

Habitability in Advanced Space Mission Design, Part Two:
EVALUATION OF HABITATION ELEMENTS

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ABSTRACT

Habitability is a fundamental component of any long-duration human habitat. Due to the pressures on the crew and the criticality of their performance, this is particularly true of habitats or vehicles proposed for use in any human space mission of duration over 30 days. This paper, the second of three on this subject, will focus on evaluating all the vehicles currently under consideration for the Mars Design Reference Mission through application of metrics for habitability (proposed in a previous paper, see references Adams/McCurdy 1999).

INTRODUCTION

Since before the dawn of the Space Age, engineers, architects, writers and laypersons have conceived space stations and space vehicles. From the Tsiolkovsky's spinning wheel which so captured Von Braun's imagination to Kubrik and Clark's "Discovery" or the "Starship Enterprise", space habitats have pervaded the popular culture of this century and our imagination of centuries to come. The spaceships with which we are all familiar have this in common, though: they all project powerful images of comfortable if high-tech spaces in which astronauts live and work.

Today, as we sit on the brink of moving beyond Earth orbit, one of the more noteworthy aspects of current planning for a human exploration of Mars is the lack of attention given to such ideas—the necessity of supporting a productive human crew—by the teams of engineers, propulsion experts and planetary scientists who are working to develop the baseline plans for this mission. Both of the Mars Design Reference Mission (DRM) scenarios developed by NASA's Mars Exploration Team call for a single habitat to be used both for crew transfer to Mars and for habitation on Mars, imposing not only a negative impact in structural efficiency and mission safety but also significant habitability challenges. In order better to assess the relative viability of these scenarios and the elements on which they rely, we have undertaken in this paper the evaluation of these habitats using the habitability criteria defined in "Habitability as a Tier-One Criterion in Advanced Space Vehicle and Mission Design—Part One: Habitability" (Adams/McCurdy, SAE, 1999).

Developing mission scenarios, mass reduction, and alternative launch platforms are giving habitats new requirements, while new breakthroughs in materials and structural technology are offering broader flexibility of options for overall vehicle form. One example is the complex system introduced by the combination of load-bearing endoskeletal structures and inflatable structure technology; in the pioneering project of this type, the development of the ISS TransHab brings inflatable structures to the forefront of interplanetary transfer and opens up fresh, more usable possibilities for planetary habitats as well.

While the options currently on the table have been studied for their relative launch, propulsion, and resupply ratios as well as mission timelines, however, one major question remains unanswered: that of their viability as human habitats and work centers. Since the entire purpose of any element to be developed for a human exploration program is the support of a human crew, it is critical that any vehicle concepts to be considered for a reference mission be excluded from the list of options until it is evaluated for habitability (lest NASA proceed with development of a concept which subsequently proves to be inefficient or even detrimental in serving its prime function).

What, then, are the issues which can be addressed to help round out the admirable work already invested in the DRM? We will first summarize the general types of vehicle under consideration and their proposed application, then open our evaluation of each with a general description of the typological, volumetric and logistical issues involved in any mission of this type. At that point each vehicle identified will be evaluated and a summary of the findings presented.

HABITATS UNDER CONSIDERATION

In the history of U.S. or Russian Space Program activities, the principal structural type for any space or planetary habitat proposed or built has been of the hard-shell, exoskeletal category; with very few exceptions, this type has taken the form of a horizontally-loaded cylinder whose primary load is borne in its hard pressure-shell. Due to choices involving the use of the Space Shuttle as sole launch platform for such modules in the US Space program, a version of this type was developed for space station Freedom and the International Space Station which is some 14 feet [4.27m] in diameter and no more than 35 feet [10.67m] in length. This type has been envisioned also as an element of the DRM, in various configurations. The 90-day study of the HEDS initiative envisioned station-derived habitation elements fixed to a rotating disk. The BIO-Plex facility at NASA/JSC proposed the use of this module in a cluster parked horizontally on the Mars surface.

Other formal variations on the exoskeletal cylinder habitat have been proposed as well. In 1994, The NASA Exploration Team released a preliminary Mars Design Reference Mission which called for 3 vertical cylinders to be used as habitats. Commonly referred to as "tuna cans", these units are broader in diameter than the ISS-type modules, and shorter in the axial dimension—with the result that they require a super-booster launch platform, and are more stable to land on a planetary surface. In the aforementioned scenario, one "tuna can" brings the crew to Mars and houses the crew there during the full planetary stay. A second habitat used only on the surface of Mars provides a laboratory. The third habitat returns the crew to earth.

