frac{\epsilon\pi}{4}\left[1-\left(\frac{1}{\delta}\right)^2\right] \tag{27}$$

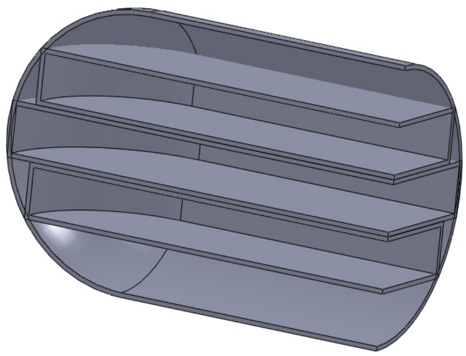

Figure 7. Three living levels in horizontal habitat

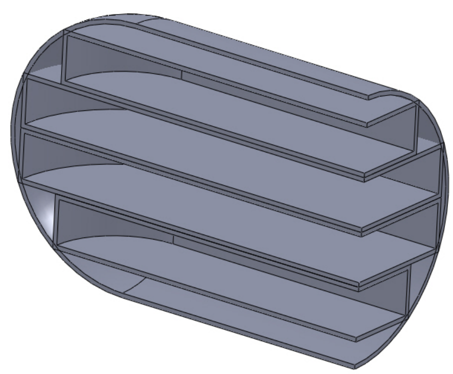

Figure 8. Four living levels in horizontal habitat

$$\frac{V_{hab,H}}{d^3} = \frac{\lambda}{\delta}\sqrt{1-\left(\frac{1}{\delta}\right)^2} + \frac{\epsilon\pi}{4\delta}\left[1-\left(\frac{1}{\delta}\right)^2\right] \tag{28}$$

Two living levels (Figure 6):

$$\frac{w}{d} = \sqrt{1-\left(\frac{2}{\delta}\right)^2} \tag{29}$$

$$\frac{A_{hab,H}}{d^2} = 2\left(\lambda\sqrt{1-\left(\frac{2}{\delta}\right)^2} + \frac{\epsilon\pi}{4}\left[1-\left(\frac{2}{\delta}\right)^2\right]\right) \tag{30}$$

$$\frac{V_{hab,H}}{d^3} = 2\left(\frac{\lambda}{\delta}\sqrt{1-\left(\frac{2}{\delta}\right)^2} + \frac{\epsilon\pi}{4\delta}\left[1-\left(\frac{2}{\delta}\right)^2\right]\right) \tag{31}$$

Three living levels (Figure 7):

$$\frac{w_{central}}{d} = \sqrt{1-\left(\frac{1}{\delta}\right)^2} \tag{32}$$

$$\frac{w_{upper}}{d} = \frac{w_{lower}}{h} = \sqrt{1-\left(\frac{3}{\delta}\right)^2} \tag{33}$$

$$\frac{A_{hab,H}}{d^2} = \lambda\sqrt{1-\left(\frac{1}{\delta}\right)^2} + \frac{\epsilon\pi}{4}\left[1-\left(\frac{1}{\delta}\right)^2\right] + 2\left(\lambda\sqrt{1-\left(\frac{3}{\delta}\right)^2} + \frac{\epsilon\pi}{4}\left[1-\left(\frac{3}{\delta}\right)^2\right]\right) \tag{34}$$

$$\frac{V_{hab,H}}{d^3} = \frac{\lambda}{\delta}\sqrt{1-\left(\frac{1}{\delta}\right)^2} + \frac{\epsilon\pi}{4\delta}\left[1-\left(\frac{1}{\delta}\right)^2\right] + 2\left(\frac{\lambda}{\delta}\sqrt{1-\left(\frac{3}{\delta}\right)^2} + \frac{\epsilon\pi}{4\delta}\left[1-\left(\frac{3}{\delta}\right)^2\right]\right) \tag{35}$$

Four living levels (Figure 8):

$$\frac{w_{central}}{d} = \sqrt{1-\left(\frac{2}{\delta}\right)^2} \tag{36}$$

$$\frac{w_{upper}}{d} = \frac{w_{lower}}{h} = \sqrt{1-\left(\frac{4}{\delta}\right)^2} \tag{37}$$

$$\frac{A_{hab,H}}{d^2} = 2\left(\lambda\sqrt{1-\left(\frac{2}{\delta}\right)^2} + \frac{\epsilon\pi}{4}\left[1-\left(\frac{2}{\delta}\right)^2\right] + \lambda\sqrt{1-\left(\frac{4}{\delta}\right)^2} + \frac{\epsilon\pi}{4}\left[1-\left(\frac{4}{\delta}\right)^2\right]\right) \tag{38}$$

$$\frac{V_{hab,H}}{d^3} = 2\left(\frac{\lambda}{\delta}\sqrt{1-\left(\frac{2}{\delta}\right)^2} + \frac{\epsilon\pi}{4\delta}\left[1-\left(\frac{2}{\delta}\right)^2\right] + \frac{\lambda}{\delta}\sqrt{1-\left(\frac{4}{\delta}\right)^2} + \frac{\epsilon\pi}{4\delta}\left[1-\left(\frac{4}{\delta}\right)^2\right]\right) \tag{39}$$

