

Lunar Architecture Team - Phase 2 Habitat Volume Estimation:
“Caution When Using Analogs”

Marianne Rudisill, Ph.D.
NASA Langley Research Center, Hampton, VA 23681
marianne.rudisill-1@nasa.gov

Robert Howard, Ph.D.
NASA Johnson Space Center, Houston, TX 77058
robert.l.howard@nasa.gov

Brand Griffin
Gray Research, Inc., 655 Discovery Drive NW, Huntsville, AL 35806
Brand.Griffin@gray-research.com

Jennifer Green
Casitair Consulting, 28870 US Hwy 19N, Suite 341, Clearwater, FL 33761
jgreen@casitair.com

Larry Toups
NASA Johnson Space Center, Houston, TX 77058
Larry.toups-1@nasa.gov

Kriss Kennedy
NASA Johnson Space Center, Houston, TX 77058
Kriss.j.kennedy@nasa.gov

Abstract

The lunar surface habitat will serve as the astronauts’ “home on the moon,” providing a pressurized facility for all crew living functions and serving as the primary location for a number of crew work functions. Adequate volume is required for each of these functions in addition to that devoted to housing the habitat systems and crew consumables. The time constraints of the LAT-2 schedule precluded the Habitation Team from conducting a complete “bottoms-up” design of a lunar surface habitation system from which to derive true volumetric requirements. The objective of this analysis was to quickly derive an estimated total pressurized volume and pressurized net habitable volume per crewmember for a lunar surface habitat, using a principled, methodical approach in the absence of a detailed design. Five “heuristic methods” were used: historical spacecraft volumes, human/spacecraft integration standards and design guidance, Earth-based analogs, parametric “sizing” tools, and conceptual point designs. Estimates for total pressurized volume, total habitable volume, and volume per crewmember were derived using these methods. All methods were found to provide some basis for volume estimates, but values were highly variable across a wide range, with no obvious convergence of values. Best current assumptions for required crew volume were provided as a range. Results of these analyses and future work are discussed.

Introduction

The lunar surface habitat will serve as the astronauts' "home on the moon," providing volume for all crew living functions, including galley/wardroom, sleep and hygiene accommodations, radiation protection, and stowage. The habitat will also serve as the location for a number of crew work functions, such as science laboratories, crew medical care & exercise, mission operations, communications with Earth, maintenance, and Extravehicular Activity (EVA), including airlocks. Adequate volume is required for each of these functions in addition to that devoted to housing the habitat systems, such as Environmental Control & Life Support, Avionics, and Power Management & Distribution.

All of these functions must be accommodated efficiently within the volume provided in the lunar surface habitation system. A complicating factor is lunar gravity; for the first time, astronauts will be living and working for long durations, not in microgravity, but in a gravity environment different from that on Earth. At present, there is no experience base from which to draw habitat volume requirements guidance (Apollo missions, our only lunar mission experience, were typically of only 3-4 days' duration on the lunar surface; present plans are for mission durations from seven days' to 180 days' duration) and there is no direct Earth-based analog environment.

During the Lunar Architecture Team (LAT)-Phase 2, a number of methods were used to estimate the volume required to support these habitation functions independent of a specific habitat design approach. Ultimately, volume values would be derived from a methodical assessment of dimensions required for crew to carry out habitat functions, such as donning/doffing EVA suits, performing lunar sample analysis, and conducting mission operations. However, the time constraints of the LAT-2 schedule precluded the Habitation Team from conducting a complete "bottoms-up" design of a lunar surface habitation system from which to derive true volumetric values. As a starting point in this analysis, the team identified a number of "heuristic methods" to perform rapid analyses of volume requirements.

Objective

The objective of this analysis was to quickly derive an estimated total pressurized volume and pressurized net habitable volume per crewmember for a lunar surface habitat, using a principled, methodical approach in the absence of a detailed "bottoms-up" design. Guiding parameters for the analysis were: four crew, lunar polar habitat, and mission durations from seven days increasing to a maximum of 180 days.

Habitation Volume Definitions

The space habitation community uses a series of terms to define types of spacecraft pressurized volumes. A primary concept is "net habitable volume," the generally accepted "usable spacecraft volume" after subsystems, stowage, outfitting, etc. have been accommodated and design inefficiencies are considered (traditionally, "net habitable volume" has equaled ~60% of total pressurized volume). These terms are used throughout this paper and their conceptual relationships are shown in Figure 1.