Of a totally different structural type is the complex, endoskeletal habitat represented by space inflatables similar to the TransHab. In an effort to develop inflatable structure

technology, NASA assigned a team of engineers to design an inflatable habitat to replace the hard-shell habitat module on the International Space Station. The habitat is designed to fit, uninflated, in the cargo bay of the space shuttle, to whose constraints only its endoskeletal, launch load-bearing core structures must respond. Independent of this constraint is the external, inflatable pressure-shell, a toroid shape which maximizes available volume once launched and deployed outside of the launch platform.

One virtue of this technology is the efficiency it offers in separating the considerations of launch configuration from those of microgravity deployment; another is the fact that this principle can be applied to develop habitats of varying shape and dimension which are better optimized for their intended function and are therefore important components of an efficient, cost-effective mission. The shape of an inflatable habitat for interplanetary transfer or for surface operations is free to vary so as to respond to the specific constraints and requirements of its function and its environment.

Thus far, however, only the TransHab has been developed sufficiently to qualify it for formal evaluation. For comparison to current designs, the toroid shape developed by the ISS TransHab team, 12.2m in length and 8.23m in outer diameter, was chosen for analysis in this study.

In sum, three habitation element types will be evaluated: the horizontal cylinder (station-derived), the vertical cylinder (DRM-derived), and the inflatable TransHab (TransHab project team).

QUALITIES TO BE EVALUATED

The primary issues involved in any mission of this type involve the question of whether the elements of the mission are appropriate to its goals. When efficiency is a major mission goal, then the degree of appropriateness required of each element is greater still. Since the mission under consideration is a long-duration human space mission, then it may be assumed that each element's primary goal is the support of its crew in performing their tasks; and, further, that any component of a mission (whether physical or programmatic) which does not contribute toward this goal must be considered completely unacceptable.

While Weaver and Duke and others have performed rigorous studies of the functional analysis of Mars mission components, these studies focus on stowage, fuels, overall mass and other logistical support. No metrics have existed thus far for human usability—or, "habitability"—nor have any such been applied to the vehicles under consideration.

Support of a human crew involves psychology as well as physiology: ergonomics, programming, orientation and other anthropometric principles are important guides to the physical form of a human habitat because they assist the crew in performing their duties with a minimum of effort and stress—and thus more successfully, for longer periods of time. This means that any function or activity implies specific dimensional or formal requirements whose purpose is enabling the crew to perform their functions. Thus, conformance with these requirements enables a habitation element to meet its prime requirement: mission support via crew support.

The fundamental qualities of any habitation element which impact its shape are: typology, volumetric requirements and scenario (or logistical context).

TPOLOGY

Typology can best be expressed as the study of the fundamental function or nature of any object. In design of objects, an efficient, expressive or well-defined object is one whose form expressly indicates its typology, in that it is physically optimized to perform its intended function in its intended environment. It is a general rule that typologically specific objects are the most efficient; that is, the more singular the intended goal of an object, the more likely it is that it can be designed or expressed simply, inexpensively and well. Multiple functions tend to generate typologically schizophrenic items (like the "spork" a '70s combination spoon and fork), and quickly deteriorates, as functions are added, into a typologically indeterminate and functionally useless object (like a contemporary of the "spork" which included in the combination the function of a knife, and which was known as the "spoonik"). A similar analogy may be made in comparing the usability and durability of a small, sharp knife and a Phillips screwdriver with those of a Swiss army knife; in the former case, each small item is well-designed for its purpose and may be used over and over again, while in the latter, none of the elements are particularly useful and the overall packaging is relatively bulky—just so that all may be immediately available in an emergency.

In short, the best object for each task is almost inevitably one which was specifically designed to perform that task under precisely the anticipated conditions, and no other. Typologically distinct elements are ones which inherently serve their singular purpose and no other. Over a long duration, these are unquestionably the most efficient. Thus, the first step to guaranteeing the efficiency and effectiveness of an effort is the rigorous definition of its typological nature. Good typology takes place at all scales, and was addressed in this study's predecessor in connection with habitability and the use of internal volumes. In this sense, it impacts the shape and size of any element which would be considered for either planetary or microgravity habitation; in the larger, more general sense, it also impacts the nature of each habitable element itself.