With these parametric equations, direct numerical comparisons can be made between the horizontal and vertical habitat orientations. Of particular interest is the choice of horizontal or vertical configuration, habitat size, length/diameter ratio for the cylindrical section, and shape of the endcaps. Figure 9 illustrates the use of the analytical forms derived above in examining endcap configuration. This single case is based on single-floor habitats, with ℓ=h so that both the horizontal and vertical habitats are examined with identical pressure vessel sizes. This graph shows that a horizontal habitat with hemispherical end caps, with the living area extended into the hemispheres, produces more useful floor area than the vertical habitat. With flat end plates, the opposite is true, which is exactly what would be expected based on simple geometric reasoning. However, the chart also shows that the two sample cases of ellipsoidal end caps (ϵ=0.25 and 0.5) also have insufficient additional living area to make up for the inefficiencies of the horizontal format.

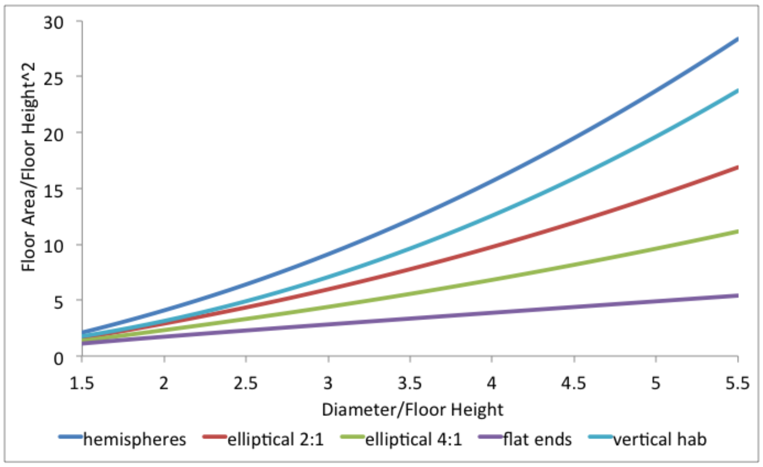

Figure 9. Habitable area vs. cylindrical diameter as a function of orientation and endcap form factor (single level, ℓ=h) - note that all cases are for horizontal orientation except the last (labeled "vertical hab"); the endcap parameter is given as diameter over height, or $1/\epsilon$; and the X-axis parameter is equivalent to $1/\delta$.

These trends can be extended into multiple living levels in both the vertical and horizontal habitats. Figures 10 through 13 show the trends in living area for habitats with one, two, three, and four levels with different end cap shapes. To keep the comparisons meaningful, the value of ℓ was set equal to the number of floors times the interfloor separation h, so the pressure hulls for the horizontal and vertical four-floor habitats are identical, as are the other three comparisons. Figure 10 shows that horizontal architectures with living volumes restricted to the cylindrical section (as is the case for ϵ=0, which corresponds to a hypothetical case of flat end caps) are at a significant disadvantage to the vertical orientation. This figure, like the other three, also shows the effect of the geometric constraint that the diameter must be greater than n times the floor-floor height h to fit into a habitat of d diameter. As the end caps become less elliptical, the feasible floor areas for the two orientations approach each other; however, only in the case of hemispherical end caps (ϵ=1) does the available floor space in the horizontal habitat exceed that of the vertical habitat in all orientations.

D. Ceiling Height

The average 2.44 m (8 ft) ceiling height in the American home is designed to accommodate the tallest individuals, and to remain out of reach for all but extraordinary jumps attempting to touch the ceiling. Given equivalent strength and muscle response, it would be reasonable to expect greater jump heights in regions of reduced gravity, requiring corresponding higher ceilings.

Although a range of specific values can be found for this parameter, assume for the purposes of this analysis that an average person can raise his/her center of gravity 0.5 m in a maximum effort standing jump.