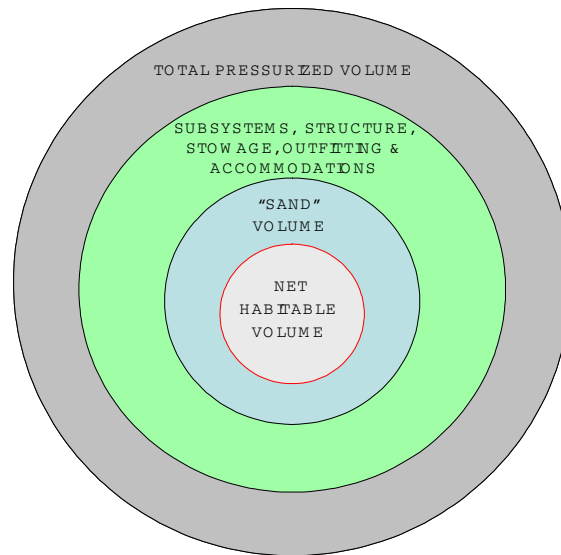


Figure 1. Spacecraft pressurized volumes conceptual relationships.

Method

Five primary “heuristic methods” were identified to perform rapid analyses of lunar habitat pressurized volume requirements based on a number of estimates:

- Historical spacecraft volumes (including both US and Russian vehicles)
- Human/spacecraft integration standards and design guidance
- Common functions in Earth-based analogs
- Parametric “sizing” tools
- Conceptual point designs

These five methods were used to generate first estimates of required lunar surface habitat volumes. It must be noted that all methods were found to have advantages and disadvantages, but they collectively provided information to determine a range of target volumes, bounding the space for lunar habitat design.

Historical spacecraft volumes

Dimension and volumetric data from past and present spacecraft (both US and Russian vehicles) were gathered and evaluated. Spacecraft vary across a number of parameters relevant to volume estimation, such as era of development, crew size, and mission duration. In addition, all spacecraft operate in a microgravity environment (other than the Apollo Lunar Module, the only vehicle for which we have crew operations data from the lunar surface, albeit for very short durations, on the order of three to four days), while we were deriving estimates for a 1/6th g environment. However, gathering and comparing spacecraft provided a broad view of volumes of built and operated vehicles.

We identified another relevant factor: mission “type.” That is, all spacecraft evaluated were found to group into either of two categories, “*transportation-like*” or “*station-like*”; understandably, vehicles used primarily to “ferry” crews to a destination serve a rather different function from those designed primarily for long-duration crew operations. This grouping of vehicle “type” can be seen in Figure 2, showing total pressurized volume as a

function of mission duration (note that the predicted maximum lunar outpost mission duration of 180 days is indicated on the X axis as a reference).

