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First Mars Habitat Architecture

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This article presents a review of design concepts for Mars exploration habitats that display design reasoning during quarter century from the 90-Day Study in 1989 to the Evolvable Mars Campaign in 2015. During this period, NASA and its academic and industrial partners began to think seriously for the first time about a long-term strategy to expand human presence enduringly beyond low Earth orbit. The two key mileposts over this period were the human return to the Moon and its eventual permanent settlement and then going on to Mars for exploration and then settlement. Consequently, Moon and Mars habitats often share much in common; the discussion of strategies for people to live and work on Mars remains linked to analogous human precursor missions on the Moon that test prototype hardware for Mars. This review evaluates these habitat architectures it in terms of their solutions to key design and operational challenges.

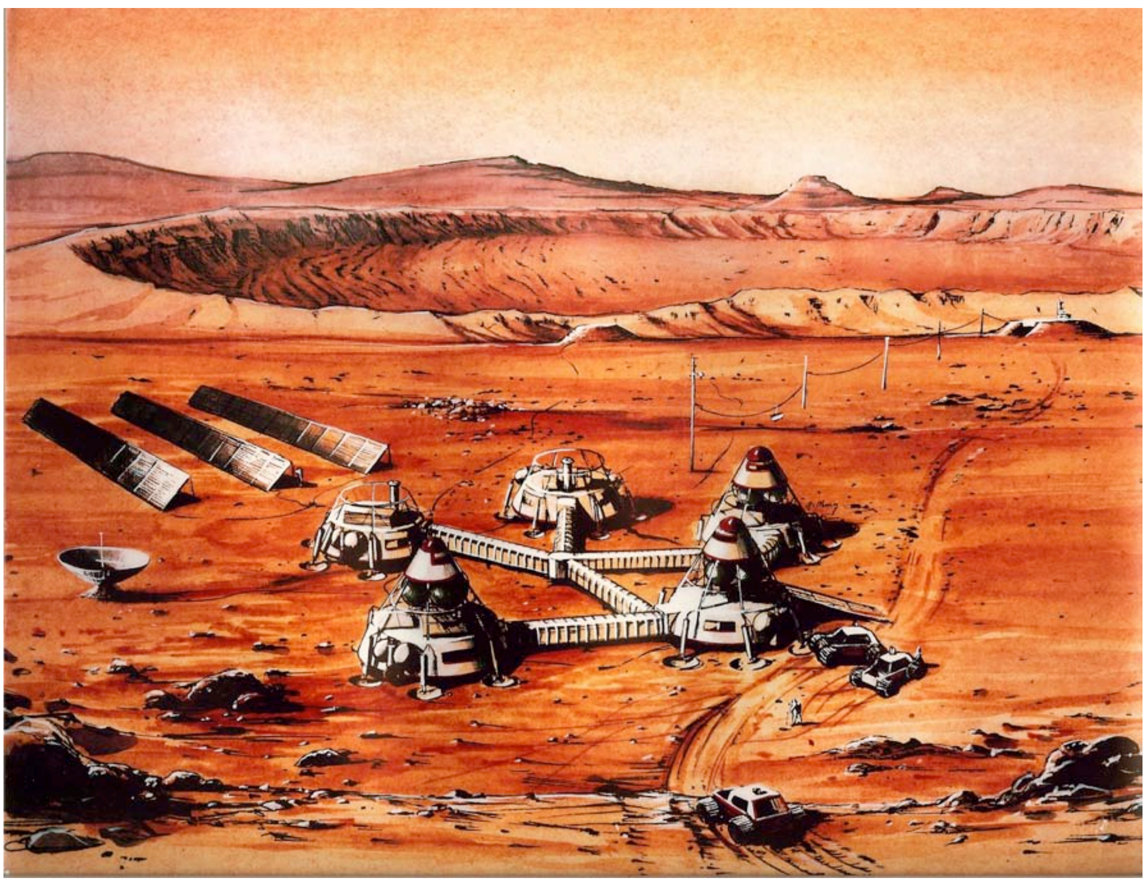

FIGURE 0. Vladimir M. Garin's 1989 rendering of an "Apollo on Steroids" concept for a Mars base (Courtesy of Vladimir M. Garin).

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KEYWORDS: airlock, back contamination, crew health, crew safety, crew productivity, EVA, forward contamination, habitability, habitation, human factors, interplanetary vehicle, Mars Design Reference Mission, microgravity countermeasure, module, radiation protection, planetary protection, regenerative life support, surface systems.

Nomenclature

AAS:	American Astronautical Society.
AIAA:	American Institute of Aeronautics and Astronautics.
Ames:	NASA Ames Research Center, Moffett Field, California
ATHLETE:	All-Terrain Hex-Limbed Extra-Terrestrial Explorer.
BEAM:	Bigelow expandable activity module, a subscale TransHab-like module made for a trial on ISS.
BIOplex:	Bioregenerative Planetary Life Support Test Complex.
CAM:	Centrifuge Accommodation Module that housed the Life Science Centrifuge intended for ISS.
CELSS:	Closed Ecological Life Support System.
CERC:	Controlled Environment Research Chamber.
DAV:	Descent/Ascent Vehicle, a vehicle that brings crew from orbit to the surface and returns them to orbit, distinguished from an MAV that lands without crew and launches crew to Mars orbit.
DSH:	Deep Space Habitat, concept to support a crew of 4 for long duration exploration beyond LEO.
ECLSS:	Environmental Control and Life Support System.
EMC:	Evolvable Mars Campaign, the idea that by developing modularity and flexibility NASA can explore Mars on the existing budget, adjusted for inflation.
EMU:	EVA mobility unit; the Space Shuttle spacesuit
EVA:	extra-vehicular activity
FLO:	First Lunar Outpost
FMARS:	Flashline Mars Arctic Research Station
HDU:	Habitat Demonstration Unit, a mockup of the idea that morphed into the DSH.
HEDP:	Human Exploration Demonstration Project, a project at NASA Ames, 1991-1994 to demonstrate "A day in the life of a planetary habitat"
HEOMD:	Human Exploration and Operations Mission Directorate at NASA HQ.
HPC:	Human Powered Centrifuge, originally part of the HEDP.
IPV:	Interplanetary vehicle.
IVA:	Intravehicular activity, inside a spacecraft, habitat, or pressurized rover in a shirtsleeves environment.
JSC:	NASA's Lyndon B. Johnson Space Center, Houston, Texas.
LEO:	low Earth orbit.
LER:	Lunar Electric Rover, a field trial roving vehicle mounting two Suitports.
LMLSTP:	Lunar-Mars Life Support Test Project at JSC.
MAV:	Mars Ascent Vehicle, a vehicle that lands without crew and ascends to orbit with crew.
MDRA:	Mars Design Reference Architecture, revision 5.0.
MDRM:	Mars Design Reference Mission, 1.0 through revision 4.0.
MSFC:	NASA's George Marshall Spaceflight Center, Huntsville, Alabama USA.
NASA:	National Aeronautics and Space Administration.
NCRP:	National Council on Radiation Protection.
NEEMO:	NASA Extreme Environment Mission Operations program.
NOAA:	National Oceanographic and Atmospheric Administration.
NRC:	National Research Council.
PLSS:	Portable life support system.
SAE:	Society of Automotive Engineers.
SEI:	Space Exploration Initiative, a series of studies 1989-1992 for exploration of Moon and Mars.
SEIM:	Surface Endoskeletal Inflatable Module, a concept by Synthesis-International
SR&QA:	Safety, reliability, and quality assurance.
TEIV:	Trans-Earth injection vehicle.
TMIV:	Trans-Mars injection vehicle.
TransHab:	Transit Habitat, the first inflatable module concept for an interplanetary vehicle.

I. Introduction

Perhaps the greatest challenge in the planning and design of space habitats is that anything delivered from the Earth must travel to the destination surface on a large, expensive transportation system. Payload mass is always at a premium in cost and propellant. The discussion of space habitats often centers upon how the mission architecture packages the habitat for launch and landing. For the purpose of this review, please assume that an adequate propulsion system will become available to deliver the habitation systems to Mars. Otherwise, the analysis cannot progress beyond the familiar but ultimately fruitless exercises on how to load modules and payloads onto landers and how to stuff them in turn into launch vehicle fairings (Hoffman, Kaplan, 1997, pp. 1-20; Cohen, 2009, pp. 9-11).

The universal priority for Space Architecture, including Mars Habitats, is to protect the health and safety of the crew and to support their sustained productivity through good design for habitability and human factors (Cohen, 2010b). This design effort provides both the space living and working environment for humans (Clearwater, 1985). The living environment consists strictly of the pressurized domain for intravehicular activities (IVA) but the working environment includes both IVA and extravehicular (EVA). Connors, Harrison, and Akins (1985, pp. 219-328) show that the longer the mission, the more demanding the requirements will become to sustain the crew.

The system engineering juggernaut is always looking for ways to cut corners in order to save cost and mass; this attitude will extend inevitable to interplanetary vehicles (IPVs) and Mars Habitats. Clearwater and Harrison (1990, p. 513) argue that for Mars Missions, the engineering temptation to "trade–off cost for comfort would be a major mistake" from the human factors point of view. Therefore, Space Architects learned that to ensure design support for the crew's living and working environment, it is imperative to establish habitability and human factors as a top level requirement in the spacecraft and habitat design process (Adams, 1998a; Adams, 1998b; Adams, McCurdy, 1999; Adams, McCurdy, 2000; Adams, McCurdy, Pauly, 2000). All the discussion that follows stands on the foundation of the sources cited in this paragraph.

The source selection approach for this article derives from three primary criteria: larger mission architecture, first human mission, and originality. Each of these criteria must be present in some degree for a habitat design to be included in this review. The ***larger mission architecture criterion*** means that the surface habitat is neither a stand-alone concept that arises *sui generis* without a system connection to a more complete Mars exploration program, nor should it be plunked down without any explanation of how it arrived on the surface. This criterion thereby excludes many of the discrete surface habitat design projects that relate only to themselves. It also would exclude similarly self-referential interplanetary habitats, except that there are actually very few of them in existence. The ***first habitat criterion*** means that the habitat must be part of the first, or the first several crew landings on Mars. It excludes concepts that can only come much later in a Mars campaign involving sintered regolith, additive manufacturing (3D printing) on-site, or development of a naturally occurring geographical feature such as a crater or lava tube. The ***originality criterion*** means quite literally that the habitat should be the first of its type or concept, or a major departure from a previous concept or an elaboration of it that advances the architecture substantially. The fact that this review may not cite most recent habitat articles does not reflect negatively on their authors of those articles. Rather, it is due to the author's focus upon original sources. For the same reason, this review does not make an effort to cover all the derivative and secondary embodiments of each original concept, although it notes a few that achieved a degree of acceptance or success. In addition, some reference citations help to provide specific concepts in their developmental and historical context.

Another question that arises frequently is why does this review not cover mass estimates. The answer is simple but discouraging: What reason is there to believe any concept's mass estimates (unless one works through the calculations for oneself in a systematic way). At least the reader can see and perhaps believe the drawings. As an example, representative mass estimates for NASA's first Mars Design Reference Mission appear in the Appendix.

II. Early Days

The current generation of movement toward establishing a permanent human presence beyond low Earth orbit (LEO) began in 1989 with the Space Exploration Initiative (SEI) under the administration of President George H. W. Bush. This evolution of concepts has taken many forms, but now, a quarter of a century later; it has produced a rich series of concepts and counter-concepts, of architectures large and small, and identified the needs for new technologies of many kinds.

The leap from designing a lunar habitat to designing a Martian habitat was in some respects not at all obvious but in other respects all too obvious. Since the Apollo program was only ended 15 years earlier and still overshadowed nearly everything NASA tried to do, it seemed a logical place to start as humanity's only experience on a celestial body beyond LEO low Earth orbit (LEO). In 1989, before the publication of the now (in)famous <u>90-Day Study</u>, Vladimir M. Garin[2] at NASA Ames Research Center proposed a multiple simultaneous landing of Apollo Command Module-type spacecraft mounted on top of Mars lander descent modules. These descent modules included habitat sections where the crew would live during an Opposition-Class mission.

FIGURE 0 shows Garin's rendering of the temporary Mars base. Although this mission architecture was somewhat limited to an Apollo-heritage vernacular Garin's rendering is instructive of the thinking that prevailed upon the cusp between the Apollo heritage and the new Space Exploration Initiative. Garin's concept shows several levels of complexity not achieved in many later proposals. The fact that the habitat sections sit so close to the surface reveal a key aspect of the terminal descent and landing design; the huge propellant tanks that figure in so many later lander concepts do not appear. Instead, Garin's lander would use a drop-stage that would separate from the main lander about 100 km before touchdown. Effectively, each lander carries its own Mars ascent, Earth-return, and Earth reentry vehicle all-in-one. The descent stage habitats would connect by inflatable tunnels, allowing the crew to circulate between them in a pressurized, shirtsleeves environment. The rendering shows five landers. Three carry Apollo Command and Service Module (CSM) type interplanetary crew vehicles that serve as Earth return vehicles. Multiple crew vehicles and multiple landers assure a degree of redundancy to help assure mission success. Two of the landers carried cargo instead of the Apollo CSM. This cargo provided the photovoltaic panels and the nuclear reactor in the crater in the distance, from which a power transmission cable is strung on poles to the base. Each lander carries a pressurized crew rover. In this architecture despite the minimal aspect of the crew vehicles and habitats, the base is power-rich and also enjoys plentiful mobility. The small amount of propellant tankage provided for the descent stage of the landers is naïve, but the overall concept is surprisingly sophisticated. The challenge it poses to subsequent Mars habitat and base concepts is: how well do they measure up to this early forerunner?

FIGURE 1a. First Lunar Outpost (FLO) beginning separation process from a heavy lift launch vehicle, jettisoning fairings, while approaching LEO (NASA Image).

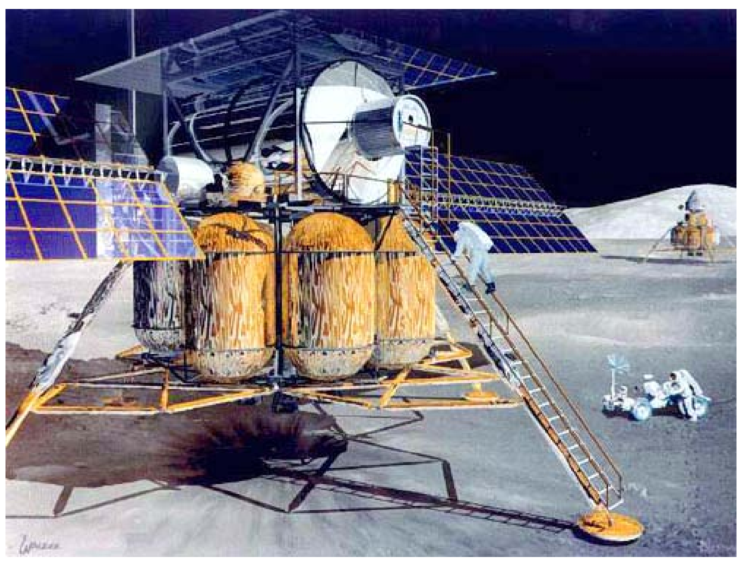


FIGURE 1b. Rendering of the First Lunar Outpost, derived from the NASA 90-Day Study (NASA image).

[2] Vladimir Garin (1940-2002?) began his career in the Soviet Space Program, where he held about 50 patents. He immigrated to the USA about 1980 and came to work at NASA Ames, where he became an important influence on the Mars initiatives.

A. The 90-Day Study and the Space Exploration Initiative (SEI)

The first of these projects was the 1989 "90-Day Study," which although not in the least realistic, set in motion the effort that continues to this day. Although Werner von Braun and others proposed Mars mission architectures in the 1950s and 60s (Portree, 2001, pp. 1-130), NASA first became engaged seriously as an agency-wide effort in thinking about Mars Exploration in the 1990s. In a "resurgence of strategic planning" (Roberts, 1991, p. 1), the 90-Day Study (Cohen, A., 1989, pp. 3-3 to 3-24) and the SEI set the stage for the effort within NASA during the 1990s to develop the first Mars Design Reference Mission (MDRM 1.0). The 90-Day Study included two types of habitat: an "initial habitat" and a "constructible habitat." The initial habitat was similar to the common module then under design for what became the International Space Station (ISS). It consisted of a rigid, cylindrical aluminum pressure vessel, oriented horizontally, with pressure port hatches at each end. The constructible habitat was something new: a spherical structure consisting of three or four floors supported by truss work, all of it enclosed in an inflatable sphere. The astronauts or robots would then cover the sphere with terraced bags or tubes of regolith for radiation and micrometeoroid protection. The initial habitat was named the First Lunar Outpost (FLO). FIGURE 1a shows a NASA interpretation of the 1992 First Lunar Outpost Study (Lindroos) mission architecture. FIGURE 1a indicates the integration of the complete FLO descent/ascent vehicle (DAV) on top of a heavy lift launch vehicle. FIGURE 1b shows a close-up of the FLO itself, consisting on a space station type long module with a crew member on a long stair-ladder either ascending or descending from the airlock at the end of the module. This great height between the lander hatch and the lunar surface posed a challenge that continued well into the Constellation Lunar Program of 2004-2010.

FIGURE 2 shows a rendering of the Constructible Habitat. Prairie View A&M University (1991) produced the first Mars Habitat design under the SEI banner, combining the initial and constructible concepts. In an early push for commonality and "Mars-forwardness" of lunar design (Mendell, Griffith, Charles; 2001) and operations (Mendell, Griffith, 2002), both types of habitat would apply to the Moon and Mars alike. This lunar design/Mars-forward linkage continues to the present (Green, Spexarth, 2009).

Soon, it became clear that a human mission to Mars would be the most complex and expensive single undertaking in human history. Because of this complexity and expense, it would necessarily become international insofar as including at a minimum Canada, the European Space Agency (ESA), Japan, and Russia – the partners on the Space Station. Despite potential cost sharing, the international participation would also drive more complexity into the program.