COMMONALITY VERSUS SPECIALIZATION / RATIONALE

In the Human Mars Reference Mission published in July 1997, the Mars NASA team introduced the idea of using a single habitat both for transferring the crew to Mars and for keeping the crew alive for the entire surface mission. Along with the dual-use habitat is the concept of standardizing all of the habitation elements used in the mission, including the surface-only laboratory habitat and the zero gravity earth return vehicle. The dual-use and commonality ideas continue to spark debate.

There is some debate concerning the virtues of multiple- versus single-task elements for such missions. Using the same habitat for Mars transfer and surface activities allows the crew to recover from the physiologically deleterious effects of zero gravity. The commonality in design eliminates design and manufacturing costs. However, the drawbacks of multifunctional (or typologically indistinct) elements are abundant. The use of a habitat in both zero gravity and partial gravity imposes human factors and technical challenges that in solving may exceed the cost of the design and manufacture of significantly different habitats. Humans require more ceiling space in gravity, whereas we desire a smaller volume in microgravity. A habitat that was used in a variable-gravity environment would require restraints for zero gravity and significantly

more structural mass and safe ceiling and wall stowage under the influence of a gravity field.

Thus it is clear that the most efficient, productive and reproducible elements of a Mars exploration mission are those which are specialized, optimally designed for a single primary purpose or environment; also, that the application of these to a mission scenario implies far less inherent risk than the use of multifunctional vehicles such as a transit/lander. The virtues of commonality need not be sacrificed in applying specialized elements; all elements should be engineered together for common interfaces and replacement units, even as each one is optimized for its function.

Fortunately, this debate has not yet been terminated. The Addendum to the Human Mars Reference Mission reveals the habitat issue in reading, "Study team members were not unanimous in the choice of a common habitat for space transit, for landing on the surface, and for surface habitation." The section concludes that, "[the common habitat design issue] is an area for further research."

VOLUMETRIC REQUIREMENTS

We demonstrated in the predecessor to this paper that good habitability for a long-duration crew implies certain objective physical or volumetric requirements of the vehicle or habitat, depending on its typology.

Based on the standards which we have established, we have set out to adapt a preliminary set of human-system metrics and apply them by evaluating each of the proposed Mars mission elements for usability as a habitable module.

EVALUATION STANDARDS

The habitation element types, described in detail below, were evaluated using standard total pressurized volume and subsystem mass, power, and volume for a crew of 6 with a 400 day total transit time and a 540 day stay on the surface of Mars. Using historical data, Kriss Kennedy of the Transhab team proposed that 90 m³/per person would be optimal for total pressurized volume. The exact dimensions of the Transhab element and transit only/surface only habitats were optimized for habitability to yield the 540 m³ of total pressurized volume. Kriss Kennedy and those who followed have developed the spreadsheet that scales by crew number, mission duration, and various subsystem options. The current sizer was used in this study to determine a standard mass, power, and volume for the habitation subsystems. These quantities will be used as a standard for evaluating the habitats.

HABITAT TYPES

- **Combo Lander**

The habitat for the Combo Lander scenario is projected to provide the crew with all of the necessities of living in space for transfer to Mars, the surface mission, and transfer back to earth. This concept involves a hard central core area with propulsion system and transfer vehicle built-in, a separate central hard-shell habitat for transit functions, and a deployable inflated outer ring to be used for habitability and science functions on the surface.

The lack of operational definition of most of these elements makes the Combo Lander concept very difficult to evaluate; in general, the proposed vehicle stands to

offer good volume in a surface application, but a very unequal amount of room for transit functions. Serious debate continues on whether this concept offers a truly viable and efficient solution to all of these requirements (it may also be said that this concept requires an architectural design study before many of these questions can actually be answered).

More details on the combo lander follow (see page 10).

- Design Reference Mission Vertical "Tuna Cans"

One habitat transfers the crew to Mars and houses the crew for the surface mission. A second habitat/laboratory supports the crew during the surface mission. The third habitat, the earth return vehicle, transfers the crew back to earth.

The habitats are 7.5 meters in diameter and 4.6 meters high with 2 elliptical end pieces. The internal volume is divided into two levels, each level being 7.5 meters in diameter and approximately 2.3 meters in height.