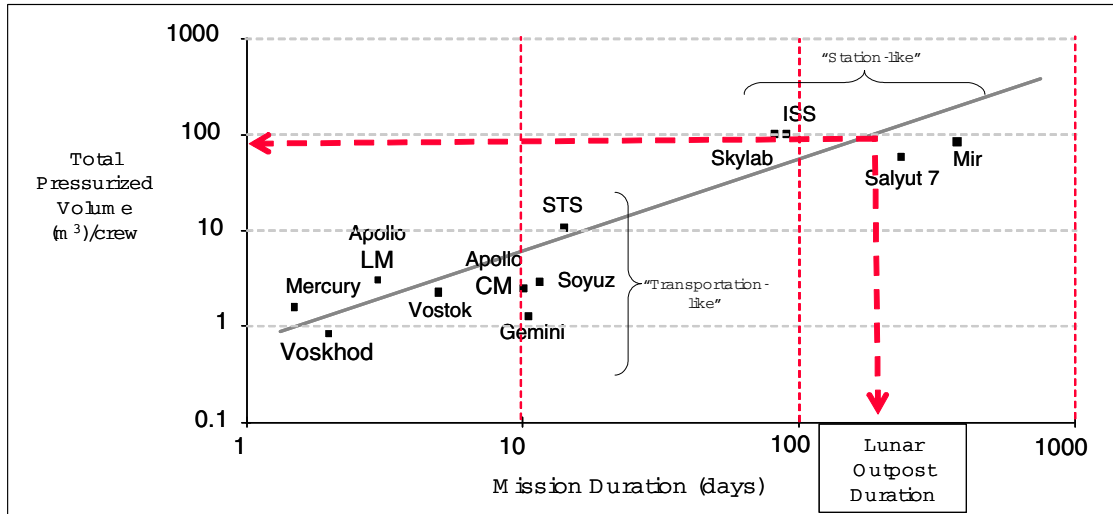


Figure 2. Total pressurized volume for “transportation-like” and “station-like” spacecraft as a function of mission duration.

Given that we were estimating volume required for a lunar surface habitat serving as an “outpost,” we focused our assessment on “station-like” spacecraft, given the long-duration nature of these missions. A summary of spacecraft volumes for “station-like” spacecraft is given in Table 1.

VEHICLE	ERA	# OF CREW	DURATIONs	TOTAL PRESSURIZED VOL (m ³) ¹	VOL PER CREW (m ³)	PRESSURIZED VOL /CREW @ MAX CONFIG (m ³) ²	ESTIMATED TOTAL PRESSURIZED VOLUME REQUIRED (Crew = 4) (m ³)
SKYLAB	1973	3	28 - 84	361	120	120	480
SALYUT	1970's - 1980's	2 - 3	17 - 237	90	30 - 45	30	120
MIR	1980's - 1990's	2 - 3	73 - 365	90 - 380*	43 - 157	127	508
ISS	2000 - present	2 - 3	128 - 195	221 - 425*	74 - 213	142	568

¹Total Pressurized Volume depends upon stage of construction from early to final configuration

²Based on crew = 3 at final configuration

Mean Pressurized Volume /Crew at Maximum Configuration = 105 m³ (per Crew = 26 m³)

Mean Pressurized Volume /Crew at Maximum Configuration (minus Skylab) = 99.7 m³ (per Crew = 25 m³)

Mean Estimated Total Pressurized Volume Required = 419 m³ (per Crew = 105 m³)

Table 1. Summary of “station-like” spacecraft pressurized volumes and estimated pressurized volume required for a lunar surface habitat.

From these data, total pressurized volumes, volume per crew member, and pressurized volume/crewmember at the maximum configuration (given that these spacecraft were typically built from multiple elements over time and were occupied by crews during their construction) were derived for each vehicle. From these values, estimated total pressurized volumes required for a crew of four were derived and were found to range from a maximum of 568 m³ (International Space Station, ISS) to 120 m³ (Salyut).

Human / Spacecraft Integration Standards & Design Guidance

We also estimated required pressurized volume from existing human/spacecraft integration standards and design guidance. A number of documents were consulted, including:

- NASA-STD-3000, *Man-Systems Integration Standards*, Rev. B
- SSP 50005: *International Space Station Flight Crew Integration Standards*
- NASA/TM-2003-210785, *Guidelines & Capabilities for Designing Human Missions*
- CxP 70024: *Constellation Program Human-Systems Integration Requirements*
- MIL-STD-1472F (1999) *DoD Design Criteria Standard: Human Engineering*
- *Handbook of Human Factors & Ergonomics*
- *Human Spaceflight: Mission Analysis and Design*

All of the references provide guidance on designing interior spaces of manned spacecraft (and, in some cases, lunar surface bases). Detailed standards are provided for the design of such interior elements as hatches, windows, lighting, and crew workspaces. However, there was no guidance specifically with regard to sizing pressurized volume. In the primary reference, NASA-STD-3000, the total guidance for estimating habitable volume per crewmember is derived from an original study (Celentano, Amorelli, & Freeman, 1963) in which the authors developed a “habitability index” based upon data from a series of simulated living conditions, summarized in Table 2.

Condition	Living Volume (ft ³)	Living Space (ft ²)	Living Space/Subject (ft ²)	# of Subjects	Test Duration	Performance Levels
Cabin A	200	39	13	3	7	Tolerable
Cabin B	1500	150	37	4	7	Performance
Cabin C	1600	400	200	2	4	Optimal

Table 2. Summary of Celentano, Amorelli, & Freeman, 1963 test conditions.