FIGURE 2. The Lacus Veris constructible habitat for the Moon or Mars, derived from the NASA 90-Day Study (NASA image, Design by Gary Kitmacher, Architect/Engineer John Ciccora).

It would no longer be possible to succeed by dictating top-down design and engineering decisions in the familiar NASA System-Engineering culture that evolved during the Apollo Program and matured during the Space Shuttle Program. Instead, NASA and the international partners would need to begin invoking a participatory planning alternative from the outset, which would include habitat and Mars base design (Cohen, 1997b). Not only would this design participation need to include NASA and international partners, it would need to develop internally to NASA. The crews would need to become actively involved in the design process to ensure the suitability of the IVA environments and EVA provisions as a way to help ensure their health, safety, and productivity (Cohen, 1990; Cohen, 2010b).

B. The Mars Underground and Mars Direct

In the early 1990s, there was a broad wave of enthusiasm for a human mission to Mars as the "Mars Underground"[3] (as they called themselves) emerged into the open and found support within NASA. One of the outcomes was the recognition that the nature of a conjunction class Mars mission -- with the crew spending about 180 to 250 days outbound in deep space, about 500 to 600 days on the surface, and about 180 to 250 days inbound on the return to Earth. This 600-day habitat would demand a different design than the SEI/FLO initial habitat or the constructible habitat.

Robert Zubrin was a key personality in the Mars Underground, who advocated strongly for a minimalist mission that he called "Mars Direct." What made it "direct" was the goal of launching direct from Earth to Mars, without Earth orbit rendezvous or Mars orbit rendezvous, but with the trans Mars injection vehicle (TMIV) aerocapturing and/or aerobraking at Mars to make a direct atmospheric entry, descent, and landing. Mars Direct was the mother of all minimalist missions (Zubrin, 1996). Its approach was to start with the smallest and most affordable concept that might be feasible. Key to this minimal payload delivered to the Mars surface would be the extensive use of in situ resource utilization (ISRU) that would include making fuel, oxygen, water, and other commodities from resources assumed to be available on the Mars surface. The initial crew would live and work under extremely austere conditions, but their sacrifices would enable the buildup of a more complete Mars base or settlement.

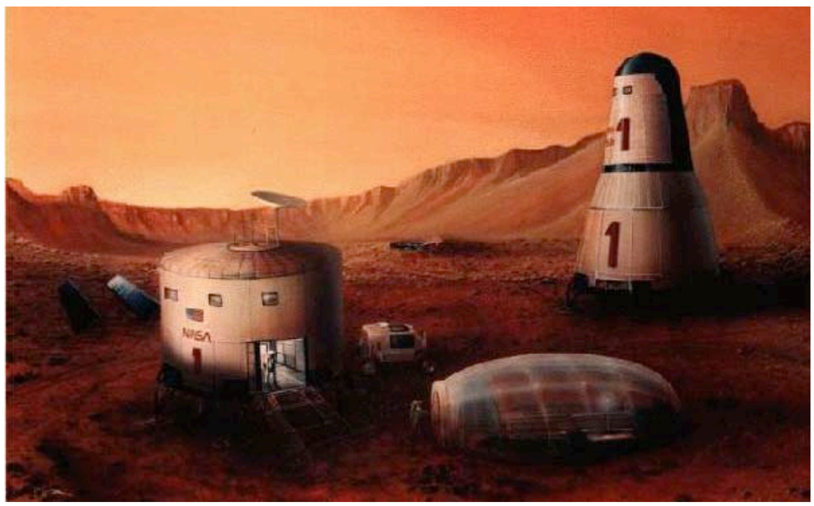


FIGURE 3. Robert Zubrin's Mars Direct minimalist concept showing the basic elements of the lander/ascent vehicle, the crew habitat, inflatable greenhouse, and rover (Courtesy of the Mars Society).

FIGURE 3 shows the Mars Direct base consisting of an unconnected cluster of elements: the biconic lander/ascent vehicle, the two story habitat, the inflatable greenhouse, and a presumably pressurized rover. One example of the minimalism is that there is no pressurized connection between the habitat and the greenhouse. To cultivate or harvest food, the crew must prebreathe pure oxygen, don a spacesuit, go through checkout, go EVA, enter the greenhouse, and then doff some or all of the spacesuit so that they may use the dexterity of their fingers and arms. To return to the habitat, they must enclose the produce in a pressurized container, repeat the space suit donning process, and walk back to the "farm house," then repeat the ingress and doffing processes.

C. Mars "Semi-Direct"

Kent Joosten, at Johnson Space Center (JSC), adapted key aspects of Mars Direct to what became NASA's Mars Design Reference Mission concept (MDRM 1.0). Joosten developed a concept for two "tuna can" modules of 8m to 10m in diameter, although eventually settled at 7.5m. John Frassanito provided the renderings for this habitat design and the associated rover concepts shown in FIGURE 3, published by Weaver and Duke (1993).

However, Dr. Zubrin disdained Joosten's approach, deriding it as "Mars Semi-Direct." The Joosten, Weaver, Duke concept involved potential rendezvous in Earth orbit to assemble a larger TMIV, allowed Mars orbit injection, and required rendezvous in Mars orbit for the Earth inbound return trans Earth injection vehicle (TEIV). Despite Zubrin's sarcasm, NASA moved ahead with the Joosten approach toward developing the first Mars Design Reference Mission (MDRM) concept.

Stoker and Emmart (Eds,1996) captured much of this creativity and raw energy, in Strategies for Mars: A Guide for Human Exploration. They posited two objectives: Mars Science Exploration and Mars Habitation. These objectives led to design problem decomposition into two portions: "getting there" *versus* "being there." Although Strategies for Mars did address some of the launch vehicle, propulsion, and trajectory issues, the overriding concern

[3] Graduate students at the University of Colorado, who developed the Case for Mars conferences and publications, founded the Mars Underground.

emphasized being there – what humans would do on Mars – which was sadly lacking from both Mars Direct and from Joosten, Weaver, and Duke's early presentations and publications.

The Mission Design Logic explicated the assumptions and constraints, with their implications. TABLE 1 presents these assumptions and constraints. These assumptions included: pre-positioning and verification of the habitat modules and energy system on the surface before launching the crew, six crew members, 600 day surface stay time, plentiful energy, and decoupling of the habitat from the trans-Mars vehicle. The constraints include precursor missions, cargo landers, robotic operations, in situ fuel generation compatibility, crew fitness, and mission abort to the Mars surface.

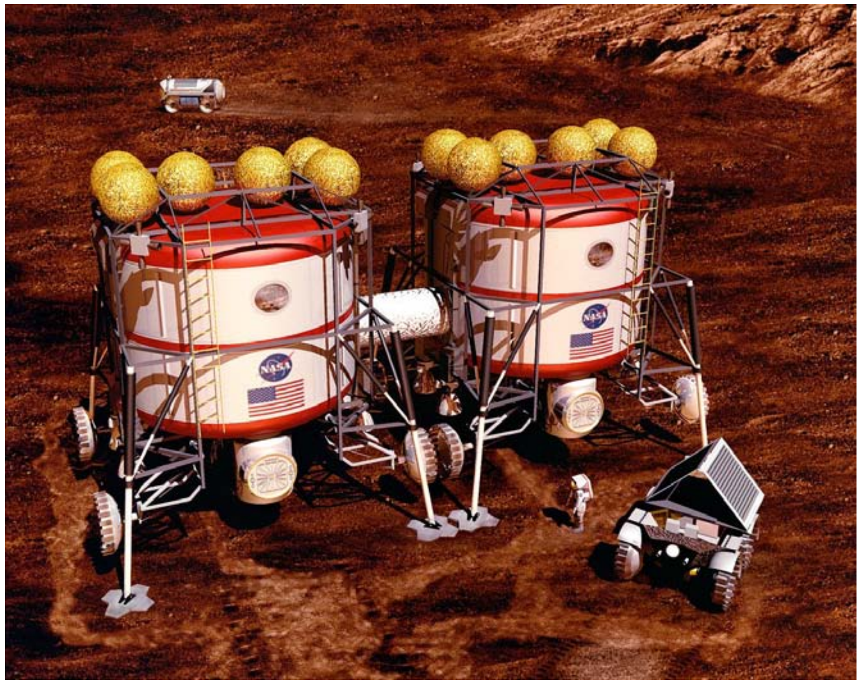


FIGURE 3. Kent Joosten's 1993 concept for the MDRM 1.0 Mars exploration habitat (NASA image, rendered by John Frassinito).

D. Strategies for Mars 1996 and the Critique of NASA System Engineering

The Strategies for Mars Study (Stoker, Emmart, Eds, 1996) took the approach of "Being There[4] instead of Getting There." The informal title for the component Habitation Strategy was "Mars 2008" to emphasize that on the 2007 Mars launch window, the mission would arrive at Mars in 2008. The purpose of the *Mars Habitation Strategy* was to go beyond the formulaic application of NASA System Engineering that focuses so much on vehicle design and launch masses. The goal was to determine not just that the design is free of error but that the assumptions and requirements are correct and that it is positively capable of achieving its goal. This approach included explicit metrics to assess when the mission design problem was sufficiently well-defined and well-structured to begin solution-seeking and designing. For the solution-seeking/designing cycle, parallel metrics applied to determine when the design is sufficiently complete to begin manufacturing (Cohen, 1996c; Cohen, 2000b).

The uniting of exploration with habitation led to an integrated approach to habitation design for the living and working environments. Strategies followed a design research methodology in a sequence of questions that inform the entire study:

- What are the key issues for Mars Exploration?
- What evidence do we seek and where should we look for it?
- What are the best means to find it?
- What support functions will we need on Mars?
- What capabilities must we deliver to Mars?

The chapter on the "Mars Habitation Strategy" (Cohen, 1996, pp. 464-512) framed four issues: the mission design logic, safety philosophy, habitation strategy, and design evaluation.

In this post-Challenger return to flight era[5] Crew safety on a Mars mission became the focus of increasing concern across NASA and particularly among the astronaut corps (Peterson, 2000). The Strategies for Mars Safety Philosophy addressed the criticality of mission functions and their failure paths. It correlated mission objectives to

[4] Apologies to Peter Sellers.
[5] Challenger was lost January 28, 1986. Discovery recommences shuttle flights on September 9, 1988, almost three years later.

risks for the three criticalities: life-critical, mission-critical, and mission-discretionary functions. These criticalities apply across the major technology areas, including radiation and other hazard protection, consumable generation, life support, automation, and extravehicular activity (See also Cohen, 2000a).

Abort to the Mars surface was a unique and defining contribution of the Strategies for Mars study. It began from the recognition that there might be multiple scenarios – some of them unforeseeable 20 or more years in advance – that might make it impossible for the crew to depart the Mars surface on schedule. Because the Earth return inbound launch windows are nearly as restrictive as the outbound windows, delay or malfunction could result in the crew spending an additional, involuntary two to three years on Mars until they would have another window to return home. It is not necessary to go into the wide range of repair, resupply, or reequip solutions that might respond to such a failure. However, the consequence was clear: the Mars crew would need a backup system and strategy to more than double their planned time on Mars. This plan was *Abort to the Surface*, at the Mars base, in the Mars habitat, which became part of the NASA Mars Design Reference Mission, MDRM 1.0.

TABLE 1. Assumptions and Constraints of the 1996 *Strategies for Mars* Habitation Strategy.

Assumptions	Constraints
• Crew of six, with a wide skill mix and cross-training in critical skills, • Conjunction class mission, • 500 to 600 days on the Mars surface, • Pre-positioning launch for the Earth return vehicle in Mars orbit, • Pre-positioning launch for the Mars Ascent Vehicle (MAV) on the Mars surface, • Pre-positioning launch for the Mars surface habitat and associated equipment, • Launch the crew only after verifying the Earth return vehicle, ascent vehicle, surface habitat, and the fueling of the ascent vehicle • In situ fueling of the ascent vehicle, and • Growing a portion of food on Mars.	• Verification of successful precursor missions are required before sending the crew on the next 26 month launch opportunity, • Cargo landers must land successfully and deploy cargo as designated, • Robotic operations, • In situ fuel generation and storage for MAV must be completed and verified before crew launch from Earth, • Crew fitness must be sustained and verifiable, and • In the event of an inability or failure to depart Mars, there will be sufficient landed resources for mission abort to the Mars surface.

The *Habitation Strategy* focused upon "human-environment" interactions, correlating the three criticalities to the habitation functions. To succeed, it became necessary to formulate a new approach to mission design evaluation, and even to NASA's iconic "System Engineering." Traditionally, the NASA System Engineering ritual pursues minimizing the resources and costs to conduct a mission "without compromising safety" as an essentially prophylactic methodology to avoid error. Harry Jones[6], Senior Scientist in the Bioengineering Branch at NASA Ames Research Center comments on this error-avoidance doctrine:

> There is something dogmatic and unscientific, unempirical going on here. The systems engineering process is presumed to guarantee success if you follow it correctly. But it is impossible to follow in practice, by defining all requirements up front, making no changes, doing all the checks, etc. So if a project fails, it is because the process wasn't followed, which proves that the process is correct!
>
> You could substitute "Elaborate voodoo ritual" for "systems engineering process," and it would work the same way. By Popper's argument, a theory is scientific only if it is falsifiable, only if it can be proven wrong by real world data. A scientific engineering approach would survey projects to see what works and try different methods to test their effects.

Jones identifies the tautological essence of system engineering in operation; if something fails, by definition, it happened because the system was not followed properly. However, there is another dimension to system engineering -- as a design discipline. This discipline measures system performance in terms of certain figures of

[6] Email to the author, 15 OCT 2010.

merit (FOMs): affordability (life cycle cost), mass (delivered payload), mission success (probability of loss of mission, PLOM), and safety (probability of loss of crew, PLOC). The problem with this construct of system engineering is multifold with respect to reducing mass, the domination of launch and hardware, and the often elusive nature of requirements:

Reducing mass -- even more than cost -- dominates the design decision-making process. However, he who makes the system engineering analysis is the custodian of the secret knowledge in which the assumptions are never stated and calculations are never shared. The less preferred design option invariably comes out with more mass than the preferred option – another dimension of the tautology.

The emphasis on building and launching hardware dominates, compared to enabling the science and technology development portions of a mission. The United States portion of the ISS was severely underutilized for the first decade of its operations because of the active discouragement of crew-tended research. It has been only with the creation of CASIS and the removal of these on-board activities from the system engineering bureaucracy that the US segment of ISS is starting to see activity approaching full utilization.

At that time especially, *there was little scrutiny to the verification and validation of requirements.* Stated simply, verification means "Is this requirement what we want" and validation means "Will this requirement obtain the result we want?" All too often, requirements arise to ensure that a particular piece of hardware or a particular Center or a favorite contractor obtains a role in the project and a commensurate share of the funding. This "requirements creep" and the turf conflicts it engenders leads to many orbital crew launch vehicle, lunar, and Mars projects being cancelled.

It is not falsifiable. Jones noted this feature, but it is more than a problem of a ritual process; because the data are not offered for discussion, the system engineering system does not encourage debate about whether its results are correct or whether a particular design offers the best performance. More often what emerges is support for one preferred alternative with one or two "straw man" competitors, against which the deck is stacked from the outset.

In contrast, the design of the Strategies for Mars mission design, habitats, and base attempted to fulfill the goal of a crew "Being There," well supported to carry out the scientific exploration mission, and to do it through an open and honest debate among the team members. FIGURE 4a and 4b show the *Strategies for Mars* explication of the Joosten/Frassanito 1993 Mars Surface Habitat to actually perform the mission rather than simply depositing hardware on the Mars surface. The key to the rendering appears in FIGURE 4c. The key refinements were:

1. *Landing Zone (LZ)*

The rendering shows a landing zone nearly out of sight in the background at a distance of 5 to 10 km. This distance is necessary to protect the assets and crew at the habitat site from the impact of a bad landing or explosion. Crews would land here in the descent/ascent vehicle (DAV) and at the end of their tour, launch from the LZ in the refueled DAV. The APPENDIX includes a discussion of landing zone separation from the base under the MDRM 1.0 that followed from the Joosten project.

2. *Sintered Road*

Although the first pre-integrated habitat might land at the base site, all the other payloads and the crew descent/ascent vehicles would land (and take off) from the LZ. The mass guideline for these payloads allowed up to 40 mTons for each.[7] It would be necessary to prepare the surface across which to move these large, heavy payloads, since the unprepared surface could be not strong enough or dangerous. The imagined method of preparation would be microwave sintering. This sintering would occur during the first 26 month interval between the first habitat's arrival and the second.

3. *Nuclear Fission Reactor in a Crater*

Mars is too far from the sun to provide sufficient photovoltaic electricity to power the Mars base. Also, in 1996 and now 20 years later, there is still not an adequate or mass-effective technology for storing power to use during the Mars night. Therefore, a power supply that can operate throughout the sol, 100% of the time, will be necessary. The reactor would be on the order of the NASA Glenn SP100 concept, providing 100 kW. The placement in a crater helps to protect against radiation and possible explosion.

[7] More recent studies place the practical limit for a payload on an SLS launch vehicle at about 20 mTons.

4. *Control Facilities Outside the Crater*

Reactor control equipment would be installed outside the crater to protect crew members from radiation when they went to adjust or maintain it. Certainly, the crew would operate the reactor remotely from the habitat under nominal conditions, but this equipment would provide an alternative or backup capability.

5. *In Situ Resource Utilization (ISRU) Production Plant*

The most compelling feature of Zubrin's Mars Direct was its adoption of ISRU production of gases, water, and propellant. The rendering shows the ISRU plant at the distal end of the inflatable greenhouses, where the gases and water would be used. A separate propellant production ISRU plant would be installed at the LZ.

6. *Inflatable Greenhouse*

Incorporate an external inflatable greenhouse to each module connected to an in situ life support consumables plant that can provide a higher partial pressure of CO_2 to the plants, crack the CO_2 in a Sabatier reactor to produce O_2, and save the carbon to make methane for descent/ascent vehicle (DAV) propellant, Mars ascent vehicle (MAV), or rover fuel.