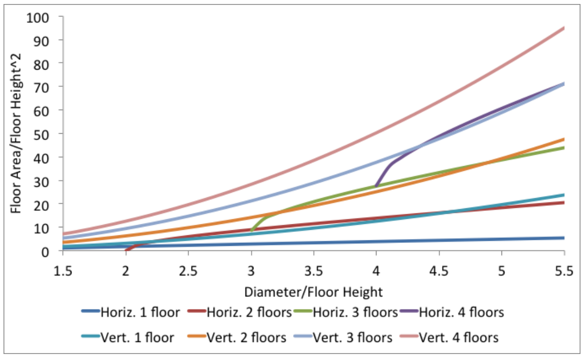

Figure 10. Comparison of habitable area in vertical and horizontal habitat configurations (ϵ=0)

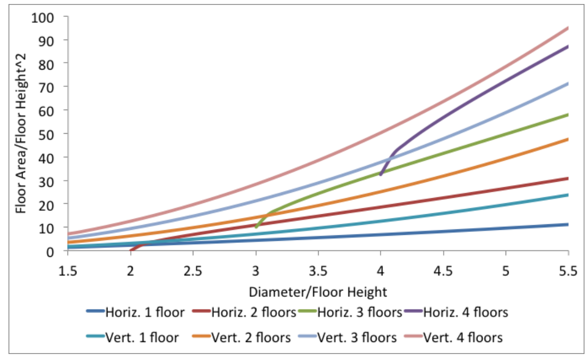

Figure 11. Comparison of habitable area in vertical and horizontal habitat configurations (ϵ=0.25)

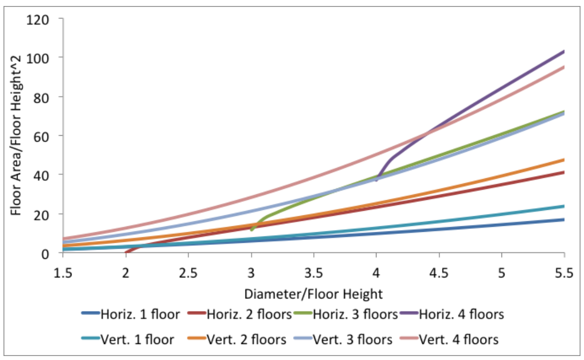

Figure 12. Comparison of habitable area in vertical and horizontal habitat configurations (ϵ=0.5)

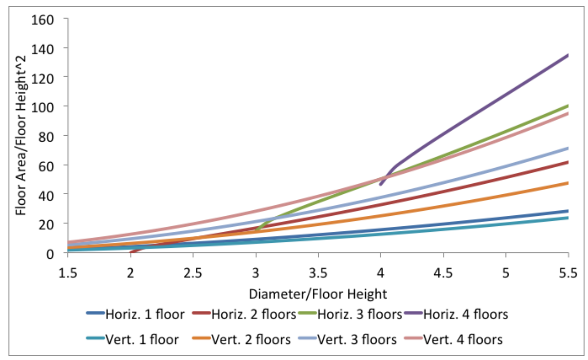

Figure 13. Comparison of habitable area in vertical and horizontal habitat configurations (ϵ=1)

Given the basic physics of the situation,

$$s = \frac{1}{2}gt^2 \implies t = \sqrt{\frac{2s}{g}} \implies v = gt = \sqrt{2gs} \tag{40}$$

this corresponds to an instantaneous vertical velocity of 3.13 m/sec at liftoff. This vertical velocity is a function of leg strength and muscle activation speed, and is the result of a given force pattern applied to the ground from the start of the jump until the feet no longer make contact and the subject is coasting upwards to the peak of their trajectory. Reduced gravity would decrease muscle effort to overcome the jumper's weight during the jump, allowing a higher take-off velocity; to first order, the assumption is made that this liftoff speed would not vary significantly due to the local gravity field, as it is a function of the applied force and the subject's body mass. Therefore transferring the same jump speed to an alternate gravitational acceleration g',

$$s' = \frac{v^2}{2g'} \text{ or alternatively, } s' = s\frac{g}{g'} \tag{41}$$

which produces an estimated jump height of 1.4 m on Mars and 3.1 m on the Moon. It should be reiterated that this is a maximum effort jump by an average American male; if we were to assume a standing jump height for a nominal jump half that of a maximum effort jump on Earth (or 0.25 m), the corresponding reduced gravity jump heights similarly scale to 0.7 m on Mars and 1.5 m on the Moon.

Another approach would be to say that the kinetic energy of the jump is equal to the potential energy at the apex, or mgs in the previous nomenclature. If we make the assumption that jump energy is the same in different environments, we again arrive at the second result in equation (41) that jump height is the Earth jump height scaled inversely by the ratio in gravitational accelerations.