From data obtained from a total of 18 subjects performing in simulated conditions for a maximum duration of seven days, the authors extrapolated *habitable volume* required for mission durations of 12 months for three “performance levels”; these extrapolated curves are shown in Figure 3.

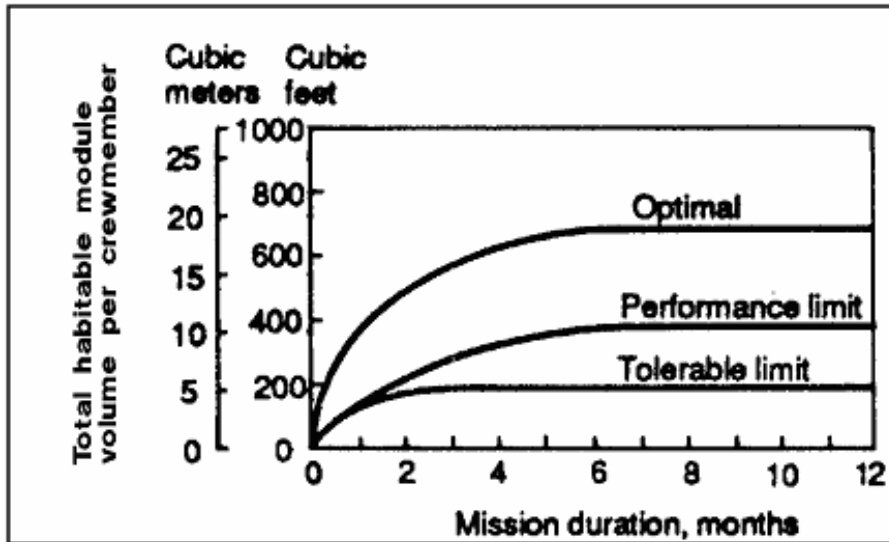


Figure 3. Habitable volume per crewmember as a function of mission duration & performance level. (NASA-STD-3000, 1995, Figure 8.6.2.1-1, from Celentano, Amorelli, & Freeman, 1963).

Although it was felt that the utility of these data was somewhat questionable, given that they were based on (1) a very small subject pool, (2) under limited simulated conditions, (3) with extrapolations to 12 months drawn from seven days of testing, the team decided to use this guidance to estimate *habitable* volumes for a lunar outpost 180-day crew mission for the three performance conditions as a data point for comparison with other methods; these estimates are summarized in Table 3.

180-DAY LUNAR SURFACE STAY				
MSSIS STANDARD	HABITABLE PRESSURIZED VOL /CREW m ³	TOTAL HABITABLE VOLUME ¹ m ³	PRESSURIZED VOLUME / CREW ² m ³	TOTAL PRESSURIZED VOLUME ³ m ³
Tolerable	~6	~24	~10	~40
Performance	~11	~44	~18	~72
Optimal	~19	~76	~32	~128

¹Based on Crew = 4
²Based on Habitable Volume ~ .6 (Pressurized Volume)
³Based on Crew = 4

Table 3. Habitable volume for tolerable, performance, and optimal conditions, derived from Celentano, Amorelli, and Freeman, 1963.

Common functions in Earth-based analogs

Common functions in a number of Earth-based analog environments were evaluated for guidance on volume requirements in a lunar outpost. Example analogs examined included undersea habitats (including Conshelf, Sealab, Hydrolab, Tektite, La Chalupa, and Aquarius), the National Science Foundation's Antarctic Research Station, the USN's nuclear submarines and research vessels, and earth exploration missions (as described in Stuster, 1996). Functions evaluated included habitation, systems maintenance, and mission operations that had some level of commonality with those that would be

performed by a lunar-based crew. Undersea habitat pressurized volumes were found to range from a minimum of 23 m³ (Hydrolab, 1-14 days' duration) to a maximum of 255 m³ (Helgoland, 7-14 days' duration).