7. *Pre-Integrated Habitat*

The habitats will be complete and tested as thoroughly as feasible before integration into the launch vehicle. The first launch window serves the pre-positioning launch of the first pre-integrated habitat-laboratory module. Because the habitat does not incorporate EVA airlocks directly, it saves the mass penalty of the airlock from the habitat launch package. The EVA Access Modules would be launched separately and connected on site.

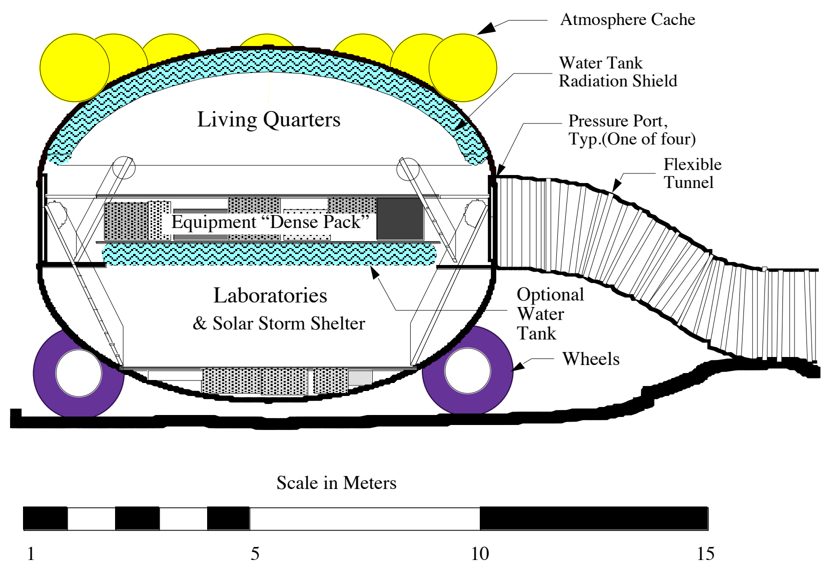


FIGURE 4a. Transverse section through the "Strategies for Mars" habitat showing water radiation shielding and solar storm shelter.

Each module provides four radial pressure ports, nominally separated at 90° around the perimeter of the habitat module. These multiple pressure ports and hatches to be enable the attachment of least three other pressurized modules to each habitat, plus one sample airlock into which robots can place containers with samples stored outside the habitats.

The transverse section in FIGURE 4a shows a Mars science laboratory on the lower level.[8] This laboratory would be where the crew examine and test samples they have retrieved on excursions outside the habitat. Another use for a lower level facility would be an agricultural laboratory where the crew would conduct experiments with plants under Mars conditions including the use of regolith for soil, water from regolith or Mars atmosphere, and of course, .38g.

8. *Flexible Pressurized Tunnels Between Modules.*

These flexible (instead of rigid) tunnels connect the modules at the "mid-deck" level of each habitat can so that there are dual means of egress from each mid-level. The tunnel is collapsible to accommodate packaging for flight and expandable to accommodate differences in distance and elevation between the modules at each end. With two habitat modules, there would be egress to the other habitat and egress to the EVA Access Module.

[8] Subsequent radiation protection studies suggest moving the crew living quarters to increase protection where the crew spends at least half of each sol to the lower level and the laboratory to the upper level.

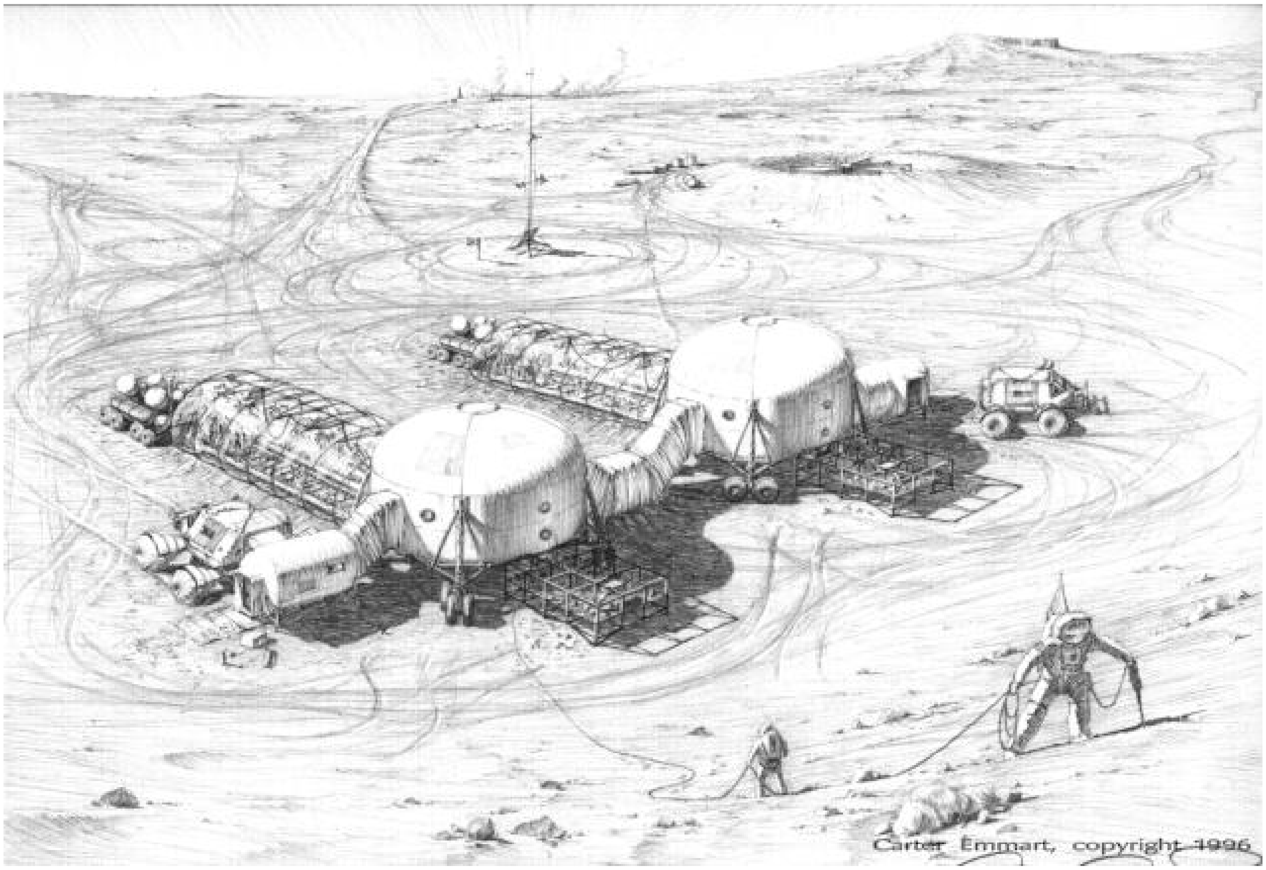
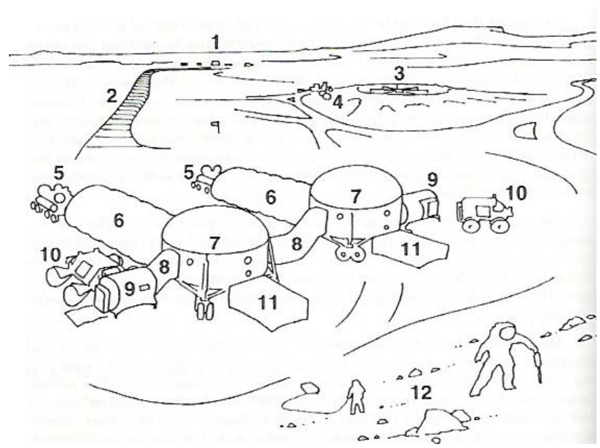


FIGURE 4b. Strategies for Mars interpretation of the Joosten, Weaver, and Duke habitat concept, designed by the Marc Cohen, drawn by Carter Emmart (renewed permission from Carter Emmart).

FIGURE 4c. Key to the Strategies for Mars Habitat



1. Landing Zone at least 5 km from the base for safety in case of a crash or an explosion.
2. Sintered road to the LZ on which to move the large payloads, including habitat modules.
3. Nuclear fission reactor in a crater.
4. Control facilities outside the crater.
5. ISRU production plant.
6. Inflatable greenhouse.
7. Pre-integrated habitat.
8. Flexible pressurized tunnel.
9. EVA access module.
10. Pressurized rover.
11. Scientific sample storage with robotic retrieval.
12. EVA astronauts exploring a nearby slope.

9. EVA Access Modules

Move the airlock units out from underneath the habitat modules to create distal EVA Access Modules that provide more docking ports for pressurized rovers and EVA hatches. These EVA Access Modules could accommodate a pair of Suitports with the suits hanging in an internal airlock that could be pressurized to allow suit maintenance and repair. In a "contingency" requiring evacuation of a habitat module, an EVA Access Module would provide a second remote means of emergency egress. Using the pressurized rover docked there, or the space suits, the crew could transfer to the other EVA Access Module to access the unevacuated habitat module.

10. Pressurized Rover

The Mars base configuration includes pressurized rovers as part of the operational ensemble. These rovers dock to a pressure port on the EVA Access Module. The rovers play an essential role in moving newly landed crew from the LZ to the habitat and vice versa for crews departing on the DAV.

11. External Scientific Sample Storage Facility

The Mars base ensemble includes an external scientific sample storage facility, serviced by inventory robots that would place the requested sample in a sample airlock connecting to the interior of the laboratory level. Sample material that is not consumed in the laboratory could be returned to the storage facility. See FIGURE 14 for more details on the operational arrangement for external sample storage, sample airlock, and laboratory processes. An early example of a "sample airlock" appears in FIGURE 6b (originally the food and supply airlock for planned long duration mission simulations).

12. EVA Astronauts Exploring a Slope

EVA systems, including suits, portable life support systems, tools, airlocks, and rovers (both pressurized and unpressurized) embody an essential capability for the crew to carry out the mission. The crew would devote the early periods of the surface mission to exploring the terrain around the Mars base, collecting samples, and taking them back to the laboratory for analysis. Some of these samples will be packaged for return to Earth, for further study and providing that they are proven to be devoid of biological activity, for distribution to laboratories around the world.

III. The First NASA Mars Design Reference Mission (MDRM 1.0)

By the time Stoker and Emmart went to press in 1996, there was a broad but lively debate and very little consensus on what should be the baseline human mission to Mars, given the shared assumptions about nearly all aspects of mission design and architecture. Stephen Hoffman and David Kaplan undertook the grueling task of combining it all into a unified and coherent document: <u>Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team</u>, commonly called the MDRM (1997). Throughout this process, the team continued to debate and work and subsequently distilled their findings. A selection of figures and tables from the MDRM 1.0 appear in the Appendix to illustrate some of the key features of the scheme that rarely received attention or scrutiny.

The reader might ask why give so much attention to the first MDRM when there have been two later published revisions. The reason is that MDRM 1.0 constitutes the foundation of NASA's humans to Mars planning. If the foundation has structural flaws, everything built upon it may be vulnerable to those flaws.

A. MDRM 1.0 Strengths

The MDRM played up the strengths of pre-positioning cargo and the first habitat and achieving reliability through redundancy and availability. In an interview with Paul Raeburn for Popular Mechanics (1999, pp. 43-45), Kent Joosten gives a more concise and elegant explication of the MDRM habitat concept than the MDRM itself:

> We look at when we would like the crew to arrive on Mars. Twenty-six months before that, we send out as much of the critical material as we can, and make sure it gets there, make sure it's operating, before we send the crew.

Then, Raeburn summarizes the relevant aspects of the MDRM:

> The mission begins with the launch . . . of two rockets to send payloads to Mars. One payload is the mission's Earth-return vehicle, which is put in orbit around Mars . . .. The second payload includes the surface habitat and its power systems, a fuel-production system, rovers, and other exploration equipment and the Mars ascent vehicle.

Raeburn quotes Joosten again:

> You can't punch out and come home any time you want to, and you can't resupply from Earth any time you want to . . .. Once you send them there, they are going to have to be self-reliant . . .. The crew has two sets of everything if they get in trouble.

Raeburn concludes:

> The second surface habitat can be designed to attach to the first, expanding crew space. Another notion is to begin growing food on Mars, using one off the habitats as a plant growth chamber.

Grigoriev and Potopov (2002, p. 3) provide insight into this crucial new dimension of crew self-reliance and autonomy on a Mars mission:

> Autonomy is the most distinctive feature of interplanetary missions as compared with orbital flights. It suggests crew independence and self-sufficiency as far as functioning, choice, and timing of psychological support measures; health monitoring, countermeasures, diagnostic investigations, and medical care are concerned. This self-reliance will add to the crew loading, responsibility, and stress . . . . so that many functions currently executed by the ground controllers will be entrusted to the crew.

Along the way, many of the Mars surface habitat details fell into the background as the MDRM team made the cognitive leaps of generalization and abstraction (Joosten, Schaefer, Hoffman, 1997). The MDRM retained the general aspects from Stoker and Emmart and TABLE 1, while in situ fueling of the ascent vehicle on the Mars surface, inspired by the "Mars Direct" mission architecture (Zubrin, Baker, Gwynne, 1991; Zubrin, Wagner, 1996, pp. 113-137) and supplying life support consumables (Meyer, McKay, 1996, pp. 363-392). However, with the exception of including fuel production from in situ resources, the MDRM 1.0 did not accept the refinements presented in Stoker and Emmart or any other alternative concept that arose over those five years, retaining the pristine 1993 Joosten/Frassinito habitat design.

Hoffman and Kaplan (1997, pp. 1-19 to 1-21) provide further insight about the MDRM 1.0 habitats:

> The crew is transported to Mars in a habitat that is fundamentally identical to the surface habitat deployed robotically on a previous cargo mission. By designing the habitat so that it can be used during transit and on the surface, a number of advantages to the overall mission are obtained.
>
> Two habitats provide redundancy on the surface during the longest phase of the mission.
>
> By landing in a fully functional habitat, the crew does not need to transfer from a "space-only" habitat to the surface habitat immediately after landing, which allows the crew to readapt to a gravity environment at their own pace.

This last assertion by Hoffman and Kaplan about landing in a "fully functional habitat" opens the Pandora's box of what became known as the "split habitat" design concept that revealed how MDRM 1.0 skewed toward its peculiar design problem decomposition. The design products of MDRM 1.0, in their simplest recounting, were:

1. An Earth to Mars crew habitat in which the crew flies from LEO to Mars on an IPV, lands, and operates the surface mission,
2. An ascent vehicle that the crew flies to Mars orbit at the end of the mission, and
3. A different Mars to Earth habitat on a second IPV, neither necessarily common with the first IPV.

B. MDRM 1.0 Weaknesses

Given these simple elements, the design for the MDRM mission architecture followed internally consistent design logic. However, paradoxically, it produced a set of habitable modules that were sub-optimized in all respects: in terms of architectural design, functions, and planned utilization. In large part, this underachieving derived from the rigid determination to retain the Joosten 1992-1993 habitat designs in their original form and to not incorporate any of the progress by others, particularly from 1993 through 1996. The MDRM 1.0 addendum (aka MDRM 3.0) also largely excluded new work except for the addition of a deployable inflatable. What the MDRM 1.0 mission architecture-driven habitats actually comprised were:

1. The TMIV habitat does double duty both as an interplanetary and surface habitat, for both of which purposes it is badly compromised;
2. The dedicated crew MAV is underutilized insofar as it is capable of landing the crew but must enter the Mars atmosphere and land on the surface, but does so without the crew; and

3. A second but differently designed interplanetary habitat on the TEIV [does not land on Mars or Earth] that is sent to Mars to wait for the crew to return but carries them only one way.

The idea that two of the three major elements of the Mars Mission Architecture (MAV and return IPV habitat) should serve only half their purpose while the third should do *triple duty* as an IPV, propulsive aerobraking lander, and surface habitat, and that the outbound IPV habitat should be different and separate from the inbound habitat was problematic from many points of view. The debate over this disposition of the Mars mission architecture began early in the decade of the 90s and raged for several years. Duke and Budden (1993, p. 17) discussed this lack of unanimity in their "workshop report:"

TABLE 2. Interplanetary Vehicle Habitat versus Planetary Habitat
Key Design Parameters for Optimization Strategies (from Cohen, 1996c, p. 11)

Design Parameter	Unique to Interplanetary Vehicle Habitat	Common to Both Habitat Designs	Unique to Planetary Surface Habitat
1. Radiation Shielding	Must launch to LEO, don't drag it down to planet.	Water possible for both, but from different sources.	Can extract water from Mars atmosphere or regolith.
2. Pressure Ports	2 Ports at distal axial ends	Dimensions, controls, structures, and mechanisms.	4 or more peripheral ports w/ dust control.
3. EVA Airlock	May incorporate an airlock and Zero-gravity optimized suits.	Both may include a separate, external EVA module.	Separately landed habitat & airlock module allows on-surface assembly.
4. Laboratory Facilities	No use for the Lab Facilities going to Mars, minimal use on return voyage.		Laboratory will provide the center of the Working Environment.
5. Countermeasures Against Weightlessness	Countermeasures such as a small diameter, human-powered centrifuge	Exercise regimens for aerobics and weight training	Zero-gravity countermeasures less important in the .38 G on Mars.
6. Gravity Orientation	Optimize for μ-g IVA operations.	NO EASY COMPROMISES	Optimize for partial-g operations.
7. Life Support	Plan for physical / chemical closed-loop regenerative system, with possible plant-growth unit.	Some common components for physical/chemical systems.	Plan for physical /chemical system that includes local resources (atmosphere) with CELSS component.
8. Safety, Reliability & Quality Assurance Strategy (SR&QA)	Pure Reliability Strategy: Propulsive character demands .99999 reliability		Availability Strategy: Resupply & repair complement standard reliability approaches.
9. Habitat Construction	Pre-Integrated Units with minimal assembly and outfitting.	Some assembly	Pre-Integrated, Pre-fabricated, Assembled, Deployed, and ISRU are all feasible and preferable.