A more astute reader might reject this simplistic analysis, since it does not account for the fact that part of the subject's muscle effort is going to counteract the force of gravity on body mass throughout the stroke of the jump itself. A more exact formulation of jumping energy would be

$$s_j = \int \left(\frac{F_j}{m} - g \right) dt \tag{42}$$

where the subscript "j" refers to the acceleration during the leg extension process of the jump. Continuing the simple assumption that force is constant throughout the jump stroke, We can relate the lift-off velocity of the jump to the stroke length by

$$s_j = \frac{1}{2} \frac{v_j^2}{\frac{F_j}{m} - g} \tag{43}$$

Accepting the previous assertion from Earth-based jump performance that the lift-off velocity is 3.13 m/sec and assuming a jump stroke length of 0.25 meters, this corresponds for an 80-kg subject to a jump force of 1280N. The total feasible acceleration is therefore 16 m/sec$^($2), which means that in a jump on Earth about 60% of the effort goes into resisting gravity, and about 40% of the muscular effort is available to accelerate the subject's body upwards.

The same physics, assuming constant jump force across environments, leads to the following scaling equation

$$\frac{v_j'}{v_j} = \frac{F_j - mg'}{F_j - mg} \tag{44}$$

Table 2 summarizes the results from this analysis, compared to the more simplistic analysis assuming constant jump velocity/constant energy. It should be noted that the column showing the ratio of jump speeds indicate that this analysis predicts an increase of a factor of 2 (for Mars) or 2.5 (for the Moon); the jump height is proportional to the square of these ratios. Thus, the new prediction for jumping ability on the Moon betters the previous prediction by a factor of more than 5. Clearly, the graphic artists creating images of lunar Olympics are on to something!

Table 2. Summary of estimates for jump height on various exploration targets

Location	Simple analysis jump height (m)	% muscle effort available for jump	$\frac{v_j'}{v_j}$	v_j (m/sec)	Advanced analysis jump height (m)
Earth	0.5	38	1	3.13	0.5
Mars	1.4	77	1.97	6.17	5.1
Moon	3.1	90	2.32	7.25	16.7

On a more critical note, this analysis is at least as suspect as the simpler approaches. Force exertion in a jump does not demonstrate constant force, and there is no data on how force profiles would differ in partial gravity. It is also unclear if the human musculoskeletal system would be capable of moving at the 7+ m/sec lift-off speed predicted; a full-blown biomechanics analysis would be an appropriate next step. Almost certainly, the true value of human jump capability is bounded by these two sets of estimates.

However, the point which may have been lost here is that any of these estimates would produce a floor-ceiling height that would greatly increase the habitat mass for a given living area. Even sticking to the simpler, more conservative jump analysis, an alternative way to consider this issue is based on inadvertent contact with the ceiling. An average 6 ft. male on Earth would have to jump 0.6 m to hit his head on the ceiling, or a jump of 120% of the assumed maximum effort jump on Earth; this ensures that inadvertent contact will never take place. For the same person and ceiling height in a planetary habitat, a 45% effort jump will result in ceiling contact with the head on Mars; the same contact on the Moon would require only a 20% effort jump. While some muscular deconditioning will occur with time on site (as well as with prolonged microgravity en route to destinations such as Mars), it would appear that lunar habitats (at least) need significantly higher ceilings... or that astronauts in a lunar habitat should consider wearing helmets at all times.

We could address this issue by scaling ceiling heights to limit head contact to a maximum effort jump; this would would require a 3.2 m (10.3 ft) ceiling for a Mars habitat, and a 5 m (16.3 ft) ceiling for a lunar habitat. While some compromise for a Mars habitat (say, to a 9 ft or 2.7 m ceiling height) would be a reasonable compromise, the lunar limit would require doubling the ceiling heights compared to conventional architecture. Storage or access on the wall above a standing reach limit would be restricted and inefficient; habitat mass would increase dramatically due to a doubling of pressurized volume without increase in usable floor area. Interdeck access would also be more complicated as the distance between decks increases. The answer will probably wind up as advising the habitat crew to "be careful" – and perhaps padding the overhead in recognition that inadvertent contact *is* going to occur in the course of everyday life in a lunar habitat.

Interestingly enough, the argument on optimum ceiling height for a microgravity habitat will focus on less height, rather than more. Partial gravity habitats on the Moon or Mars will have crew moving from place to place using various gaits, which each have unique ground reaction forces pushing upwards on the human while moving. In microgravity, the crew "glides" in straight-line trajectories from place to place, based on pushing off at the start point and applying gentle corrections by touching fixed surfaces along the way. Having a ceiling height low enough to touch allows the use of the ceiling for mid-course corrections. When stopped at a work site, touching the ceiling with one hand at the same time as touching the floor with the feet allows three-point contact, which is the most stable method of reacting external forces into the contacts without affecting body position, short of ingressing a foot restraint or other body restraint device. Large open volumes, such as the orbital workshop section of Skylab, were much loved by the crew for recreational exploration of microgravity gymnastics, but could only be traversed in straight-line trajectories until a wall or other fixed hardware came within reach at arrival.