- a. Outbound/Surface

The outbound transit/surface habitat transports the crew from earth to Mars and houses the crew for their entire duration on the surface. This scenario requires the habitat to function (in terms of habitability and engineering) both in zero gravity and in 3/8 of earth's gravity field. The outbound transit and surface habitation requirements are met with one habitat to reduce risk to the crew by duplicating habitats on the surface and by allowing them more time to adapt to a gravity field. The study team detailed one internal arrangement option for feasibility and costing. In the proposed configuration, the top level includes the crew quarters, galley, wardroom, and hygiene area. The bottom level contains the airlock, suit room, body waste management system, exercise area, and medical health care facility. [Figures and Drawings from DRM?]

- b. Earth Return (zero gravity only)

The Earth-return transit-habitat only functions in zero gravity. The earth-return habitat has the same configuration as the outbound transit/surface habitat except that the earth-return habitat does not include stores of consumables used in the surface mission. Despite several significant operational differences, the study team configured the earth-return habitat identically to the outbound transit/surface habitat.

- c. Hab/Lab (3/8G only)

The surface laboratory/habitat (lab/hab) functions only in 0.38 of earth's gravity field. The lab/hab supports scientific research activities. The first level of the habitat contains a large stowage area where consumables are stored. The area can be used for other functions, such as plant growth experiments, when the space becomes available. The second level houses the laboratory equipment and research area. The lab/hab contains the primary airlock for extravehicular activities.

In general, the arguments in favor of using the "tuna can" components for multiple uses are their ability to support standardization, and (theoretically) a lower building cost due to the simplicity of the shell. However, the cost of testing and training for such a habitat

works against it, as well as the inefficiency and design waste inherent in any attempt to respond to such dissimilar habitability requirements and gravity fields. Also in disfavor is the necessity of accommodating at least three radically different sets of requirements for static and dynamic performance of structures; meeting all of these will inevitably require overdesign and redundant internal structures, as well as the related impact in increased mass and decreased pressurized volume.

LOGISTICS

The final issue inherent in any evaluation of a human exploration mission is the logistical scenario and the role each element is expected to play within the total picture.

Options:

- Discrete functions
- Universal connectivity/interchange
- Multiple-function craft

- Discrete Task Habitats

In this scenario, the crew uses one habitat for transfer to Mars and transfer back to Earth, while the second habitat houses the crew on the surface of Mars. The transfer habitat is only used in weightlessness and orbits Mars during the surface mission. The surface habitat is only used in the 0.38-G gravity field on the Martian surface.

1. Horizontal Cylinder Concept - International Space Station-derived
Not yet applied or tested in ground configuration—BIO-Plex will commence this process.

2. Vertical Cylinder Concept - Design Reference Mission Version 1 –

The first version of the Design Reference Mission calls for three types of habitation elements. The Mars Study Team contends that the standardization of the three habitats will be more cost-effective than designing markedly different habitats with simpler requirements. The standardized subsystems include primary and secondary structure, windows, hatches, docking mechanisms, airlock function, crew egress routes, safety features, power distribution systems, life support, environmental control, stowage, waste management, and communications.

3. Inflatable Transhab Concept - Addendum

The Addendum to the Human Exploration of Mars incorporates the inflatable Transhab-based habitat. Since spring 1997, the Transhab study team has been studying the use of inflatable structure technology. Improvements identified in the Addendum include improvements in the environmental life support system and structural improvements.

The Addendum proposes two scenarios. In the combination lander scenario, all hardware for the mission is launched in one opportunity. The outbound/surface habitat includes a Mars descent stage and ascent stage. The earth return habitat is launched at the same time as the crew. In the split mission scenario, the hardware is pre-deployed at Mars. The earth return habitat is sent to a parking orbit in Mars. These scenarios do not impact habitability since crew duration in each habitat element does not differ between scenarios.

- Separate-task habitats

This latter approach tends to focus on optimizing each habitat for its specific environment and function, rather than attempting to derive one unit which can support a healthy and productive crew in multiple extreme environments. The separate-task habitats may be of the same fundamental types as the multifunctional discrettes listed above, but tend to be lighter and are characterized as follows:

- **Multiple-function craft**
Because of various operational and logistical requirements, many mission scenarios include at least one multiple-function habitat. The principal version of this type discussed is the Outbound/Surface hab, which might be accommodated by any of the three basic shell types currently under consideration. This scenario is also the target mission for the new Combo Lander design.