The Ames Research Center study team . . . has made the argument that the prime importance of the surface mission will make it imperative that the surface habitat system be designed specifically and totally for use on the surface. They argue that functionality of a space vehicle and a surface habitat will be incompatible. Thus, they disagree with a basic premise of the current reference mission that the crew will be transported to the Martian surface in their transit habitat, which will augment the surface habitation already delivered to the surface robotically. If the crew is landed in a short-term crew lander, there are significant implications from the requirement that they transfer from the lander to the habitat in a short period of time, thus requiring that they land in a physical condition that is suitable to that transfer. This in turn, could dictate an artificial gravity space

> transit vehicle or other equally severe requirements. Thus, the implications on total mission design and cost is severe. This disagreement needs to be tested in additional trade analysis and studies.

This critique developed until it became possible to enumerate the objections in detail, as shown in TABLE 2. Hoffman and Kaplan remark upon the debate in the MDRM itself (1997, p. 1-31) where they acknowledged it:

> 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. Some argued that, due to the different requirements, a common design was not in the best interest of the mission. This is an area for further research.

TABLE 2 shows nine key differences between an IPV habitat and a Mars surface habitat that would be impossible to reconcile in the triple-duty IPV habitat/lander/surface habitat. In arguing the rebuttal to the objections conveyed in TABLE 3, the split-habitat advocates cited three main justifications for their set of design decisions:

1. "System engineering voodoo" (as Harry Jones described it): there was some quantitative analysis, known only to a few, that showed that the MDR 1.0 split habitat mission design involved the least resources, mass, and cost. None of the three published DRMs nor their addenda reveal this quantitative analysis.
2. Entering the Mars .38g environment would afford a countermeasure against the time the crew spent in μ-g on their way to Mars. Hoffman and Kaplan (1997, pp. 1-19-1-21) conveyed this complacency that remained largely unchanged 12 years later in MDRM 5.0:

   > "By landing in a fully functional habitat, the crew does not need to transfer from a 'space-only' habitat to the surface habitat immediately after landing, which allows the crew to readapt to a gravity environment at their own pace."

The only real differences between designing a transit and a surface habitat were the magnitude of gravity (μG vs. .38g and the local vertical gravity orientation), which difference can and should be minimized (Hoffman, Kaplan, 1997, p. 1-21). Therefore the TMIV habitat could meet the demands of both gravity regimes without difficulty.

Item 2, the therapeutic effects of .38g stood solely on an article of faith. This MDRM 1.0 statement expresses the magical thinking that the 0.38g of Mars will provide a sufficient countermeasure simply because it is some gravity. This assumption has no basis in science or any other credible source, but reveals how mission planners are willing to bet on fantasy before accepting the necessity of supporting the vital life science research. The fantasy that landing on Mars somehow provides a countermeasure to six months in μ-G has been refuted by laboratory science. Ellman et al (2011) and Wagner et al (2010) demonstrated experimentally by partial-weight suspension of jacketed mice that .38G "loading" does not cause the desired therapeutic effect of reversing bone loss, but instead that bone demineralizes very much like it does in μ -G. However, this magical thinking continues within the exploration community, to this day.

C. MDRM 1.0 Credibility Gap

Taken all together, these three rationales left a credibility gap. From a design methodology perspective, these three rationales and justifications failed to explain the totality of the design decisions as well as several of the most important specifics. What remained completely unexplained was why there should be two different IPV habitats, one for TMI and the other for TEI, each the product of separate design, development, technology, and engineering processes. It thus became necessary to dig deeper into the design logic and the design politics underlying MDRM 1.0.

When pressed very hard, the split-habitat advocates confessed that the hidden design logic came in applying the "Big Lesson Learned" from the Space Shuttle and Space Station programs (the Lesson Learned that was never published with all the other lessons learned).[9] In the case of Shuttle and Station, the original concept was to build the space station as the key destination for the Shuttle. In the early to mid-90s, crew operation of the ISS appeared

[9] Personal conversations with John Connolly, Mark Craig, Bret Drake, Michael Duke, Stephen Hoffman, Kent Joosten, David Kaplan, Wendell Mendell, David Weaver, and many others. Mike Duke explained these lines of reasoning to the author, although he did not exactly advocate or defend them. However he did allow that if an IPV habitat contained 42 tons of water, he would not want to land it on the surface (please see section IV Interplanetary Vehicle, below).

to be still at least a decade away; it would be 25 years after the Shuttle began flying in 1981. The Big Lesson Learned conveyed two findings regarding the Shuttle and the Station. First, without the Space Station, the Shuttle "had nowhere to go." Lacking an "anchor in space," the Shuttle program could fall prey to cancellation or could grow obsolescent before the Space Station began full operations. Second, and conversely, without a vigorous program of various Shuttle upgrades and extensions, or alternatively the development of a "next generation" crew spacecraft to replace the Shuttle, there might be no means to transport crew to the Station to operate it. Both these aspects of the "Big Lesson Learned" *proved prophetic* as applied to the ISS, the Orion, and the Commercial Crew Program.[10]

Applied to the Mars mission architecture, this lesson warned that it would be all too easy for politics in the administration or in Congress to separate the Mars mission elements and build only one or two but never carry out the complete Mars exploration program. For example, if an IPV with habitat could fly a crew round trip to Mars, then the same thing could happen as did with Shuttle and Station: an administration might request funding only for the IPV or Congress might fund only the IPV, resulting in a 25 year gap until funding became available for the surface habitat.

The only way to comprehend this MDRM 1.0 design logic, was to recognize that each of the major elements was a puzzle piece intended to fit together into a total mission architecture completed puzzle, but that none of them would be useful by itself. No one piece should be able to accomplish any a portion of the mission solely by itself. Therefore, the IPV habitat could not return the crew to Earth because it must land on the surface. The MAV would not land the crew on the surface separately from the IPV habitat because its purpose was only to launch the crew from the surface to the Earth-return IPV. The Earth-return IPV could not deliver the crew to Mars because it would unnecessarily duplicate the purpose of the IPV/Surface Habitat. Therefore, each major element would be utterly useless unless Congress funded NASA to build all three at the same time.

A further subtext existed in the two different IPVs and their different habitats. Both the two "Code M Centers," the human spaceflight development centers -- JSC and Marshall Space Flight Center (MSFC) -- wanted to develop their own major spacecraft, their own propulsive vehicle and habitat. In the Space Station development process during the 1980s and early 1990s, there here had been a battle royal over which Center would build the nodes, the modules, the EVA airlock, the outfitting for all of them, and which Center would provide control of which operations. Since MDRM 1.0 was an agency-wide cooperative effort, the election of two IPV/habitat developments could satisfy each Center; each could look forward to designing and building its own "full service" spacecraft, and avert a repetition of the bruising inter-center "space station wars."

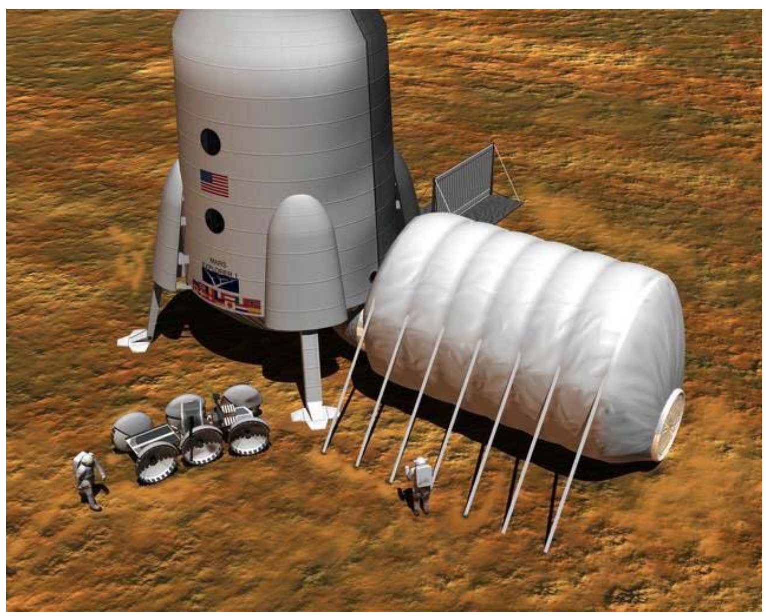


FIGURE 5. MDRM 3.0 hybrid pre-integrated IPV/ Habitat/ Lander and its inflatable extension. Note the unpressurized rover and the absence of a visible airlock (NASA Image).

E. MDRM 3.0 Addendum

The next year, NASA issued a revision to the original MDRM, labeling it the MDRM 3.0 Addendum (Drake, 1998). This revision deleted the pre-positioning launch of the first Mars Surface Habitat, based on the rationale that an inflatable section could provide an equivalent amount of pressurized volume (Drake, 1998, p. A2.2). In the completely biased perception of the author, the first MDRM disturbed NASA management because of the size and scope of the commitment that it implied. Even before MDRM 1.0 (1997) came out in print, NASA management directed a small group to reduce scope and cost, and especially to reduce the number of launches. Prepared in camera – perhaps because of the unease it engendered -- MDRM 3.0 came as a surprise to the many MDRM 1.0

[10] https://www.nasa.gov/exploration/commercial/crew/index.html

team members outside a small circle in Houston. This reduction came at the expense of sacrificing the entire prepositioning and reliability strategy laid out so eloquently in Weaver and Duke (1993), Stoker and Emmart (1996), and Hoffman and Kaplan (1997). The crew would need to fly to Mars in the same habitat as they use to land and live on the surface, eliminating any prospects for separate and distinct interplanetary and surface habitat designs. 3.0 also eliminated the opportunity to include a Mars Surface Science Laboratory, which had been an option in 1.0 with two pre-integrated habitats. And despite the putative efforts to reduce cost, there would still be a split IPV habitat incurring two separate, duplicative, costly development processes. It appeared that the system engineering voodoo was to sacrifice most of the measures to ensure mission success and crew safety to give an appearance of reducing cost.[11]

III. Habitat Analogs, Mockups, and Simulators

One of the most encouraging aspects of the productive period of the 1990s was the number of habitat mockups, analogs, and simulators that Mars enthusiasts built and began to use for testing. These analogs, mockups, and simulators foster a beneficial but complex interaction between concepts and physical and operational realization. Mohanty, Fairburn, Imhof, Ransom, and Vogler (2009), provide an overview of these efforts.

NASA researchers started habitat simulator projects such as the Human Exploration Demonstration Project (HEDP) in the Controlled Environment Research Chamber (CERC) at Ames Research Center and the Bioregenerative Planetary Life Support Test Complex (BIO-Plex) at Johnson Space Center. The HEDP was collaboration among four research divisions: Human Factors, Information Science, Life Science, and Life Support (Clearwater, 1992; Cohen, 2002a). HEDP focused on renovating the S-18 Altitude Chamber – originally built in the 1960s to simulate a human Mars Mission – and using it as a research laboratory (Chevers, Korsmeyer; 1993; Gross, Korsmeyer, Harper, Force, 1994; Rosen, Korsmeyer, 1993). FIGURE 6 shows the upper and lower level views of the HEDP, with the working environment on the upper, entry level of the CERC and the Human Powered Centrifuge (HPC) installed and operating as a research facility in the lower level.

FIGUIRE 6a. Crew accommodation outfitting in the upper level of the Controlled Environment Research Chamber (CERC) (NASA Photo).

FIGURE 6b. The rebuilt upper level of the CERC before installation of the crew accommodation outfitting (NASA Photo). Note the "sample airlock" to the left of the pressure hatch.

[11] One of the pieces missing from the MDRM 3.0 addendum was an errata that the editors promised, to include corrections to the MDRM 1.0. Perhaps, most notable of these repeat errors and omissions was that Table 3-14 for the "Earth Return Habitat Element Mass Breakdown" for a single duty habitat that operates for only ~200 days one way in deep space should how exactly the same masses as Table 3-13 Mars Transit/Surface Habitat Element that would do triple duty as a ~ 200 day IPV habitat, aero-entry lander, and surface habitat for 500 to 600 days operation. An earlier draft version showed that whereas the "dry mass" for 3-13 was 29.4 mTons, the dry mass for 3-14 was 15 mTons. This late change and the lack of correction of an acknowledged error was especially problematic insofar as it gave the appearance of trying to obscure the details of the split habitat in the return IPV; it cast further doubt on the entire system engineering methodology.

With respect to μ-g countermeasures, Joan Vernikos[12] states:

> The Centrifuge is the best thing we know but need to find out how much, how often, how long, when etc. To validate it in space we must get it done on ISS or to possibly on the Moon. Make a long-lasting research commitment to get the answers to the formula otherwise we can talk about exploration but we do not mean it [emphasis added].

These countermeasures against long term debilitating effects of zero-G and Mars will be critical to conducting successful missions in deep space and in partial-G on Mars. Vernikos and Schneider (2009) published a review article on intermittent gravitational loading, space, and aging effects. They narrate how prolonged exposure to μ-g acts as an accelerated mode of aging for the skeletal system, with increased bone-demineralization. They suggest intermittent high-g centrifugation as a potential countermeasure for both conditions.

At Ames, David Bubenheim built a large crop growth chamber with liquid-cooled lighting at Ames Research Center. Bubenheim his team at Ames pioneered engineered plant growth research for bioregenerative life support (Bubenheim, Luna, Wagenbach, Haslerud, Straight, 1989; Bubenheim, 1991; Bubenheim, Wydeven, 1994). The parallel HEDP team made plans to incorporate bioregenerative systems into the CERC during HEDP's later phases of development.

FIGURE 6c. The Human Powered Centrifuge (HPC) in motion in the lower level of the CERC (NASA Photo).

FIGURE 6d. The HPC in the lower level of the CERC, showing the active and passive subject couches, the auxiliary bicycle drive, and the ship ladder to the upper level (NASA Photo).

At JSC, Dan Barta and Don Henninger (1994) made the case for the need to develop Bioregenerative (closed-loop) life support systems, particularly based upon plant growth. Thus, the BIO-Plex originated primarily as a life support laboratory. Research efforts in the BIO-Plex focused initially on plant growth and biomass production, although there were also some habitability experimental mockups installed (Barta, Castillo, Fortson, 1999; Finn, 1998; Imhof, 2000; Jones, 2000; Jones, Finn, Kwauk, Blackwell, 2001; Perchonok, Vittadini, Swango, Toerne, Peterson, 2001; Weaver, Hurlbert, Ewert, 1998).

Both simulator projects met a similar fate; after seed funding and a promising start, it was difficult to sustain the effort in terms of funding and agency support, with both falling off, HEDP by 1995 and BIO-Plex by 2002. However, in the case of HEDP, the HPC has been retained as a research facility and still is in very active use by the for biomedical research.

One simulator project achieved a lasting milestone of success, perhaps because it was planned to operate over a limited period with very specific objectives and did not require building, outfitting, and maintaining an expensive and complex facility on a permanent basis. That project was the Lunar-Mars Life Support Test Project (LMLSTP),

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[12] Past Chief of the Life Science Division at Ames Research Center and Director of Life Sciences at NASA HQ, e-mail to the author, 7 Oct 2010, http://www.joanvernikos.com/.

which was installed and operated in the 20-Foot Atmosphere Chamber at Johnson Space Center in the latter part of the 1990s. The LMLSTP involved a series of crew-isolation; partially closed chamber test runs, including a 60-day and a 90-day test (Barta, Henderson, 1998; Lewis, Packham, Kloeris, Supra, 1998; Meyers, Staat, Tri, Smith, 1997).

FIGURE 7 shows the 20-Foot Altitude Chamber at JSC where the researchers conducted the LMLSTP Analog studies were not limited to the laboratory or NASA centers. Soon after the 90-Day Study, there was a surge of interest in analog studies into exploration expeditions and Antarctic bases as an analog to Mars habitation and exploration (Anderson, McKay, Wharton, Rummel, 1990; Harrison, Clearwater, McKay, 1991; Tanaka, Watanabe, 1994). These ideas and field research continued and grew (Bishop, 2002; Dudley-Rowley, Nolan, Bishop, Farry, Gangale, 2000), and produced data that can help the design of Mars Habitats (Dudley-Rowley, Whitney, Bishop, Caldwell, Nolan, 2001).

FIGURE 7. View of the 20-Foot Atmosphere Chamber at JSC where NASA conducted the LMLSTP (author photo, January 2010).

Perhaps the most notable of these Mars analog simulation projects is the Mars Society's Flashline Mars Arctic Research Station (FMARS). FMARS was based loosely on the habitat concepts from Mars Direct. Kurt Micheels (1999, 2004) the Architect of Record for FMARS provides illuminating insights into the challenges, and initial successes, and failures of this enterprise. FIGURE 8b shows views of the FMARS EVA activities in 2009.

FIGURE 8a. View of the FMARS habitat site on Devon Island, summer of 2009 (Photo credit: by permission of Brian Shiro http://www.astronautforhire.com/).