Particular attention was given to Aquarius, NOAA's undersea habitat that NASA presently uses as a lunar analog via the NEEMO ("NASA Extreme Environment Mission Operations") Project. Aquarius is representative of a lunar surface habitat in size (~3 m diameter x 14 m long), in construction (hard shell cylinder), in crew size (research crew of four, with two maintenance crew), in crew facilities (including workstations, galley/wardroom, crew bunks, waste management, and personal hygiene), in operations (e.g., daily excursions similar to lunar surface EVA, tests of remote medical operations), and in minimum mission durations (typically 14 days). The Aquarius has three habitation compartments providing a total of ~74 m³ of habitable living and working space (Wet Porch = 20 m³; Entry Lock = 14 m³, Main Lock = 40 m³ volume).

However, there are some notable differences between Aquarius and a lunar base that need to be considered when using this undersea habitat as an analog. Some of these differences are:

- **Life Support:** On Aquarius, the life support system is encased in a buoy at the surface, rather than integrated into the habitat.
- **Crew Provisioning:** Given the nearby location of the support facility, Aquarius crews are supplied with provisions daily; thus, there is little volume devoted to stowage in the undersea facility. This is quite different from the logistics system on a lunar base and potentially significant volumes associated with stowage and handling of provisions may be required.
- **Crew Health Care:** Given that the support facility is nearby, a crew medical problem can be handled rather directly (although bringing a crewmember to the surface is not immediate because of decompression requirements). On a lunar outpost, there must be a portion of volume devoted specifically to a crew healthcare system. In addition, because of the nature of human deconditioning when not in 1 g, lunar crews will most likely need to exercise regularly (although how much exercise is required has not been determined, given the sparse lunar surface operations experience base).
- **Mission Control:** Primary mission control for Aquarius is at the surface base. On a lunar base, mission control will remain in Houston (as presently exists for the ISS, for example); however, given the distance between a lunar polar base and the Earth, it is expected that lunar crews will operate with some autonomy. In addition, one purpose for the lunar outpost is to permit NASA to simulate a Mars mission, which undoubtedly would operate with a high degree of autonomy. Therefore, it is expected that daily oversight of mission operations would migrate to the lunar outpost.

NASA has, thus far, fielded seven NEEMO missions to the Aquarius habitat, specifically to test potential lunar base systems and operations and to gain first hand knowledge of these types of operations. The mission durations have ranged from seven to 18 days. In addition, we have developed a habitation questionnaire to administer to NEEMO crews that will give us first hand information about living in the Aquarius facility to use in designing the lunar base and we trained the last NEEMO crew to take dimension measurements to enable us to build a detailed model of the Aquarius habitat. NASA plans to continue to use Aquarius as a lunar habitat analog and the potential is to eventually conduct NEEMO missions to be more similar to those planned for a lunar base; we will use the NEEMO information and that derived from other earth-based analogs to design the lunar base.

Parametric “sizing” tools

There is no parametric tool available that focuses specifically on determining spacecraft habitable volume requirements. However, there are a number of “tools” in varying stages of development that perform somewhat related sizing functions. We focused on three existing tools in this analysis:

- (1) *EXAMINE*: This Excel-based tool was developed primarily for spacecraft sizing and parametric analysis by D.R. Komar at the NASA Langley Research Center. A first step in extending the tool to include sizing of manned space vehicles and habitats was made during this study; detailed values for crew accommodations and provisions (with information provided by crew integration personnel at JSC) were integrated into the model, then functions were developed that allowed such information to be included in the analysis.
- (2) *HabEST*: Built by Analytical Mechanics Associates, Inc., this Excel-based tool instantiates the assumptions of the Celentano, *et al.* (1963) habitability index and relates the three performance levels to categories of crew provisions. Given this foundation for the tool, the values derived were identical to those from consideration of the design guidance in NASA-STD-3000 and this tool was not used further in this analysis.
- (3) *HabSizer*: Built by SpaceWorks Engineering, Inc., this parametric sizing tool is based on published and historical data for various spacecraft and subsystem designs. They modeled the crew surface habitation concepts in development (see next section) and performed a sizing analysis and independent assessment. The tool predicts outfitted mass, “sand volume,” and power required based upon crew functions and such factors as crew size, assumed number of EVAs, level of life support system closure, and mission duration. *HabSizer* estimated the following “sand volumes” to fulfill the listed crew functions:

- EVA, Maintenance, and Spares Stowage: 14.9 m³
- Sleep and Personal Hygiene: 8.7 m³

- Mission Operations, Galley, and Wardroom: 20.5 m³
- EVA, Science, Crew Health & Medical Operations: 18.3 m³

In the absence of a usable, validated habitat sizing tool, the habitat team developed an Excel-based “Master Equipment List” (MEL) tool for collecting and organizing masses and volumes associated with habitat concepts for LAT. In addition, the EXAMINE tool is presently being enhanced to explicitly perform such analyses as habitat subsystem estimation, sizing, and volume calculations for multiple habitat geometries and user-defined parameters. This tool is presently in final development and will be available for future lunar habitat studies.