Concerns about this concept focus primarily on the danger of a single-point failure in complex system; in addition, however, there may be issues of efficiency due to the need to provide redundant structural support in order to accommodate complex loading scenarios. As we proceeded with our study, we became increasingly concerned at the implications these bore for additional mass and reduced usable volume within the vehicle.

HABITAT TYPE EVALUATION

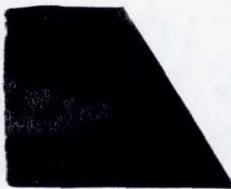
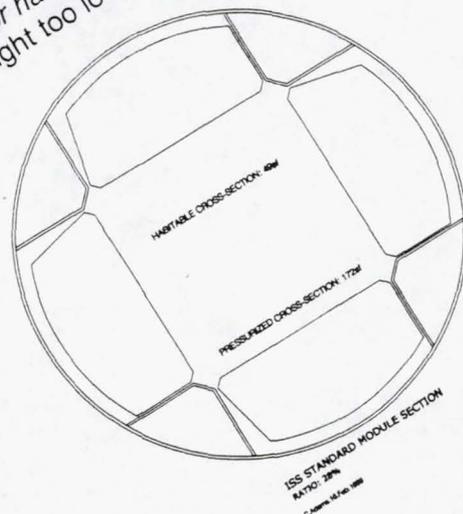
When the three basic hab typologies in the first section are applied to the three or four structural types under consideration, the result is a possible ten different habitats which might be considered for various applications in an interplanetary exploration mission. Each has particular physical, structural and typological characteristics which may render it very useful in one application and less so in another; overall, however, the number of variables involved in the general field of selection requires that a standard be established for evaluation of each in terms of its responsiveness to the principal area of mission risk probability: support of the human system.

While this is a complex field which will require many years of test and evaluation, we propose to begin human-factors risk-mitigation in this field with a simple, quantitative method. Based on the dimensions and requirements we proposed in the previous paper for a vehicle which would support a minimum acceptable level of habitability for a 6-person crew, we have created a chart for measuring the relative usability or appropriateness of each hab type, for each of the possible applications. The elements we have evaluated are the following:



1. Descriptions of habitats evaluated

Horizontal cylinder--Transfer (ISS standard)
 4.5 m diameter; micro-gee; 11.2m length; 2.15m square central open volume
 floor area: 24 sq.m ; 178 cu.m. internal clear volume
 additional 126.5 cu.m. stowage/equipment volume (71% of total)
 Need two for habitat
 Ceiling height too low for exercise—alternate solution possible (TBD)

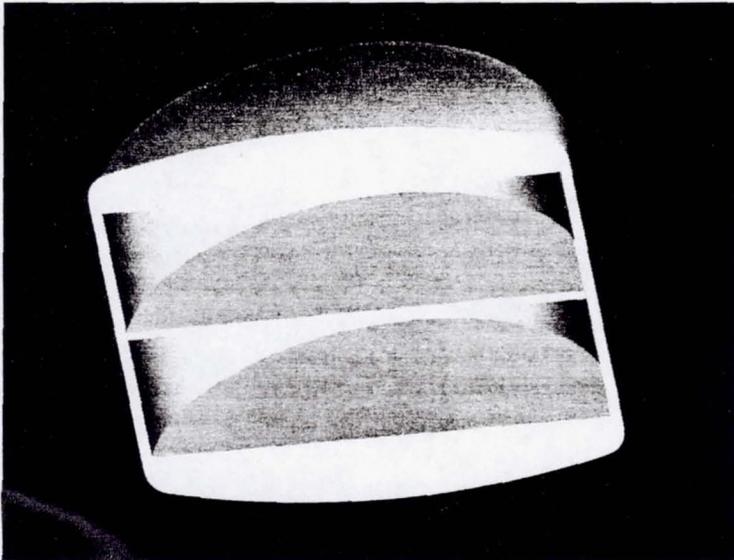


2. **Horizontal cylinder--Surface** (BIO-Plex std.)
 4.5 m diameter; partial gee; 11.2m length; two floors at 1.9F
 total floor area: 55 sq. m; 178 cu.m. internal pressurized v
 additional 90.64 cu.m. stowage (51% of total)