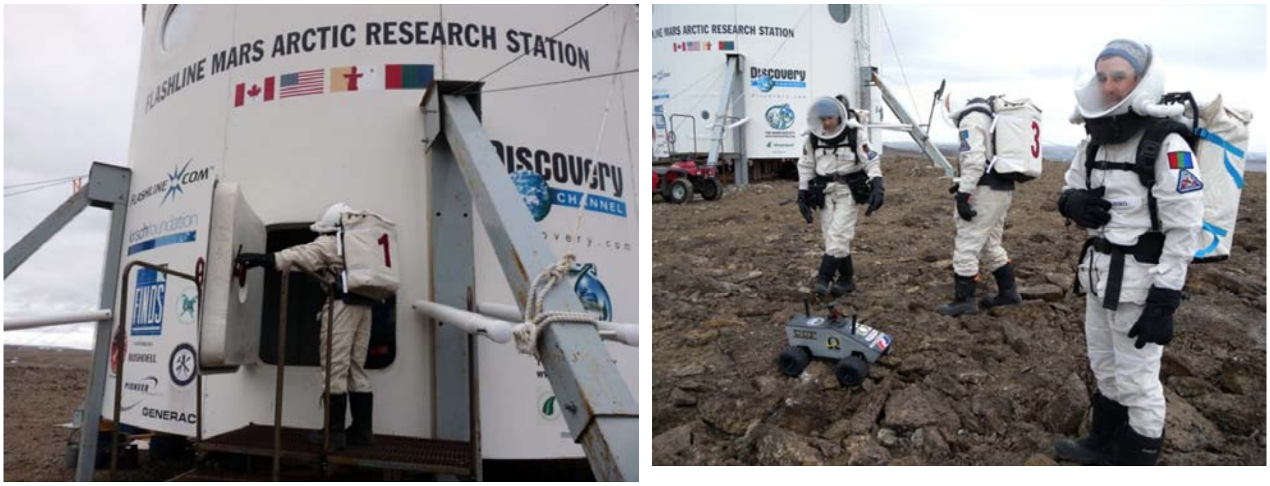

FIGURE 8b. Views of the FMARS habitat on Devon Island, summer of 2009 (Photo credit: by permission of Brian Shiro http://www.astronautforhire.com/).

The selection of appropriate analog models and the design of simulation for the Moon and Mars emerged as an active topic of discussion in both the serious and semi-serious humans to Mars initiatives (Bannova, 2010; Nixon, Ovrum, Clancy, 2009). 2010 saw the start of the 500-day "EuroMars 500" simulation in the closed chambers at the Institute for Biomedical Problems in Moscow. EuroMars 500 produced a wealth of data, or at least anecdotes, about the crew interactions, including workload, multi-cultural, and social interactions, and relationship to "Mission Control" over a 20 minute communications time latency, to name but a few areas of the results. However, it does not appear to have produced much new information about habitat design.

The Institute of Medicine reported (Ball, Evans (Eds), 2001, pp. 140-131) that analog studies could provide "instructive data:"

> Data from analog settings are instructive since those who have spent considerable periods of time in isolated, confined, and harsh, dangerous environments have confronted many of the external stresses common to long-duration space missions. Two examples are sailors on U.S. submarine patrols and groups wintering over in the Antarctic. . . .
>
> Among men and women spending 6 months living together during an Antarctic winter, where evacuation was nearly impossible, the Australian National Antarctic Expeditions Health Register estimated the rate of mental disorders to be 2.3 percent. As with the experienced astronauts aboard Mir, the incidence of behavioral problems was dramatically less among seasoned veterans.

Ball and Evans (2001, pp. 145-146) state a caveat about observations and data collection from small groups in analog environments:

> The conditions under which such experimental observations or even observations from analog environments are made usually differ considerably from those encountered in operational spaceflight situations. The benefits and disadvantages of traditional approaches to the study of small-group dynamics have been well documented. When observations of the behaviors of small groups are made when the groups are in their natural habitat or in an analog environment, the generally ethnological monitoring and recording of both current and long-term events lack experimental rigor. On the other hand, data gathered on small groups in controlled experimental settings may demonstrate functional relations, but the analysis of progressive changes in external influences and the development of internal group equilibrium is [sic] often neglected.

This discourse extends to the limitations and contraindications for analog studies. Rudisill, et al, (2008, p. 7) discuss the differences between NOAA's Aquarius undersea habitat (that NASA uses for the NEEMO program) and a lunar base. They describe four areas of difference as life support, crew provisioning, crew health care, and mission control. Rudisill et al (2008, p. 10) found also "no convergence" among the analogs they studied for estimating requirements for crew volume.

IV. The Interplanetary Vehicle

In the latter half of the 1990s, it became possible to focus upon the unique and peculiar characteristics of an optimized interplanetary habitat as opposed to the MDRM 1.0's deliberately sub-optimized IPV habitat design concept. Outside of the MDRM innermost circle, there was widespread dissatisfaction with the split-habitat design, aggravated by lack of understanding of how it became part of the configuration.

A. 1997 Interplanetary Habitat

This effort substantiated the distinguishing features that would differentiate it from a surface habitat. FIGURE 9 shows the 1997 Interplanetary Habitat (Cohen, 1997a) that incorporated 42+ tons of internal water shielding for radiation protection. There would be no reason to land this water on the Mars surface.[13] Instead, it would stay in space and the crew could transfer it from the outbound interplanetary vehicle to the inbound one.

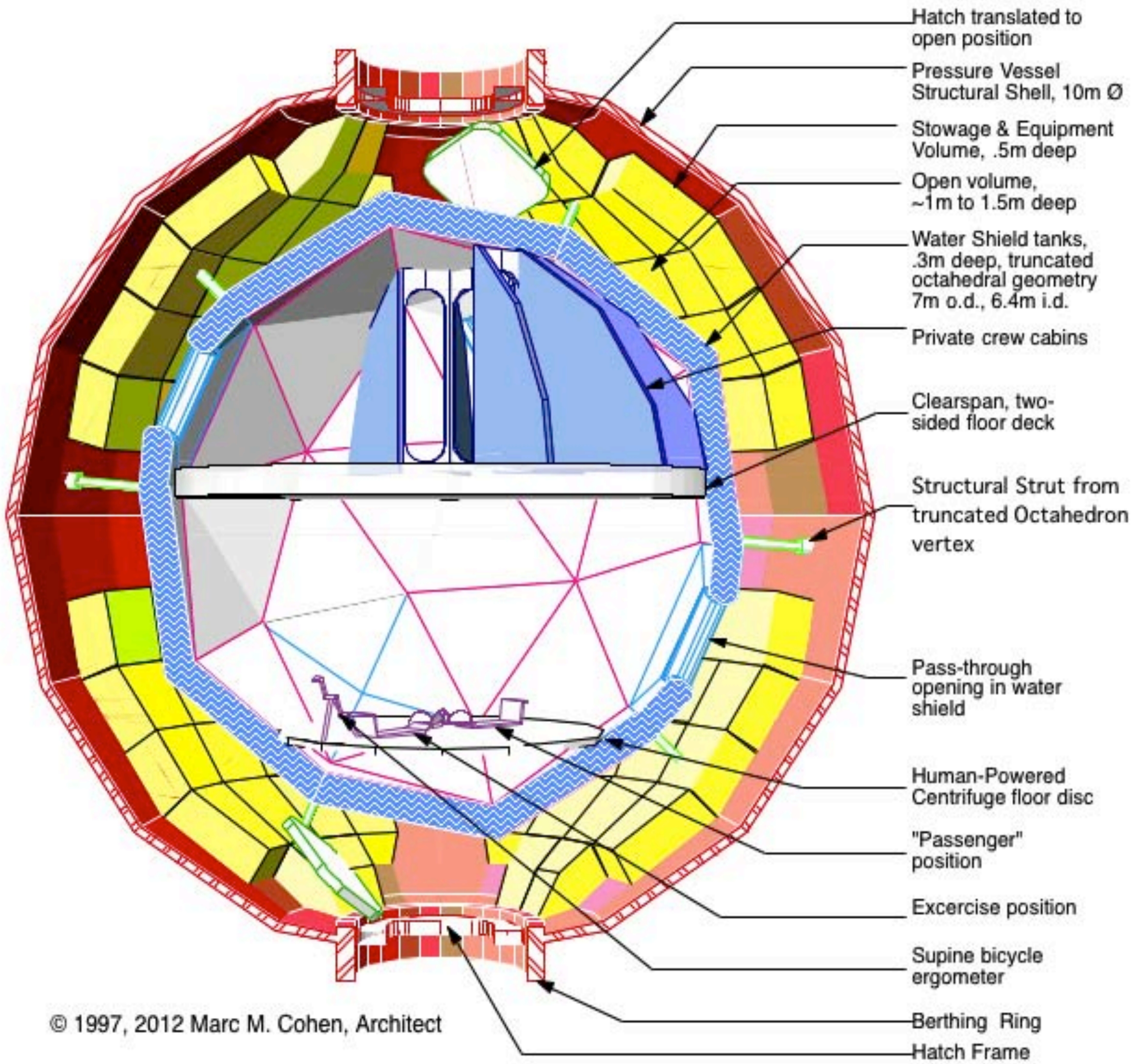

FIGURE 9a. The 1997 Interplanetary Habitat featuring internal water shielding for radiation protection surrounding the crew living quarters and a human powered centrifuge on its lower level (Cohen, 1997).

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[13] In 1998, after publication of the MDRM 1.0, Mike Duke confessed to the author that if the IPV habitat did contain 42 tons of water for radiation shielding, he would not want to bring it down the Mars surface, but instead would find a way to use the habitat, or at least its water, in the return TEIV IPV.

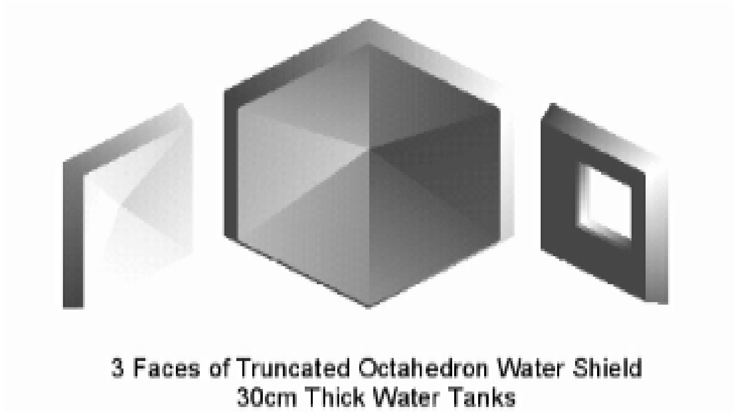

FIGURE 9b. Water tanks shapes for the truncated octahedral geometry of the radiation shield in the 1997 Interplanetary Habitat (Marc Cohen, 1997).

B. The TransHab

The dissatisfaction with the MDRM 1.0 IPV habitat persisted and grew. NASA JSC began to develop an alternate solution as a dedicated interplanetary habitat, intended exclusively for in-flight use, known as the Transit Habitat (TransHab) for the journey to Mars and back, but not for landing on the Mars surface. Kriss Kennedy and Constance Adams worked as the principal architects of the original inflatable TransHab concept at JSC. The TransHab emerged as a remarkable development that combined a full-scale mockup, technology testing, and an alternative to the MDRM 1.0—3.0 habitat-of-all-trades.

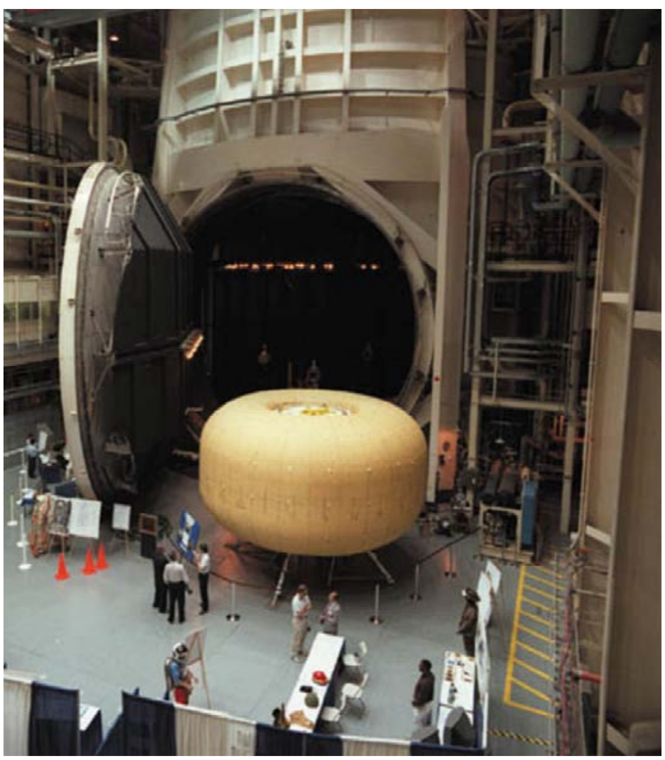 

FIGURE 10. TransHab prototype undergoing testing in the vacuum chamber at NASA JSC (NASA photo) and a cutaway view of a TransHab module-outfitting concept (NASA image).

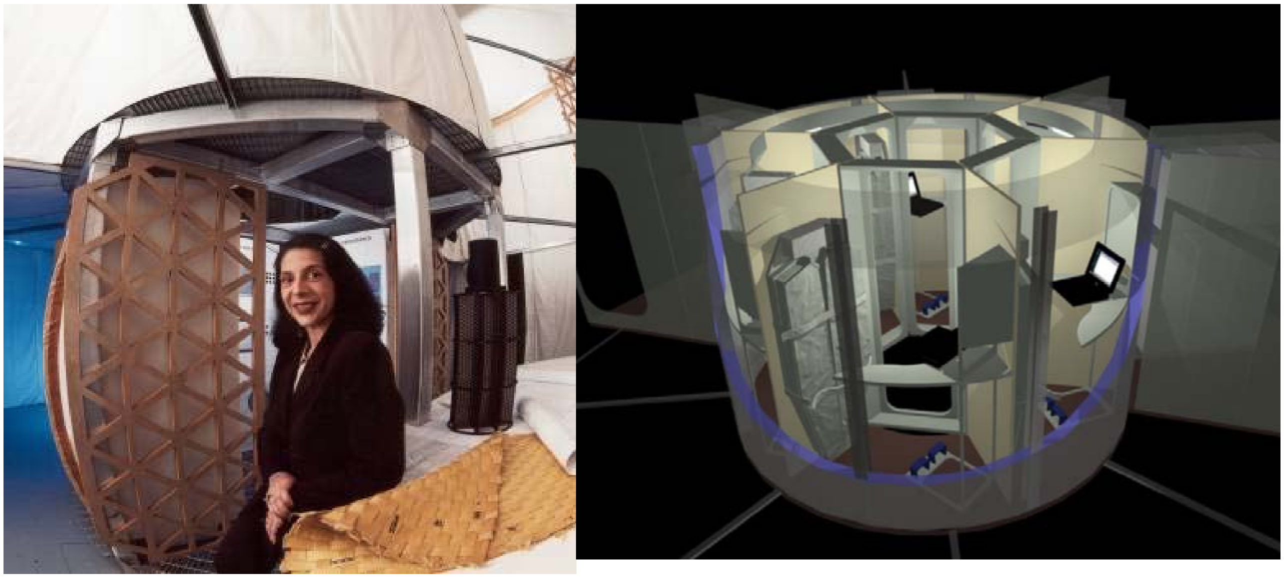

FIGURE 11. Constance Adams with crew accommodations mockups for the TransHab interior and a CAD rendering of the crew sleep quarters with water-shield walls.

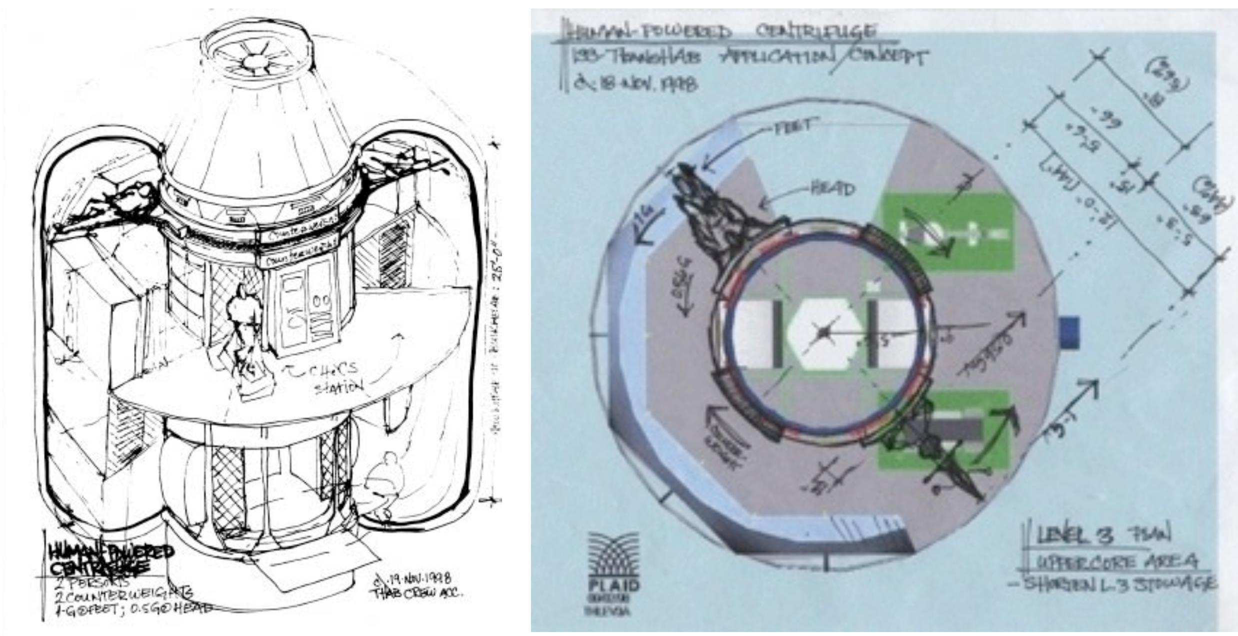

FIGURE 12a. Constance Adams' sketches for the installation of a human-powered centrifuge as the TransHab outer middle deck (Courtesy of Constance Adams).

The TransHab is an inflatable module deployed from a rigid central axial core, somewhat like a fat tire (Kennedy, 2009b, pp. 81-88). FIGURE 10 shows a TransHab prototype module in a large vacuum chamber at JSC for testing plus a cutaway view of the TransHab interior. The crew sleep quarters are on the middle deck and the galley and wardroom on the lower deck. FIGURE 11 shows a CAD rendering of the crew sleep accommodations on the middle deck. The thick blue cutaway walls represent the water shields containing 5 to 10 tons of radiation protection around the crew sleep compartments. FIGURE 12 shows Constance Adams' sketches to install a variation of the HPC on the middle deck – in fact as the middle deck. FIGURE 13 shows the TransHab attached to an interplanetary vehicle on its way to Mars (Borowski, Dudzinski, McGuire, 2002).