E. Exterior Access

One of the most precious parameters in habitat design is wall area. External surfaces are required for windows, mounting internal and external equipment, hatches, suitports, docking interfaces, scientific airlocks, and other components requiring physical proximity to the pressurize shell. While the entire external surface is potentially available for microgravity habitats, exterior access for many purposes in macrogravity is related to the local orientation and position. Suitports, airlocks, and docking interfaces are all typically at the lower end of the habitat, so that the change in altitude while accessing the local surface is minimized. In fact, the functionality of most of these exterior access ports on a planetary surface precludes "stacking" them vertically, and the metric for usable external access regions of the habitat hull becomes the linear measure of external wall at the ground level. For a vertically oriented cylinder, this surface access perimeter is

$$L_{surf,V} = \pi d \tag{45}$$

In comparison, a horizontally oriented cylinder has the entire length of the cylinder walls on each side, as well as the surface length around the ellipsoidal endcaps, for potential siting of external access hardware. The corresponding maximum surface access perimeter for horizontal cylinders is

$$L_{surf,H} \approx 2(d + \ell) = 2d(\lambda + 1) \tag{46}$$

although this presumes that the centerline of the habitat is in contact with the lunar surface. Obviously for larger habitats resting on the surface without entrenching, the available perimeter at surface level is considerably reduced.

Both of these equations hold regardless of the number of internal floors the habitat contains. In many respects, the most "valuable" real estate in a planetary surface habitat is the surface-level floor, which controls the number and type of exterior access paths which are available. Except for very low ℓ/d values, a horizontal cylinder is superior to a vertical cylindrical habitat in terms of exterior access options.

F. Interior Access

Another area of greater importance to macrogravity than microgravity is moving between vertical levels in the habitat. In microgravity, the only issue is ensuring physical clearance for the crew to move through the open volume, irrespective of relative positions. With a noticeable gravity level, work has to be done to supply the necessary potential energy to go "upstairs", and access equipment (stairs, ladders, or elevators) have to be provided to help, particularly when heavy equipment or storage items have to be transported between floors.

The standard for moving between floors on Earth is the stairway, where the user takes steps with width of w_s and an individual height of h_s at a composite angle of ϕ. With a typical set of stairs on Earth, the designer will use a 40° rise angle with stair heights averaging 0.19 m (7.5 inches) and width of 0.75 m (30 inches). The horizontal length of the complete stairway –that is, the length of floor space taken up by the stairway itself – is therefore

$$\ell_s = \frac{h}{\tan\phi} \tag{47}$$

Since the person's head is gaining altitude throughout the walk up the stairs, typically the upper-level deck area above the stairs is removed for head clearance, resulting in a loss of deck area of $w_s\ell_s$ on each floor connected by the stairway. Using the Earth values for a stairway, the upper level deck loses a rectangular area 2.9 m × 0.75 m, or a total area of 2.2 m^2. The same deck area is lost on the lower deck to the stairway itself, although there are possibilities for the use of volume under the stairs for stowage or fixed equipment. In a 5 m diameter vertically oriented cylinder, the two decks have a total area of 19.6 m^2 each, so the stairway represents an 11% loss in useful floor space and a corresponding loss in potential habitable volume.

There is also a question as to the optimal design of stairways in reduced gravity situations. A typical ascent rate for the Earth-based stairs is two steps/second, which corresponds to a vertical velocity of 0.356 m/sec. The power required to walk up the stairs can be found by

$$P_{stairs} = \frac{mgh}{t} = mgv_{vert} \tag{48}$$

or 278W for the average 80 kg human. In reduced gravity, an equivalent climbing power level would result in a faster climbing rate, or

$$v'_{vert} = v_{vert}\frac{g}{g'} \tag{49}$$

Referring to the analysis in the section on ceiling height, the same stair-climbing power on Mars as used on Earth would result in a vertical velocity of 0.97 m/sec, and a "loft" of 0.13 m – in other words, the Mars climbing velocity is sufficient to cause the foot used to step upwards to float upwards off of the departing step almost to the next step. The equivalent values for the Moon are v_{vert}=2.2 m/sec and an upwards "float" of 1.6 meters with each step - in other words, astronauts on the moon should need to take only two steps on a standard 2.4 m high staircase! Clearly, the different reduced gravity levels will demand different solutions in stair angle and step height for the particular destination, but this research has not yet been performed.

A macrogravity alternative to the staircase is the vertical ladder. This has the advantage that the deck area devoted to ladder operations is only about 1 m^2 on each end, although transitioning on and off of a ladder at the top end is more fraught with potential disaster (particularly in Earth gravity) than starting down a staircase. The issue above on step height also pertains to distance between rungs, typically 0.3 m (12 inches) on Earth. The SSL performed a series of ballasted underwater reduced gravity experiments investigating ladder designs at lunar gravity, and came to the conclusion (independently from the analysis above) that the most practical way to move between decks on the Moon was a single intermediate platform to reduce the problem to two hops, each of about 1.2 meters.