3. **Horizontal cylinder--Dual Use** (ISS modified)
4.5m interior diameter; 11.2m length; 2.4 m square central open volume
26.88 sq.m floor area: 169.1 cu.m internal pressurized volume-[5% removed for additional structure]
additional 108 cu.m. stowage included (64% of total)
need two for either habitat
ample stowage; good ceiling height
difficult to access floor/ceiling volumes in partial-gee
crew safety an issue on landing
additional internal structure needed to brace against landing loads-5 - 10%

4. **Vertical Cylinder--Transfer** (assumes Shuttle-analogous Magnum Booster vehicle)
7.5 m interior diameter; micro-gee; 6m. total height; 2.45m lower floor/2.3m upper floor
88.4 sq.m total floor area ; 265 cu.m. internal clear volume
additional 55.14 cu.m. for stowage and equipment (21% of total)
need one for habitat; additional volume for stowed items may be desirable?
ample ceiling height
ample clear usable volume



5. **Vertical Cylinder--Surface** (assumes Shuttle-analogous Magnum Booster vehicle)
7.5 m diameter; partial gee; 6m. total height; 2.45m lower floor/2.3m upper floor
88.4 sq.m total floor area ; 265 cu.m. internal clear volume
additional 55.14 cu.m. for stowage and equipment (21% of total)
need one for habitat; additional volume for stowed items WILL be necessary
difficult to access floor/ceiling volumes in partial-gee
ample ceiling height
ample clear usable volume

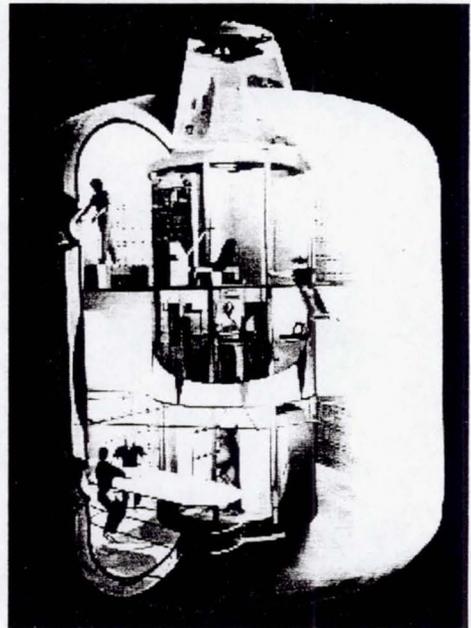
6. **Vertical Cylinder--Dual Use** (assumes Shuttle-analogous Magnum

Booster vehicle)

7.5 m diameter; variable gee; 6m. total height; 2.3 m lower floor/2.15m upper floor
84 sq.m total floor area ; 251.75 cu.m. interior free volume [5% removed for additional structure)
additional 52.36 cu.m. for stowage and equipment (21% of total)
need one for habitat; additional volume for stowed items
difficult to access floor/ceiling volumes in partial-gee
ample ceiling height
ample clear usable volume
crew safety an issue on landing
additional internal structure needed to brace against landing loads-5 - 10%

7. **TransHab--Transfer** (ISS-TransHab standard)

8m diameter; micro-gee; total height in core: 7m; outside core ht. varies from 7m to 9m
Three levels-Level One and Level Three at minimum ht. 2.45m; Level Two (CQs) at 2.15m
Total Floor Area: 125.6 sq.m-no added area for stowage/equip (included in available area)
Ample ceiling height for all functions
Ample volume for all applications



8. **TransHab--Surface** (ISS-TransHab modified: *unknown*)

8m diameter; micro-gee; total height in core: 7m; outside core ht. varies from 7m to 9m
Three levels-Level One and Level Three at minimum ht. 2.3 m; Level Two (CQs) at 2.15m
Total Floor Area: 119.2 sq.m-no added area for stowage/equip (included in available area)
Ample ceiling height for most functions
Ample volume for all applications *except crew sleep quarters*
Need to modify water tank design
Structure not proven-subtracted 5% from available volume for additional structure

9. **TransHab---Dual Use** (ISS-TransHab modified: *unknown*)

8m diameter; micro-gee; total height in core: 7m; outside core ht. varies from 7m to 9m
Three levels-Level One and Level Three at minimum ht. 2.3 m; Level Two (CQs) at 2.15m