Conceptual point designs

In addition to analyses using historical spacecraft data and lunar outpost analogs, a series of conceptual point designs were developed; some of these habitat concepts have been presented at this conference. These conceptual point designs were created to explore a large design/trade space and included consideration of such factors as:

- Number of habitat elements: one, two, three, five
- Habitat geometry: e.g., cylinder, torus, “tuna can”
- Mission durations: seven to 180 days
- Mission type: polar outpost, sortie
- Maximum mass for each habitat element: 6 mT to 18 mT (based on estimated lander downmass capability)
- Environmental Control & Life Support closure: Open, Partially Closed, Closed
- Cargo Handling Capability: multiple approaches
- Habitat Mobility

To the greatest extent possible, a MEL was developed for each concept that detailed the masses and power requirements for all habitat systems, the EVA system (including airlocks/suitlocks), crew support facilities, and outfitting. In addition, estimates were made of crew consumables and associated stowage requirements. An example MEL summary table, detailing masses for each subsystem for three habitat elements, is given in Table 4.

The mass values for each subsystem were generated by subsystem experts, who developed supporting data to the component level. Unfortunately, a list of associated component volumes was incomplete at the time of this analysis and it was, therefore, not possible to estimate volumes required for habitat systems from MEL values. However, in ongoing concept development work, subsystem component *volume values* as well as

mass are being provided by subsystem experts, giving us our first detailed estimates of habitat subsystem volume requirements.

HABITAT SYSTEM	OUTPOST MASSES	HAB -1	LAB -1	HAB -2
Structures	6210	2204	2204	1802
Protection	798	331	233	233
Power	702	295	295	113
Thermal	510	243	222	45
Avionics	217	108	104	5
Life Support	3045	1278	1621	146
Airlock/Suitport	1200	600	600	N/A
Outfitting	1820	136	1260	424
30% Growth	4351	1558	1962	831
TOTALS	18854	6752	8501	3601

Table 4. Example MEL summary masses for three lunar surface habitat element subsystems.

Summary & Conclusions

Estimates for total pressurized volume, total habitable volume, and volume per crewmember were derived using five estimation methods. These five methods – historical spacecraft volumes, standards and design guidelines, Earth-based analogs, parametric sizing tools, and conceptual point designs – all provided some basis for volume estimates, but values were highly variable and varied across a wide range. The lowest estimated values were derived from standards and design guidance (19 m³/crewmember) and the largest estimated values were derived from “station-like” historical spacecraft (63 m³/crewmember). There was no obvious convergence of values and the best current assumptions for required crew volume (for four crew, 180 days) fall into the following ranges:

- Total Pressurized Volume = 160 to 280 m³
- Total Habitable Volume / Crewmember = 40 to 70 m³

Future Work

It must be noted that all spacecraft volumes were for microgravity-based operations and not the 1/6th g of the lunar surface; a more appropriate metric may be “*minimum floor space*” rather than a “*volume required.*” Future work will focus on this metric. In addition, the *Human-Systems Integration Standards* are presently being updated and will include more architectural design guidance in future versions. A “*NASA Human Integration Design Handbook*” is in preparation and it is also planned to include architectural design guidance. Work is continuing on assessing habitability within Earth-based analogs, in particular the Aquarius Undersea Laboratory through NASA’s NEEMO Project. Lunar habitat concepts will continue to be developed with more refined mass and volume values for subsystems, crew facilities, and accommodations, and 3D models are presently being constructed that allow more detailed understanding of space usage. A logistics and supportability model is in development that will refine our understanding of crew consumables, handling, and stowage requirements. And the first version of the Excel-based habitat parametric analysis and sizing tool is nearing completion and will be used in future habitat concept development work.

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