One last design issue for ladders is the location internal to the habitat. For vertically oriented cylinders, the default locations tend to be the center axis of the cylinder, or along one wall. While the discussion above on the value of wall access still holds, experience with center-access stairways in simulators such as the NASA Habitat Demonstration Unit (HDU) clearly demonstrate that the center of the habitat is also a high-value area, and a central ladder or stairway (or elevator, as in the HDU) is an impediment to access and cross-habitat access on both levels.

G. Ergonomics and Layout

From the standpoint of the ergonomics of habitat layout, a critical issue is human body pose and required dimensions around each activity site. In full gravity, humans stand erect, sit, or lie down depending on their activity. Although there is no focused experimental evidence to confirm it, basic biomechanics would indicate that the same poses would be used at the reduced gravity levels of Mars and the Moon. On the other hand, it is well established[5] that humans in microgravity adopt a standard neutral body posture (Figure 14) which represents the lowest-energy equilibrium state of muscles evolved and routinely used to standing erect in full gravity.

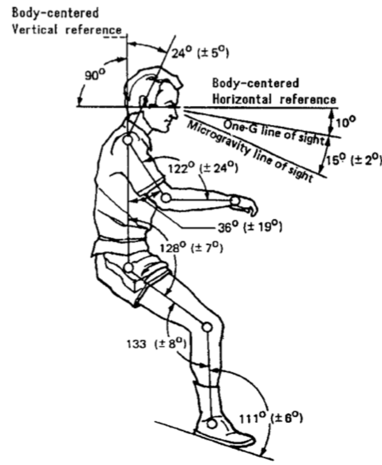

Figure 14. Human neutral body posture in microgravity[5]

One approach to understanding the differences between microgravity and macrogravity habitats would be to develop models of human space requirements for each task performed, and "stack" the resultant volumes in a somewhat optimal manner to arrive at internal layouts for both cases. For example, a sleeping compartment in macrogravity must have sufficient area perpendicular to the gravity vector to allow the occupant to lie down for sleeping. In microgravity, the occupant might be either floating in a NBP or restrained into an upright posture, but there is no preferred orientation in reference to the rest of the habitat. This is evident in the fact that most microgravity habitats (e.g., Skylab and International Space Station) have crew "bunks" in a "standing" orientation with respect to the preferred orientation of the rest of the habitat. Since the sleeping quarters must fill the "standing" head height of the rest of the habitat module, orienting the sleeper to be "standing" takes care of the problem easily. The alternative solution, required for macrogravity habitats, would be to use stacked sleeping quarters (i.e., "bunk beds") to fill the necessary vertical space efficiently.

At the start of this study, the intent was to define a series of volumetric shapes, representing the exclusion zone for the human body in various poses (standing, seated, lying down, NBP) and look at geometric concatenation of the various volumes to create a habitat interior which fulfills all mission objectives with the minimum overall volume. While this certainly could be done, a survey of several thousand photographs from International Space Station demonstrated that it would be an academic exercise of limited utility in real-world habitat design. This is because of the flexibility of the human body in microgravity, and the numerous instances of ISS operations when the astronaut is in what appears to be a highly contorted pose, generally to find the most favorable set of foot restraints to react forces and torques during the designated tasks. Looking through all posted NASA photos for the last six ISS crews, the number of times in which an astronaut was performing a task in the canonical NBP (as in Figure 14) was vanishingly small.

Given the prior analysis in this document, and the intent to hold to the principle that microgravity habitats should have a single enforced orientation direction throughout each module, if not the entire habitat, it seems clear that there are more minor differences between microgravity and macrogravity habitats than major ones. Macrogravity habitats differentiate between seated and standing interfaces; in microgravity the only relaxed pose is the neutral body posture, and planned microgravity work stations are best based on that, even if experience indicates that astronauts in microgravity easily adapt to working in a variety of orientations and poses. Macrogravity systems can rely upon gravity to allow multipurpose work surfaces (tables, desks) for multiuse applications (food preparation, report preparation, recreational computer usage), whereas microgravity systems must require installed systems (or at least the availability of restraints) to prevent the loss of constituent components. When performing a major repair task on Earth, assemblies and subassemblies are frequently removed from the installation to a workbench or other horizontal surface, where the person performing the repair can work on the hardware in a more comfortable situation. In microgravity, the human operator is more comfortable in complex poses without gravitational loads, and it may often prove easier to perform maintenance work in place. On Skylab, the largest issue in unplanned maintenance was safely collecting noncaptive fasteners; some of the Skylab crew took such items to the large OWS air return filters so the air flow would entrain small particles and hold them against the filter screens in microgravity. While microgravity still presents a wide range of challenges for the designer raised in a gravity field, current experience from extensive ISS operations indicates that the crews are productive working from a range of poses and restraint conditions. From the ergonomics point of view, microgravity may release the designer from a rigid adherence to ideal body poses and work envelopes, simplifying the design process for crew interfaces as compared to macrogravity habitats.