Total Floor Area: 115 sq.m-no added area for stowage/equip (included in available area)
Ample ceiling height for most functions
Ample volume for all applications except crew sleep quarters
Need to modify water tank design
Structure not proven;--subtracted 5% from available volume for additional structure
crew safety an issue on landing
additional internal structure needed to brace against landing loads-5 - 10%

10. **Combo Lander** (NASA-JSC conceptual; surface only?)
4.3 m diameter tube; 2.1 m ceiling height in inner tube and xfer vehicle;
Inner tube width: 1.5 m; outer inflatable ring @ 2.16m radius; 2.45m clear height; total outer diameter 17.38m
total clear floor area at 2.45m height: 194.5 sq.m (assumes pressure shell thickness 45cm)
additional stowage/equipment volume:
total pressurized volume:
May need to subtract additional volume for structural supports
internal/theoretical---status unknown



Each of these ten habs was evaluated according to its ability to meet the habitability requirements and mission scenario as discussed in our previous paper. These include the ability to accommodate at least 58.6 sm of usable floor area with a 2.15m clear height in a surface application, and about 40 sm at the same height in a transit or micro-G scenario. These areas as described must meet all the basic requirements already established for real usability, and are considered activity centers only—exclusive of almost all stowage and all major life support and other equipment. (Additional figures proposed for the addition of each of those items tend to be undernourished due to the

fact that they are gross estimates which assume 0% volume for access paths; ie, the proposed units provide little or no room for the crew to access their stowage or machinery).

First, the ability of each type to accommodate the proper functional areas was rated, based on the assumptions stated above. A rating system of 0 – 2 was used, with 0 signifying unacceptable accommodation, 1 shows neutral ability to accommodate, and 2 rated an outstanding ability to accommodate the requirement.

Separation of Functions: Layout of Usable Area									
Hab Type	Translati on	Dining	Conferenci ng	Recreatio n	Food Preparatio n	Exercis e	Sleepin g	Person al Hygiene	Waste Managemen t
Horizontal Cylinder - T [Transfer]	2	0	0	0	1	0	0	0	1
Horizontal Cylinder - S [Surface]	2	1	0	1	2	0	1	1	1
Horizontal Cylinder - DU [Dual Use]	2	0	0	0	1	0	0	0	0
Vertical Cylinder - T	0	2	2	1	1	2	2	1	1
Vertical Cylinder - S	1	2	2	1	1	2	2	1	1
Vertical Cylinder - DU	0	2	2	1	1	2	1	1	1
TransHab - T	2	2	2	2	2	2	2	2	1
TransHab - S	0	2	2	2	1	1	1	1	1
TransHab - DU	0	2	2	2	1	1	1	1	1
Combo Lander	1	1	1	1	1	2	2	1	1

Separation of Functions – Cont.							
Hab Type	Changing clothes	Personal workstatio n	Scientific experimen ts	Inventory management	Trash manage ment	Crew Health	Total
Horizontal Cylinder - T [Transfer]	0	2	2	1	1	1	11

Horizontal Cylinder - S [Surface]	1	2	2	1	1	1	17
Horizontal Cylinder - DU [Dual Use]	1	2	2	1	1	1	11
Vertical Cylinder - T	1	1	1	1	1	1	18
Vertical Cylinder - S	1	1	1	1	1	1	19
Vertical Cylinder - DU	1	1	1	1	1	1	17
TransHab - T	2	2	1	2	2	2	28
TransHab - S	1	2	1	2	2	1	20
TransHab - DU	1	2	1	2	2	1	20
Combo Lander	1	1	1	1	1	1	17

The second step involved insertion of these results into an evaluation of the overall habitability of each type, with a stepped rating. Since the overall habitability was rated on a scale of 0 to 5, with 0 signifying a poor result and 5 an optimal rating, the total rating for each under "Separation of Functions" was calculated as follows:

- 0 - 2 rated a "1"
- 3 - 5 rated a "2"
- 6 - 8 rated a "3"
- 9 - 11 rated a "4"; and
- 12 - 14 rated a "5".