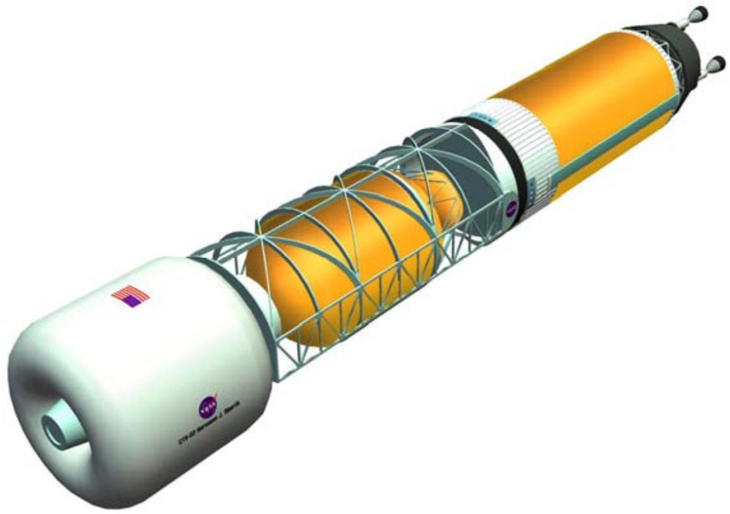

FIGURE 12b. **TransHab mounted on an interplanetary vehicle (NASA-Glenn Research Center, NASA TM-1998-208834/Rev 1).**

TransHab has gained a life of its own, since Bigelow Aerospace licensed the patent from NASA and began developing it with innovative design and new approaches to system integration for a private space hotel (Herman, 2009). Bigelow currently has two prototype inflatable TransHab-derived habitats in LEO, Genesis I, and Genesis II. Bigelow also is preparing the Bigelow Experimental Activity Module (BEAM) to be berthed to the ISS for crew testing and evaluation.

C. Longboats to Mars

In 2008, Donald Barker published a detailed study of Mars mission architecture that he called "Longboats to Mars." The image of the Viking longboat suggests a degree of autonomy, flexibility, and survivability that he saw as missing from extant concepts. Barker was a student at the University of Houston when the Mars Habitat concept with the inflatable top (FIGURE 21) was developed. In Longboats, he provides further detail on the inflatable portion of the habitat.

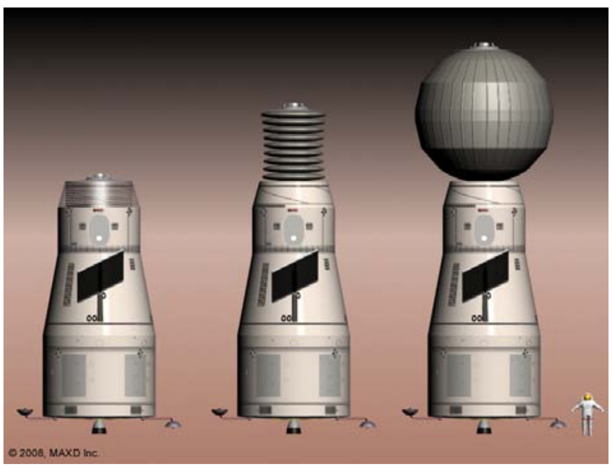

FIGURE 13a. The deployment sequence for an inflatable habitat on top of a "Longboats" lander on Mars (Courtesy of Don Barker).

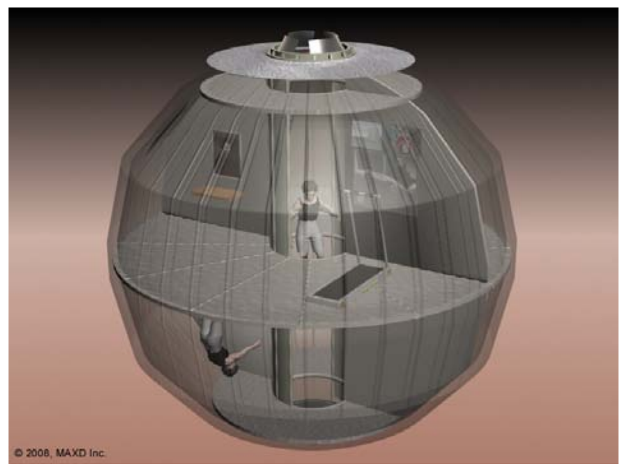

FIGURE 13b. Transparent view of the inflatable module, showing deck dividing upper and lower chambers (Courtesy of Don Barker).

His drawings show first in FIGURE 14a the deployment sequence for the pre-packaged inflatable, then a transparent view of the fully deployed sphere in FIGURE 14b.

In these illustrations, Barker accepts the reality that a sphere is the most natural form for an inflatable to take, assuming equal pressure distribution inside. It does not try to sculpt the inflatable into some artificial hemispherical or mushroom-like shape. Although the inflatable may appear like a large mass, in fact it is quite lightweight compared to the bulk of the lander, and should not pose a risk of overturning. In principle, this inflatable sphere could deploy in deep space while on the TMIV or TEIV trajectory, and also deploying after landing on the Mars surface.

V. Typologies of Habitat Construction

In the last years of the 1990s, NASA's focus was beginning to shift from design of the International Space Station, for which the Russian Space Agency launched the first module in 1998. Given the enormous demands of

ISS on people and resources, NASA responded by trying to become more systematic and process-oriented in its approach to almost every program and its systems and technologies to make them more predictable. This movement took the form of creating program and technology "roadmaps" on a semi-standardized template to make the programs and projects comparable in parallel over time so that they would become more predictable, rational, and hopefully sustainable (Mankins, 2001b).

Space habitats fell under this technology "roadmapping" campaign. As a way of organizing a system of classification for habitat types, Cohen and Kennedy (1998; Kennedy, 2009a, pp. 7-21) presented a "Habitats and Surface Construction Roadmap for the Moon and Mars." This roadmap centered upon an architectural taxonomy of habitat variations, and through successive iterations developed more sophistication about planning and structures (Cohen, 2002a; Cohen, Benaroya, 2009). It identified three main classes of habitat:

- Class 1: Pre-Integrated (e.g. ISS module or tuna can),
- Class 2: Deployable (including constructibles, deployables, and inflatables), and
- Class 3: Constructed or manufactured from In-Situ Resources.

Initially, these classes served to make clear distinctions among exploration program phases. Type 1 was the primary candidate for a First Lunar or Mars Habitat. Type 2 habitats constituted the "growth" area to expand the pre-integrated habitats and make a bridge to in-situ construction. Haym Benaroya (2002, 2010a, 2010b) published extensively about Type 3 habitats, particularly on the Moon, for permanent bases and settlements.

The evolution of habitat concepts beyond Type 1 shows more of a hybridization of typologies. Three recent examples of hybridization appear in the NASA Mars Design Reference Mission 5.0 (Drake, 2009), the International Space University (2009), and Cohen, Fox, and Thangavelu (2010). The MDRM 5.0 posits a lunar lander cum surface habitat that combines a pre-integrated descent module and airlock with an inflatable habitat, making it essentially a hybrid of Type 1 and Type 2 habitats. The ISU places inflatable and pre-integrated habitats in lava tubes on Mars, combining Types, 1, 2, and 3. The Cohen, Fox, and Thangavelu program for the Technical University of Vienna's "Destination Moon" architectural design studio requires modules that may be pre-integrated or inflatable to be installed under a cover of 3 m of lunar regolith, making it essentially a hybrid of Type 1 and Type 2 habitats. ISRU living environments may also be included. Within each of these initial types, there have been a number of refinements and variations that suggest the tripartite division may no longer be sufficient to describe the taxonomy; refinements and more detail in the typology may be necessary to keep up with the technology and design concepts.

VI. The Working Environment: Mars Surface Laboratories and EVA Systems

Once the MDRM development process was exhausted through version 3.0 in 1998, some team members began to turn their attention to what the crew should actually *do* on Mars. The design of mission systems still needed coordination and integration with the science objectives and strategies that scientists were beginning to articulate (Stoker, McKay, Haberle, Anderson, 1992). This new attention moved in two directions: the development of surface science laboratory concepts, including planetary protection measures against contamination and EVA systems for sustained exploration traverses away from the habitat. The surface science lab created a new focus upon the scientific work that the crew will do on Mars (Cohen, 1999; Cohen, 2000c). FIGURE 12 shows an example of the sample handling process for potential biologically active samples that the Mars surface laboratory in the Mars surface habitat must accommodate.

The prospect – however remote -- of finding extant life on Mars raises a host of philosophical, practical, and ethical planetary protection issues (Race, Criswell, Rummel, 2003; Sherwood, 2004). This concern goes beyond the standard preventative measures against the release of Earth microbes that could contaminate Mars (forward contamination). It goes to the far more serious concern of protecting the crew on Mars and protecting the Earth from alien microbes or potential diseases (backward protection). Extravehicular Activity will be a primary working environment for the crew, while exploring the surface and searching for scientific samples of all kinds. Planetary protection applies to airlocks, EVA suits, habitats, and rovers alike.

The key difference between this Mars exploration and the Apollo missions is that the crew on Mars will do much more than just pick up rocks to return to Earth for later analysis and science. Instead, the crew will conduct the great majority of scientific inquiry – at least the preliminary assessments for them – on Mars, using the laboratory facilities in the habitat. The EVA activities have become a major force in their own right with the annual Desert Rats exercises that started with advanced spacesuits, added simulated pressurized rovers, and in 2010 includes a sophisticated mobile habitat (NASA Desert Rats 2009, 2010).

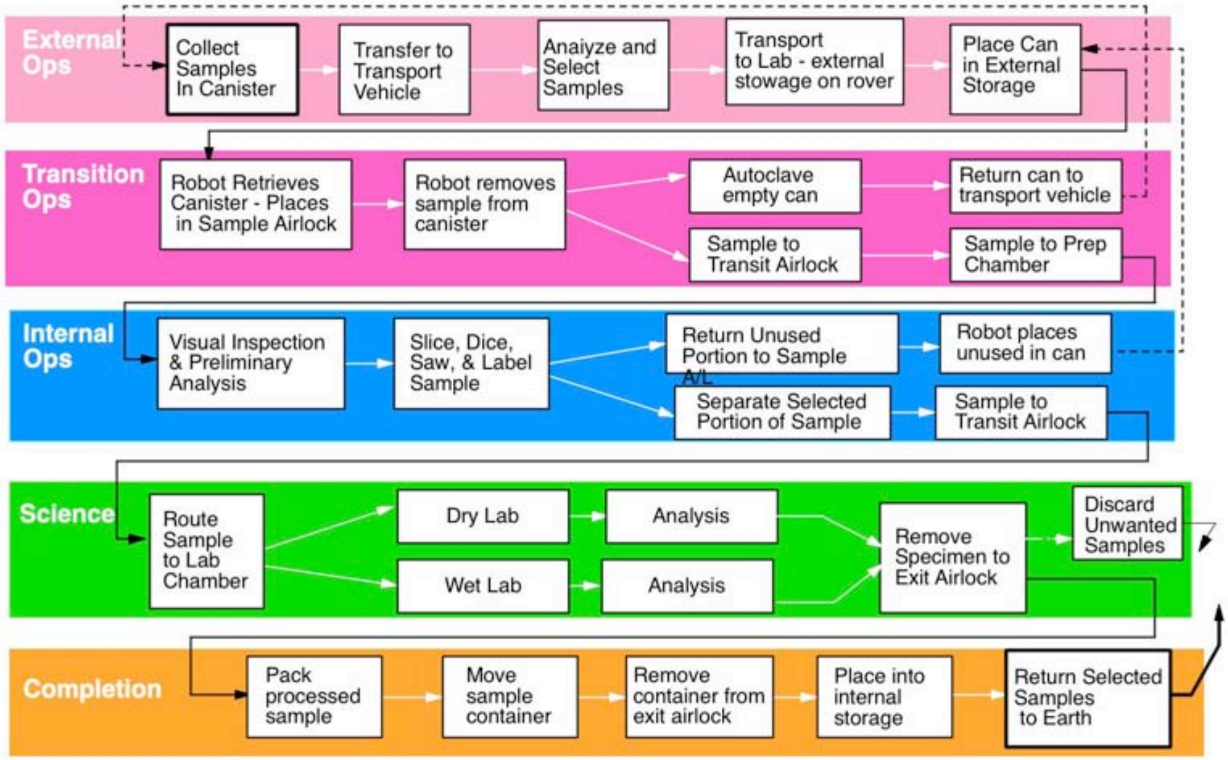

FIGURE 14. Sample handling process for the Mars surface science laboratory (Cohen, 1999, p. 14; Rev. 2000).

Race, Criswell, and Rummel (2003) raise several important points about the role of Habitability, Human Factors, and the design of the working environment in relation to Planetary Protection (PP):

> All operations of an initial human mission to Mars should include isolation of humans from any direct contact with materials from Mars for both PP and scientific purposes (p. 3) . . . .
>
> General human factors need to be considered along with PP issues for a human mission to Mars. Physical effects which [sic] lead to debilitation and reduced performance capability in astronauts may lead to unintended actions or behaviors which [sic] could in turn lead to mishaps with potentially serious planetary protection consequences. Mistakes are much more likely when people are tired, ill, and/or overstressed (p. 4) . . . .
>
> The presence of pathogenic microbes in sick astronauts would presumably raise more containment issues. Sickness could also impair the alertness and productivity of astronauts, with implications for operational difficulties and breaches of protocols (p. 7) . . . .
>
> Research and development will be needed on: . . . studies of the psychological stress of long-term missions on crew performance including the evaluation of the potential problems and solutions associated with human behavior and operations. Maintaining a barrier between the Martian environment and the crew will depend on strict compliance with isolation and operational protocols. In developing the protocols, it will be important to consider the possibility that the crew might intentionally violate the protocol, thereby creating potential PP problems (p. 10).

What is perhaps most important, Race, Criswell, and Rummel address the interaction of life support and PP, and the implications for pre-positioning and verifying a habitat on the Mars surface.

> Life support will clearly need far more attention than it has received to date. While closed loop systems are preferred for planetary protection, it is unclear how this will be done technologically? [sic] Can a habitat be deployed or build robotically on the surface, and its operational readiness be fully verified prior to sending humans there? Does venting of habitat products create problems or

raise contamination issues? In preparing for the return of crew to Earth, should wastes be left behind, and if so, where and under what conditions? Will space suits need to be sealed completely? Will rovers of the habitat likewise need complete sealing? (p. 7).

The answers to these questions lie in future research that is not yet even a gleam in the eye of the NASA budget. Even more than the all-important budget itself, the spirit of inquiry must overcome the spirit of denial to make meaningful progress.

VII. Base Location, Mobile Bases, and the Habot

A key strategic issue for the development and investment in a lunar or Martian base is where to locate it on the surface. It is a huge wager to pick one location on which to land tens of billions of dollars of equipment. What if, after a short period of further exploration, the crew or science observers discover a much better site too far from the Mars base to "commute?" In addition, the idea of coupling so much of the crewed Mars mission so closely together in one or two immense pieces of hardware evoked reservations and doubts. Clark (1991) recommended an alternative approach of "highly decoupled elements and conservative practices" that would not put so many eggs in one fragile basket.

What are the odds of picking the optimal Mars base site on the first try? What was the probability of success to land one 40 ton habitat or other payload at that site on Mars? From these concerns, alternative position arose, arguing that at least for the initial series of human Mars (or Moon) landings, the capability should arrive in multiple smaller payloads and be mobile rather than stationary. The ideas of decoupling the elements, leveraging modularity at a smaller scale, and enhancing mobility on the Lunar or Mars surface raised the question: why not make everything mobile? This mobile habitat and lab would potentially include an EVA airlock, a sample airlock, and a docking pressure port to access the surface habitat (Cohen, 2000d). There would be no pretensions about flying the crew to Mars in such small modules; they would need to be separate and distinct from the IPV habitat. However, it might be possible to convert such a small crew module to a DAV. On the other hand, one potential advantage of the mobile base design problem decomposition was that it would not be necessary to human-rate the mobile modules for the crew in flight as a propulsive vehicle – only on the Mars surface. This distinction could lead to substantial reductions in complexity and cost.

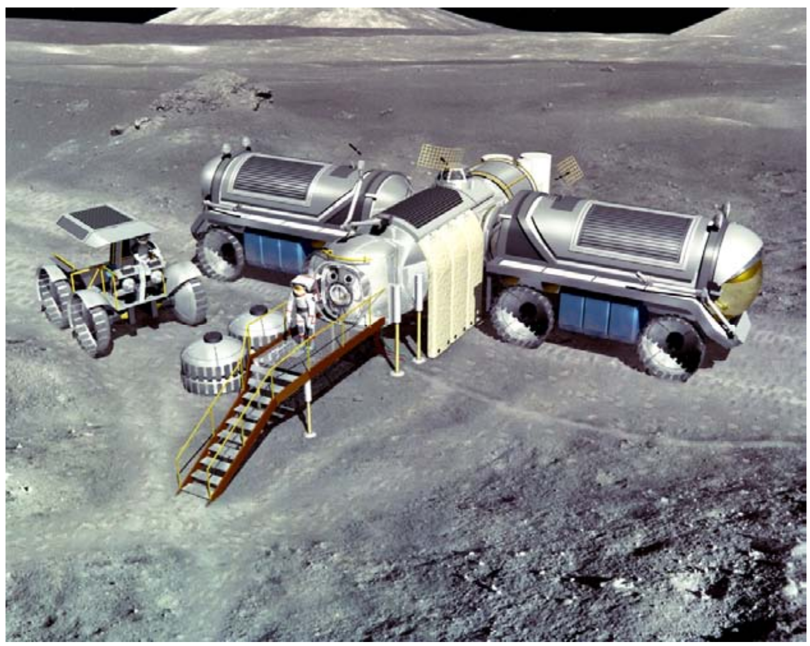

FIGURE 15. Wagon Train Base ~1993 (top, NASA Image, Artist Credit: John Frassanito).