IV. Earth-based Simulation Issues

Given the preceding discussions, modeling, and analysis, we reach the conclusion that the differences between macrogravity and microgravity habitats are primarily in crew mobility and restraint, rather than in gross details of equipment layout or volumetric allocations. Microgravity habitat layouts *need not* be similar to macrogravity habitats, but (especially with a mandated enforcement of a fixed reference direction throughout the habitat) can be functional if similar in layout at the same time. What is currently unclear is what the cost of the "fixed orientation" mandate is in habitat design, which is at a finer level than can be discerned from the present modeling exercise.

It should be emphasized that while this study is paying specific attention to methodologies for Earth-based simulation, it is not in the context of crew training. The U.S. has been flying crew trained almost exclusively in 1g to space and getting excellent results in microgravity operations; there is no citable data whether the positive results are due to training methodologies (such as neutral buoyancy, virtual reality, and haptic feedback devices) or to the adaptability of the crew complement, or some combination thereof. Instead, this paper is primarily concerned about test validity for habitat designers to be able to test their concepts, and have some reason to believe that a decision made based on Earth simulation methodologies will also be shown to be the correct decision when the habitat and its crew arrive in space.

While it would be beneficial to have a higher fidelity alternative to 1g simulation, there has been little analogue activity associated with microgravity habitats in Earth-based microgravity simulations. Parabolic flight is the most dynamically valid simulation medium on Earth, but is outrageously expensive ($250,000 per flight on a dedicated basis[6]) and frequently produces false results due to the requirement to chop all activities into 20-25 second intervals matching the parabolic flight profile. Virtual reality has been used to good effect in crew training and has been used at UMd and elsewhere for virtual "walk-throughs" of candidate habitat designs,[7] but lacking a CAVE or other immersive virtual environment that allows full-scale motion of the test subject through the simulation, is still more of a "video game" than a high-fidelity evaluative experience.

Based on the capabilities and limitation of the alternatives discussed above, there is a real place to be filled by neutral buoyancy simulation of habitat designs, both for microgravity and (through appropriate ballasting of body segments) partial gravity systems. The NEEMO tests have done some of this in terms of EVA operations, but the habitat itself is fixed in configuration, and there is no mechanism to simulate alternative gravitational accelerations inside the habitat. A water-filled habitat module, along with test subjects using full face masks for two-way communications, supplied with air via "hookah" umbilicals to remove the bulk and dynamic inaccuracies of a back-mounted scuba tank, can allow a realistic simulation of human motion throughout the habitat, body restraints at representative work sites, and assessment of gravitation-specific accommodations such as ladders, access hatches, and ceiling heights. An underwater habitat will not provide long-term simulation support; it will not be amenable to multiday continuous simulations, allowing the crew to take breaks to eat, or even interact with functional equipment without some specific hardware development activities. Viscous forces will reduce the fidelity of the observed dynamics, although past work in modeling human body hydrodynamics in the SSL has provided a methodology for maximizing simulation fidelity.[8] Even with its limitations, however, neutral buoyancy simulation would be far superior in those tasks to which the environment *is* well suited as compared to simply doing everything in Earth's gravity.

V. Conclusions

When developing the control panel for the Apollo Telescope Mount in Skylab, engineers set up exactly what worked best in 1g: a large desk at the proper height for a standard chair, and verified that it worked well in ground-based testing and crew training. Once on orbit, the crew discovered that the human body could not assume a seated position for long hours in microgravity without significant pain from lap belts and overstimulated stomach muscles, and that reaching controls at extreme limits in microgravity was far more complicated than getting up slightly from a seated position on Earth to extend their reach.[4] Since the design engineers had no opportunity to test their design in simulated microgravity, or even to experience the environment to get a more intuitive understanding of microgravity design, their final product proved to be inadequate to the demands of the mission.

This paper has attempted to define parameters based on simple physics, geometry, and biomechanics to quantify issues in space habitat design, with specific attention to issues where there are significant differences between full gravity (Earth), reduced gravity (the Moon and Mars), and microgravity (all other known human destinations within the planning horizon). The premise of this initial effort is to better understand the basic types of choices in habitat design, to examine if there are meaningful differences based on the specific gravitational environment under consideration, and try to determine how to validate and extend these models based solely on Earth analogue testing.