Overall Habitability Evaluation											
Hab Type	Scale 1:5 Poor--0; Highest Rating --5										
Criteria	Separation of Functions	Socialization	Local Vertical / Spatial Quality	Safety	Reach Envelope	Translation Ratio	Maintainability and Access	Operational Efficiency	Layout Optimization	Suitability	Total
Horizontal Cylinder - T [Transfer]	2	0	1	5	3	0	3	4	1	3	22
Horizontal Cylinder - S [Surface]	3	2	2	4	2	4	3	3	2	4	29
Horizontal Cylinder - DU [Dual Use]	2	0	1	1	0	0	1	1	0	0	6
Vertical Cylinder - T	4	4	3	4	5	5	5	4	5	4	43
Vertical Cylinder - S	4	5	4	4	5	4	5	4	5	5	45
Vertical Cylinder - DU	3	4	3	1	5	4	5	3	3	2	33

TransHab - T	5	5	5	5	5	5	5	4	5	5	49
TransHab - S	4	5	4	4	5	4	5	3	4	3	41
TransHab - DU	4	4	3	1	5	4	4	2	1	1	29
Combo Lander	3	3	2	0	2	1	2	1	3	3	20

Thus, even before a detailed layout is made of each module with full stowage/mass/fuel calculations, it is clear that certain element types are more favorable for an extended human exploration mission. Although much can be achieved with the ISS/BIO-Plex type horizontal cylinder, under no circumstances is it truly optimized for support of its crew. Despite its substandard height, a two-level surface application for this vehicle rates as high as the lowest-rating vertically-oriented elements; however, as a group the horizontal type rates lowest overall. Meanwhile, the vertical cylinder "Tuna-can" vehicle performed well in both surface and transit categories; perhaps the greatest factor working against this craft is outside this field of study, in the area of launch vehicle availability.

The combinant inflatable TransHab rated highest of all categories in the transit-only category, with a grade of 49 out of possible 50; lowest was the Dual-Use ISS-type module. While the JSC Combo Lander came in next lowest, this was with a rating of 20—suggesting that this vehicle might well gain in viability with more rational design work. All evaluators expressed concern that they might be rating this vehicle incorrectly, due to a lack of consistent information.

Also, certain mission scenarios seem to be deselected on the basis of these metrics. For instance, none of the Dual Use (DU) typologies rated particularly favorably—partly due to conflicting ability to accommodate both environments with an equal degree of operability, maintainability, and efficiency. Volume was lost in each DU craft to added structure and different translation modes, as well as to the layout changes required to accommodate sleep and maintenance activities. Lastly, the DU vehicles performed poorly in the safety category, due to the risk complexity of subjecting the crew to transit, braking, landing, and surface (and possibly reorbit) scenarios within a multifunctional vehicle.

It therefore appears unlikely that a multiple-use vehicle can be a preferred alternative for mission planning, and that mission designers might best focus their attentions on how they might optimize the transfer operations between separate-task habitats which are highly rated for their respective environments. Because all of the DU elements evaluated were ranked lower than their typologically-similar, single-task counterparts, mission planners concentrating on conceptual design should first attempt to focus on separate stages. Alternately, planners proposing a mission which demands multiple-use vehicles should be prepared to offer strong arguments justifying their choice.

SUMMARY

While the consistent support of the human function remains the greatest area of unaddressed risk within any extended human exploration mission, we have shown that it is possible to introduce a rational process for anticipating, calculating and reducing some important aspects of this failure mode. Metrics in this area have been difficult to come by until now, but we find that there are ways of introducing general human-factors

metrics whose results are well within the boundaries of a reasonable, objective system. Although good habitability involves many complex, detailed subsystems which interact in order to support the crew, a broad definition of physical requirements consistent with habitability can be constructed. Furthermore, these high-level requirements can be applied to any vehicle within any mission scenario, and they can also be used even to evaluate conceptual mission designs.

A preliminary evaluation of all vehicle types proposed to date has shown that some of the proposed elements are more satisfactory for specific goals than for complex ones, and that neither of the currently favored mission scenarios is optimal for a low-risk, efficient, reproducible mission. We have established an objective set of metrics for habitability as a major driver of both vehicle form and mission design, and have applied these to the current elements and scenarios under consideration for the Mars DRM. In our next paper, we will address the question of the optimal scenario and, based on these findings, propose a Mars mission architecture which would, on preliminary analysis, be most efficient and effective in meeting its single goal: the support of a human exploration team on Mars.

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