A. Wagon Train Concepts

During the Apollo era, North American Aviation (1971) proposed a "Lunar Sortie Vehicle" that was a train of modules on wheels towed and pushed by an "engine" at each end. This train without tracks was the first mobile base concept. Over the next four decades, architects and engineers have proposed a further variety of mobile base concepts (Cohen, 2003; Cohen, 2004a). These concepts fall into three families: tractor trains, mega-mobile bases, and wagon trains (Cohen, 2003). Perhaps the most ambitious was the proposal by Kozlov and Shevchenko (1995) to build a single immense three-wheel vehicle from nine heavy-lift payloads landed on the Moon or Mars.

In the early MDRM 1.0 era, John Frassanito proposed a multi-vehicle pressurized rover approach, consisting of a core docking module and two primary roving modules/vehicles. His rovers with the large hemispherical gold window in front appear in the background of many of the Joosten vintage habitat illustrations. FIGURE 15 shows this original "wagon train" concept as a base cluster comprised of three pressurized rovers. This concept for a mobile lunar base involved the minimum of three pressurized vehicles: two exploration rovers and one multiple docking module with an EVA airlock and a Space Station-derived cupola on top. All three feature body-mounted radiators. The large gold-tinted windows resemble the face plate of a space suit helmet. A power source is not evident in this rendering, but would be necessary.

B. The Habot

John Mankins (2001a) recognized the potential for the mobile base comprised of multiple small, self-mobile habitat-rovers that could join together autonomously to form a base, then separate and travel independently overland to a new site. As the lead for advanced space technology development at NASA HQ, he commissioned a study on this Habitat Robot or Habot concept (Cohen, 2004a, b, c; Cohen, Tisdale, 2009).

FIGURE 16a shows the Habots as walking robots on the Moon, with some formed into a hexagonal "benzene ring" base and others being "driven" by astronauts or walking autonomously across the regolith. Subsequently all Habots appear with wheels instead of legs and "feet." FIGURE 16b shows a detail of the crew module portion of the Habot. It reveals the simple internal layout and geometry, with a floor deck and a loft above the main crew cabin. The ECLSS and thermal systems would be installed below the floor deck. The crew sleep-quarters and most other habitability functions would be in the loft. The hygiene and sanitary facilities would be installed on the main crew cabin floor to make a direct connection for the plumbing to the ECLSS system.

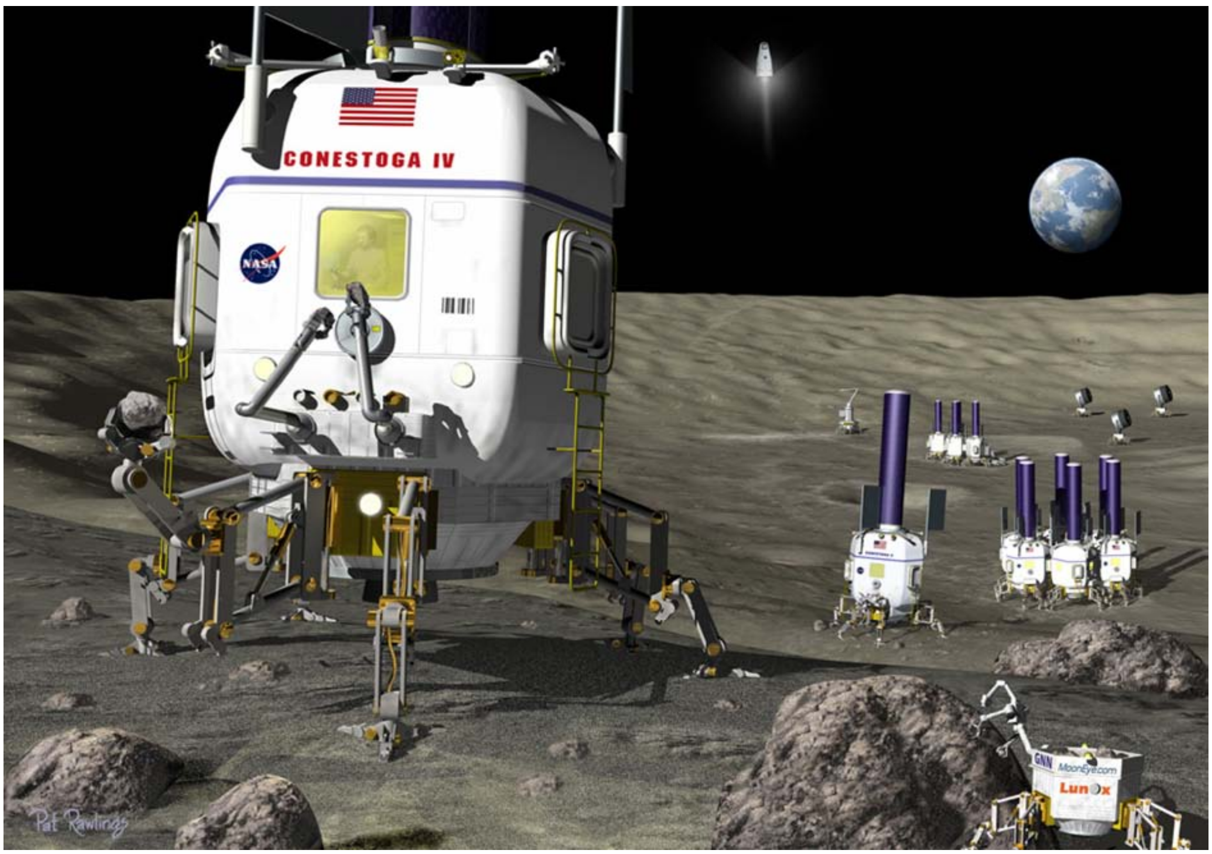

FIGURE 16a. Habitat Robots (Habots) on the lunar surface (NASA image, Habot Concept: John Mankins; artist credit: Pat Rawlings).

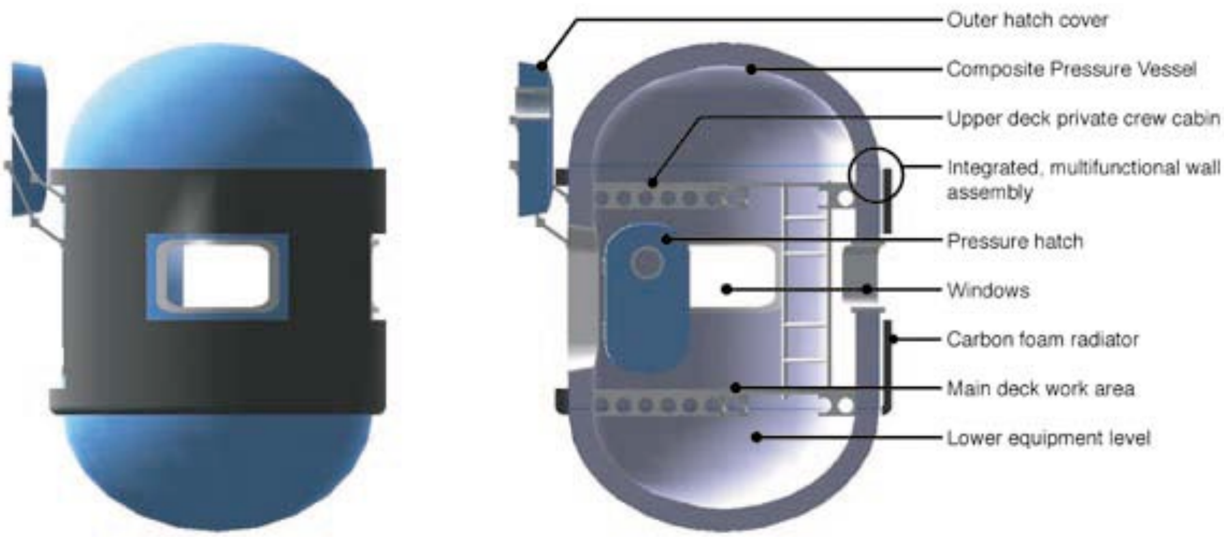

FIGURE 16b. Concept for a Habot module (Drawn by Ross A. Tisdale).

C. Howe's Mobitat

A. Scott Howe took the habitat robot construct to a more advanced level with the Mobitat1, featuring double rocker-bogie wheels and the ability to unload and reload large payloads such as the habitat itself (Howe, Gibson, 2006; Lai, Howe, 2003). FIGURE 16 shows the Mobitat2 that would self-assemble using the Trigon self-assembling robotic system with a soft and foldable interior membrane for the pressure vessel.

Of the diversity among mobile base concepts, the two that seem to supply the most influence are the Habot and the wagon train. Also sponsored by John Mankins, the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE[14]) -- with wheels instead of legs – represents the mature embodiment of the mobility system for the Habot. NASA is currently conducting field tests with two "second generation" ATHLETES carrying small habitat modules (JPL, 2010), as shown in FIGURE 17.

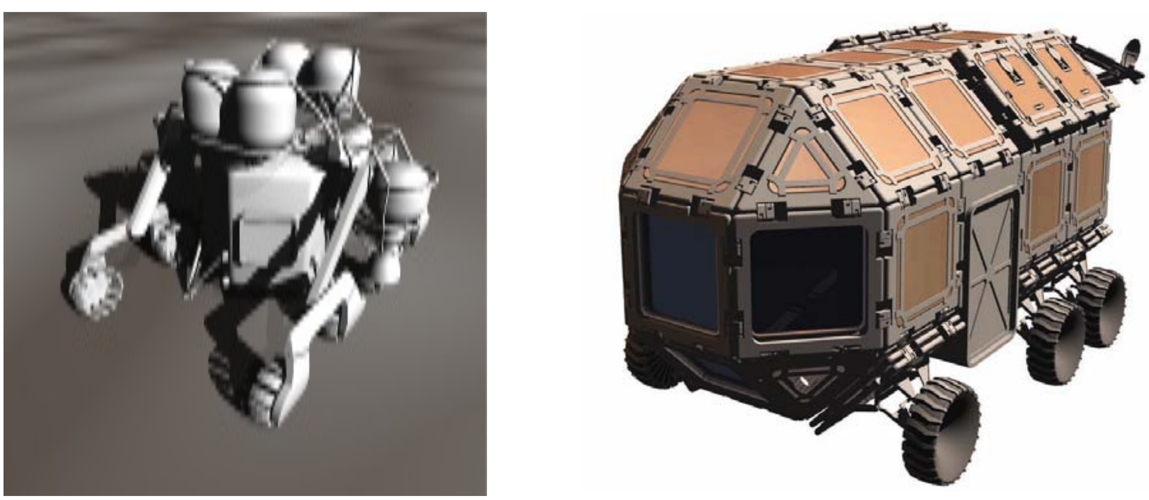

FIGURE 16. Howe's 2003 Mobitat1--left and 2006 Trigon-Mobitat2–right (Courtesy of A. Scott Howe).

[14] JPL ran out of six-letter acronyms.

FIGURE 17. ATHLETE rovers carrying habitat modules during the 2010 Desert Rats exercise (NASA photo).

D. Mobile Home

The wagon train concept reappeared under the title of the "mobile home" option in the MDRM 5.0 (Drake, 2009, p. 36). FIGURE 18 shows the "mobile home" option from MDRM 5.0. It has been reduced to two pressurized rovers; there is no docking module to provide the core of a temporary base cluster.

FIGURE 18. MDRA 5.0 "Mobile Home" option in 2008 MDRM 5.0. (NASA Image, Artist Credit: Pat Rawlings).

The pressurized rovers in the “Mobile Home” concept appear much more insect-like than the other mobile base concepts. The extended rocker-bogie wheels of the drive system give it a much wider base area. The design of the front observation bubble looks like a compound eye. The module carries a body-wrapped radiator to dispel waste heat. It tows a trailer that presumably carries a power system, incorporating the circular photovoltaic array, which appears similar to the Orion spacecraft’s solar array. The operating concept is that these vehicles would travel in a “buddy system” to provide redundancy so that if one rover fails, one crew can help the other make repairs; in the event of a total breakdown, the other mobile unit can take the crew home safely. It was not clear whether these modules would incorporate an aft docking port for IVA crew ingress and egress, or an airlock to conserve atmosphere, or merely a hatch for EVA transfer by the crew, while sacrificing the atmosphere.

VII. Advanced Habitat Technologies

During the first decade of the 21st Century, NASA, industry, and academic architects and engineers developed a new abundance of lunar-Mars habitat concepts and technologies. The earliest serious, technical proposals for lunar inflatable habitats began to appear in the first half of the 1990s (Sadeh, Criswell, 1993; Sadeh, Abarbanel, Criswell, 1995). The TransHab stands as the precursor to a second generation of inflatable concepts.

A. Surface Endoskeletal Inflatable Module (SEIM)

The most direct inheritor of the TransHab in terms of surface habitats is Adams and Petrov’s Surface Endoskeletal Inflatable Module (SEIM), which is essentially a TransHab-type structural envelope landed on the Moon or Mars surface (Adams, Petrov 2005; Petrov, Adams, Steinfield, Jajich, 2006; Petrov, Park, Adams, 2010). Illustrations of SEIM, which features an off-center axial core, appear in FIGURE 19. FIGURE 19a shows a view of the SEIM with a transparent skin. It reveals that this design can accommodate not only floor decks, but also “floor to ceiling” partitions that can afford privacy and a measure of acoustical isolation. FIGURE 19b shows three habitat modules around a spherical node, forming a base cluster. Each of these modules appears to incorporate an airlock at the distal end, plus a berthing port at the proximal end connecting to the node.

FIGURE 19a. TransHab-derived Surface Endoskeletal Inflatable Module (SEIM) detail of interior.

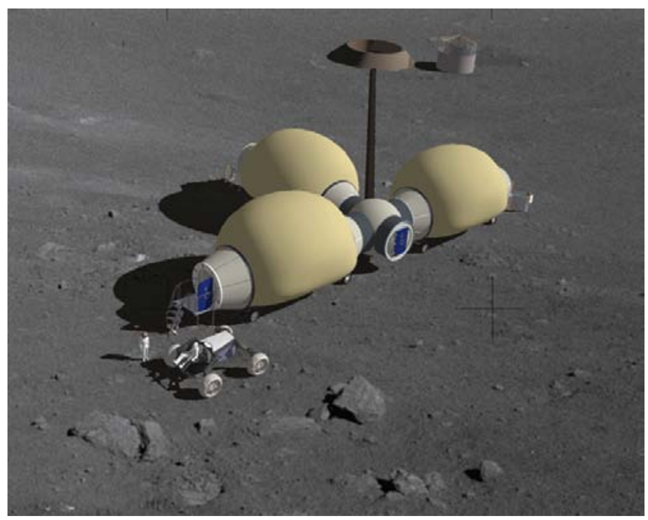

FIGURE 19b. SEIM habitat modules forming a base cluster on the lunar surface.

B. Toups’ Flat Floor Inflatable

Another design concept with several advocates is the “flat-floor” inflatable (Cadogan, Scheir, 2008; Lowe, 2009; Toups, Cadogan, Scheir, 2009; Versteeg, 2003). Toups, Cadogan, and Sheir built a full-scale flat-floor inflatable and deployed it for testing in Antarctica as shown in FIGURE 20. It incorporates real time system health monitoring (Rojdev, 2009).

C. Hybrid Pre-integrated and Deployable Habitats

The MDRM 3.0 habitat with the inflatable expanding from the side of the crew transit, descent and landing, and surface pre-integrated module represents an early attempt at a hybrid habitat. However, that inflatable was geometrically, structurally, and functionally unrelated to the pre-integrated portion of the ensemble. The only thing they shared in common was attachment at a pressure port and hatch.

FIGURE 20. JSC-ILC Dover flat-floor inflatable habitat deployed in Antarctica. The participants stand from the left: Jeff Cole (Raytheon Polar Services / National Science Foundation), Larry Toups (NASA), Craig Scheir (ILC Dover), Dave Cadogan (ILC Dover), Mike Delaney (Raytheon Polar Services / National Science Foundation), Todd Hong (NASA), Gerard Valle (NASA), Scott Hafermalz (NASA) (NASA photo, courtesy of Larry Toups).

More sophisticated hybrid habitat designs followed. Olga Bannova and Larry Bell (2006) presented an early concept for an inflatable deploying from the top of a hard, pre-integrated "tuna can" module. Students at the University of Houston built a model of a Mars base incorporating such a hybrid habitat as shown in FIGURE 21. What is interesting about the University of Houston Concept is that it employs a kind of non-identical modularity. There are three pre-integrated habitats. One sports an inflatable upper level. This implementation suggests that in a set of habitats, it is not necessary for all to include the same features. Presumably, the ones without the inflatable tops would arrive first, followed by the more full-featured version.

D. Minimum Functionality Habitat

In 2008, NASA competed contracts for the "Minimal Functionality Habitat." The idea of minimum functionality was to design the project initially as "single string" with just the smallest number of components for it to function successfully if nothing should go wrong. Then, the designers would analyze the risk factors and introduce operational and safety backups including redundancy and more capable solutions as needed to meet the stated reliability goals. In the case of the 2008 Lunar Lander Development Study, NASA defined those goals as Probability of Loss of Crew at 1/1000 or better and Probability of Loss of Mission at 1/250 or better. The three contract winners were Boeing, ILC-Dover, and the University of Maryland. Boeing and ILC-Dover each included the University of Houston on their separate teams.