Acknowledgements

The author would like to thank the students of the Space Systems Laboratory for their hard work on all of the SSL research programs referred to here specifically or implicitly. I would also like to thank numerous productive interactions with members of the NASA Habitat team over the past years, for sustaining student interest in habitat design and for creating a community that reaches out to academia and industry beyond their own experimental efforts.

References

[1]J. T. Celentano, D. Amorelli, and G. G. Freeman, "Establishing a Habitability Index for Space Stations and Planetary Bases", AIAA 1963-139, *AIAA/ASMA Manned Space Laboratory Conference*, Los Angeles, California, May 1963.

[2]Marc M. Cohen, "Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume" SAE 2008-01-2027, *38th International Conference on Environmental Systems*, July 2008.

[3]Wilie Heineman, "Design Mass Properties II: Mass Estimating and Forecasting for Aerospace Vehicles Based on Historical Data" NASA JSC-26098, November 1994.

[4]Henry S. F. Cooper, *A House in Space* Harper-Collins, 1978.

[5]Keith H. Miller, ed., "Man-Systems Integration Standard" NASA-STD-3000, Rev. B – July 1995.

[6]Zero G corporation; accessed at http://www.gozerog.com/ on May 25, 2012

[7]David L. Akin, Massimiliano Di Capua, Adam D. Mirvis, Omar W. Medina, William Cannan, and Kevin Davis, "Minimum Functionality Lunar Habitation Element", Final Report for NASA Grant NNJ08TA89C, University of Maryland Space Systems Laboratory, July, 2009.

[8]M.L. Bowden and D.L. Akin, "Underwater Simulation of Human Dynamics and Productivities in Extra-Vehicular Assembly" IAF 79-109, *XXVIII Congress of the International Astronautical Federation*, Munich, Germany, September 1979

Appendix – Past Habitat Study Data

Name of Habitat	Source Document	Overall Mass (kg)	Overall Volume (m^3)	Crew Size	Mission Duration (days)
Lunar Surface Emergency Shelter	NASA-CR-195551	10,000	8.56	4	5
Concept 1	AIAA 2009-823: Lunar Surface Base Architecture Mass and Cost Comparison Results	7,596	15.53	3	14
Pressured Lunar Rover	NASA-CR-192034	6,197	49.5	4	14
Pressured Lunar Rover	NASA-CR-192033	7,015	125.7	4	14
Scaled Apollo	Scaled Apollo Command Module Mass Estimate	14,965	25	4	21
Orion Zero Base Vehicle	Scaled Apollo Command Module Mass Estimate	17,535	40	4	21
MOLAB	http://www.astronautix.com/craftfam/lunbases.htm	3810	12.8	2	21
Concept 2	AIAA 2009-823: Lunar Surface Base Architecture Mass and Cost Comparison Results	11,790	26.13	3	30
Concept 1	(NASA-TM-104114) Concepts for Manned Lunar Habitats	17,060	162.07	4	30
Concept 2	(NASA-TM-104114) Concepts for Manned Lunar Habitats	24,510	273.68	4	30
Concept 3	(NASA-TM-104114) Concepts for Manned Lunar Habitats	8,608	131.31	4	30
First Lunar Outpost	First Lunar Outpost Report (Puerto Rico Doc)	No Data	446.6	4	45
First Lunar Outpost	AIAA 93-4134: A System Overview of the First Lunar Outpost	29,986	337.5	4	45
LESA	http://www.astronautix.com/craftfam/lunbases.htm	9,700	80	6	90
Habot	Mobile Lunar and Planetary Bases	10,000	98	4	100
Concept 3	AIAA 2009-823: Lunar Surface Base Architecture Mass and Cost Comparison Results	22,313	38.07	3	180
Horizontal Hard Shell Habitat	Constellation Architecture Team-Lunar Habitation Concepts	14,376	234	4	180
Inflatable Habitat Concept	Constellation Architecture Team-Lunar Habitation Concepts	13,867	426	4	180
Hard Shell "Core Habitat"	Constellation Architecture Team-Lunar Habitation Concepts	13,332	220	4	180
Concept 4	AIAA 2009-823: Lunar Surface Base Architecture Mass and Cost Comparison Results	34,974	90.56	3	365
DLB Lunar Base	http://www.astronautix.com/craftfam/lunbases.htm	52,000	662	9	365
Habitat Module	Project LEAP	No Data	445	6	Indef
Lunar Surface Base Shelter	Lunar Base Synthesis Study (Volume III)	59,460	1,200	12	Indef
Standard Habitat Unit	A Habitat Concept for the MOONBASE-2015, H.H.Koelle	60,000	1,965	24	Indef
Lunex: Lunar Expedition	http://www.astronautix.com/craftfam/lunbases.htm	61,000	No Data	3	No Data
Horizon Lunar Outpost	http://www.astronautix.com/craftfam/lunbases.htm	22,000	No Data	21	No Data