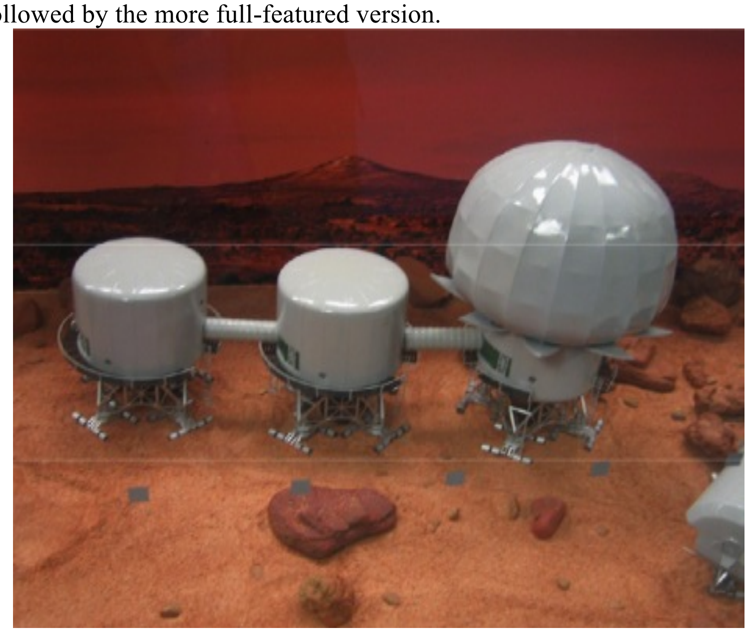

FIGURE 21. University of Houston concept for a Mars base with an inflatable on top of the habitat (author photo, December 2006).

The University of Maryland team designed a pre-integrated Type 1 habitat comprised of a monocoque aluminum pressure vessel, and built a full-scale mockup of it (Akin, DiCapua, Mervis, Medina 2009). Each module incorporates two Suitports, plus either one tunnel connection hatch or a hatch to an exterior airlock, or two tunnel hatch connections. FIGURE 22 shows the UMD concept for a lunar base cluster.

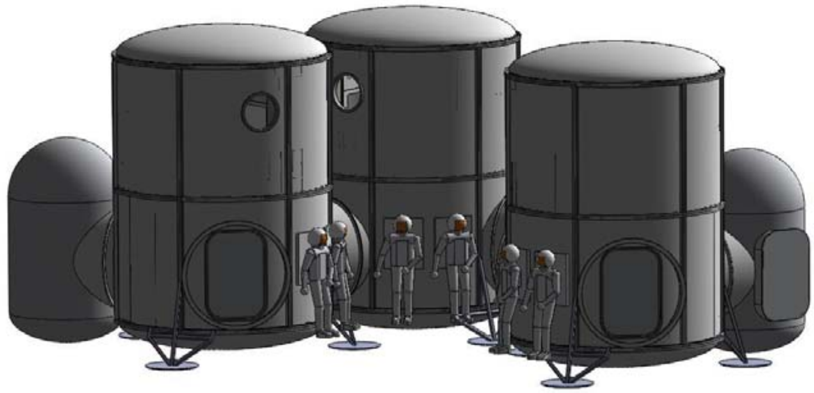

FIGURE 22. The University of Maryland concept for a lunar [or Mars] base comprised of three minimum functionality habitat modules, courtesy of Dave Akin.

Boeing took more of an overall systems approach that identified a wide variety of options. One of the options they adopted was the hybrid module with an inflatable on top (Bienhoff, Graves, Gentry, 2009). However, this inflatable would not be pre-installed in the baseline pre-integrated habitat; it would arrive separately on the seventh lunar landing – no indication of which landing for a Mars habitat.

The ILC-Dover team presented an inflatable on top of their horizontal ISS-like module for the unique function of a "thermal chimney" to provide passive cooling to the ECLSS for their Minimum Functionality Contract (Lin, Knoll, Hinkle, et al, 2009). Unlike the University of Maryland concept that combines pre-integrated and inflatable, the ILC-Dover prototype is all-inflatable. It features two oblong, vertically oriented envelopes. The entry airlock comprises the first inflatable, which opens into the main habitat volume. The Habitat features small circular windows set into the fabric in a square frame. Each of the two balloons is supported by four legs that appear to connect structurally to an interior floor deck. The ILC all-inflatable prototype appears in FIGURE 23.

FIGURE 23. ILC-Dover prototype for an all-inflatable habitat displayed at NASA-Langley Research Center. (NASA photo).

E. Habitat Demonstration Unit

Allowing that it would be possible to expand the habitation volume by attaching an inflatable, it was perhaps even more important to analyze and develop the pre-integrated base module from which the inflatable would deploy. By this time of NASA's minimum functionality studies for all kinds of applications, the space architecture community had compiled a compelling collection of improved habitat concepts.

FIGUREs 25a and 25b show some of these improvements in the Habitat Demonstration Unit (HDU). The HDU became the basis for later planetary habitats concepts, such as the "monolithic habitat" in the Evolvable Mars Campaign (EMC). The HDU was also related in some ways to the Deep Space Habitat, although many of the artist's renderings show it as a long narrower cylinder and not as the squat cylinder shown here.

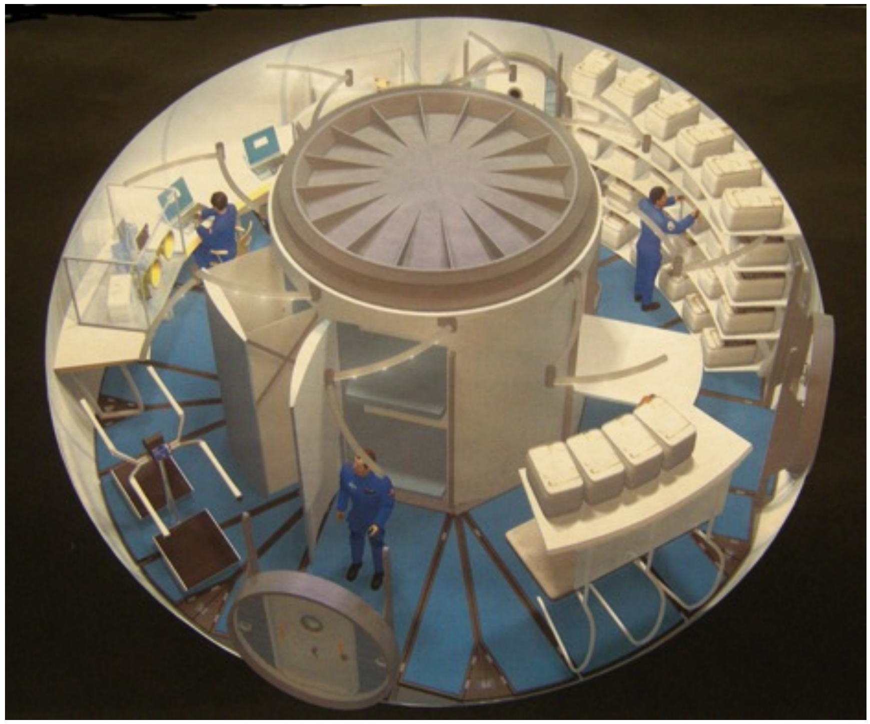

FIGURE 25a. Transparent Isometric of the Habitat Demonstration Unit (HDU)/embodiment of the Deep Space Habitat (DSH) concept. NASA image, courtesy of NASA JSC.

FIGURE 25a shows a CAD drawing of the HDU with a transparent skin, revealing the crew's workstations of various types, stowage, and circulation around the center core. This center core would include a vertical translation ladder or perhaps spiral stair for the crew to use in ascending to the inflatable above. The circular grid of rings on top of the HDU in FIGURE 25b provides a platform to mount the inflatable expansion unit. Connecting the pressurized atmosphere of the HDU to that of the inflatable is somewhat of a challenge. The HDU requires a hatch at the top to which a hatch in the floor of the inflatable must line up and connect through a short tunnel. The crew would then need to install a ladder to enable them to pass through the hatches between the two volumes.

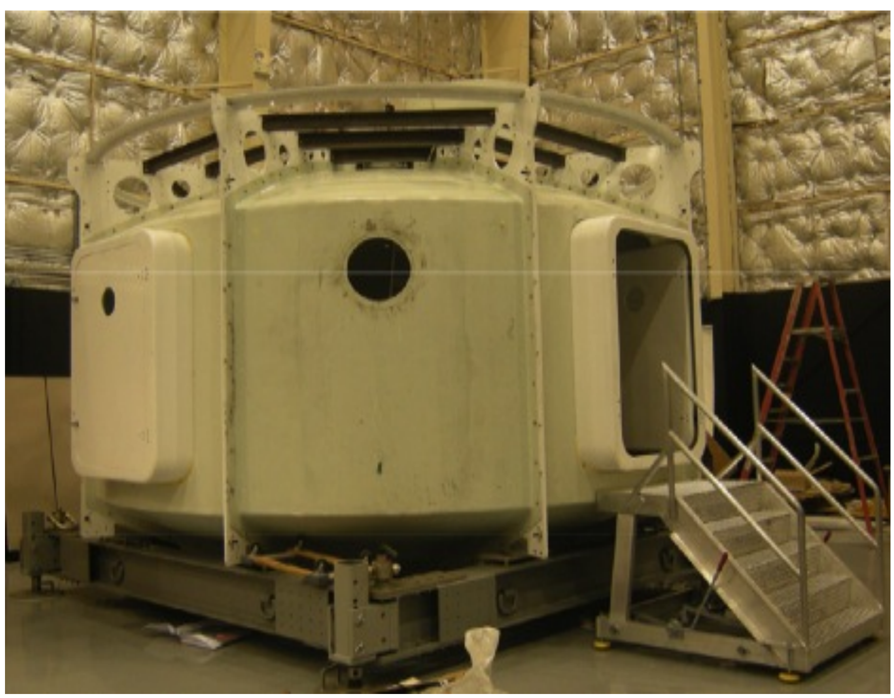

FIGURE 25b. NASA Habitat Demonstration Unit (HDU) in JSC Building 220, Kriss Kennedy, Architect (author photo, January 2010).

F. Desert Rats Field Trial

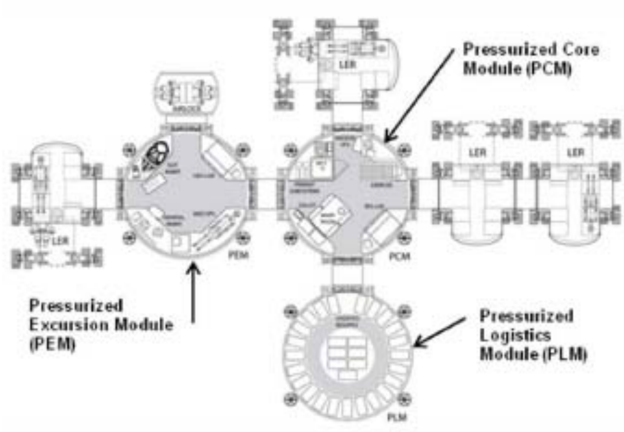

Figure 26a. 2010 Desert Rats plan for one HDU and two Lunar Electric Rovers (NASA drawing).

The NASA Desert Rats exercise in 2010 premiered a more sophisticated and integrated approach to habitat design and lunar-Mars base planning. It combined the stationary Habitat Demonstration Unit (HDU) with mobile habitats in the form of the Lunar Electric Rover (LER). Kriss Kennedy's design for the HDU breaks definitively out of the one-port MDRM mold, by providing multiple pressure hatches giving access to other pressurized volumes – another HDU, an airlock, or a rover.

FIGURES 26a and 26b align on this page so that the Pressurized Logistics Module at the bottom of the plan in 25a corresponds to the vertical cylinder with the American flag and NASA Meatball on it. Behind this logistics module sits a prototype HDU. On each side of the HDU is an LER, connected to a radial port by a flexible tunnel. In this arrangement, the Desert Rats ensemble shows the insights of the Strategies for Mars habitats with radial ports and flexes tunnels connecting to the EVA Access Modules, of which the LERs take their place.

FIGURE 26b. Desert Rats 2010 deployment of the Habitat Demonstration Unit, and 2 Lunar Electric Rovers (NASA Photo).

IX. MDRM Redux: MDRA 5.0

Since the initial printing in 1997, the MDRM has gone through four rounds of addenda and revisions, two of which – 3 and 5 – have been published. It would be plausible to assert that the MDRM reached a low point in 1998 when the habitat pre-positioning launches and dual habitats were eliminated from MDRM 3.0, without consulting the original contributing authors or the original team as a whole. From 1998 until the publication of the Mars Design Reference *Architecture* (MDRA 5.0) 11 years later, the Reference Mission remained highly problematic and probably infeasible because of these omissions.

MDRA 5.0, published in 2009 indicates a positive turn around and progress once again in the right direction for habitats. Perhaps most significant improvement involves the inclusion of the Mars science community, leading to the stronger emphasis upon Mars science objectives (Drake, Hoffman, Beaty, 2010, pp. 1-7). The MDRA 5.0 preferred option is the "commuter" strategy that combines pressurized rovers with a stationary "Monolithic Habitat" (Drake, 2009, pp. 37-39). This Monolithic Habitat appears as hybrid with an inflatable on top on the cover of the 2009 NASA-SP (Drake, 2009). FIGURE 27 represents the selected "commuter strategy," with pressurized and perhaps unpressurized rovers journeying out from the base.

These improvements to what NASA would actually deliver to the Mars surface include the following areas. It also includes the most major improvement, the surrender of the split habitat concept. Instead, the IPV habitat stays with the single IPV and carries the crew round trip from the Earth to Mars and return.

A. Recognition of Science Objectives

Perhaps the most encouraging aspect of MDRA 5.0 is the much stronger and more detailed consideration given to supporting science objectives on Mars. Although it does not go into detail about the design of a Mars surface science laboratory, presumably these lab functions must find a home in the habitat or the pressurized rovers. Compared to the MDRM 1.0, however, the phasing of launch and landing on MDRA 5.0 is less than obvious. Given the sequence of delivery in the MDRM 1.0 flight manifests, it is a stretch to imagine three rovers with one landed habitat.

B. Separate and Distinct Interplanetary and Surface Habitats

The interplanetary vehicle habitat and the surface habitat are separate and distinct. The interplanetary habitat is quintessential TransHab. The surface habitat is a basic tuna can with an inflatable expansion volume on top. See FIGURE 27b with the TransHab.

C. Habitat Quasi- Pre-Positioning Launch

The habitat lander launches on the opportunity preceding the crew launch. The habitat vehicle goes into Mars orbit to await the crew 26 months later. While in orbit, the Mission Control checks out and verifies the status of all the systems. The arriving crew transfers to the habitat lander in orbit, and then use it to land on the surface.

What is missing from this slight improvement is the recognition that although checking out the habitat in Mars orbit may be prudent, it would be *de minimus* in importance compared to ***checkout on the Mars surface.*** The passage through the Mars atmosphere and the impact of a less than perfect landing could result in damage that the crew might need to repair upon arrival at the next launch window. Unfortunately, the magical thinking continues to prevail in MDRA 5.0 that landing the crew in a habitat module will enhance their ability to recover from six months in μ-g. Again, there is no evidence that being in .38g will help the crew recover muscle or bone. The NASA biomedical program established a system of "evidence books" to ensure that all decisions that purport to protect the health of the crew be based on evidence. Where is the evidence to support MDRA 5.0's failure to preposition the habitat on the surface?

FIGURE 27a. NASA MDRA 5.0 "Commuter option," showing the single landed habitat and multiple pressurized rovers on Mars. (NASA image, artist credit: Pat Rawlings).

D. Partial restoration of the External EVA Airlocks.

On the 1993 Joosten and the MDRM 1.0 habitats, the EVA airlocks were positioned on the center axis directly under the tuna can. For MDRA 5.0, the EVA airlocks are "dropped-down" and pulled out to the side, modestly suggesting the EVA Access Modules of the 1996 Strategies for Mars habitats. However, the crew members must descend a ladder in a vertical tunnel about 3 to 4 m high to enter and egress the airlock module, which would not bode well for bringing bulky equipment or cargo into the habitat via the airlock.

However, these MDRA 5.0 airlocks do not go far enough in adopting the appropriate EVA airlock technology. The Lunar Electric Rover that incorporates Suitports appears in the Desert Rats deployment shown in FIGUREs 25a and 25b. One of the justifications for this omission is that the drop-down airlock has only one hatch or pressure port, and installing a system of Suitports would create a conflict. As Strategies for Mars and Desert Rats both demonstrate, there are multiple easy ways to avoid this conflict and produce a more efficient and optimal EVA airlock system.

E. Closer integration of stationary and mobile habitats.

The MDRM 5.0 habitat and the contemporaneous 2009 and 2010 Desert Rats exercises indicate an increasing sophistication in integrating the mobility systems and the monolithic habitat. The drop-down airlocks with increased accessible surface area for docking ports enable this improvement.

F. Hybrid inflatable and pre-integrated habitat.

This addition to the Mars habitat shows the incorporation of a Type 2 deployable inflatable with the Type 1 pre-integrated hard, rigid module. It affords more pressurized volume for crew accommodations for less mass, and confers increased flexibility in the assignment and utilization of floor area and volume.

G. Suitport EVA Airlock.

MDRM 5.0 provides options for one or two Suitports as an expedited system of astronauts going EVA (Cohen, 1989). The Suitports offer the promise of faster EVA ingress and egress, reduced loss of atmosphere, reduced pumpdown power, time, and cooling, and some protection from contamination by Mars dust.

FIGURE 27b. NASA MDRA 5.0, an interplanetary vehicle that flies the crew round-trip from Earth to Mars. The habitat is a TransHab. The side-docking Orion CEV behind the habitat appears to derive from the IPV in Cohen, 1997a, p. 24.

H. Recognition of Planetary Protection Requirements.

A major new feature in 5.0 is the section on Planetary Protection in the Addendum (Drake, 2009b, pp. 35, 45, 126-128). It cites Hogan, Race, Fisher, Joshi and Rummel (2006) and some of the National Research Council (NRC) reports on Planetary Protection. This addition as a top-level requirement is encouraging, but it still needs to be incorporated in to the (next) NASA MDRM/MDRA.

X. MarsOne: One-Way to Mars?

Although MarsOne does not meet all of the selection criteria in terms of a larger mission architecture, it has made such a public impact and attracted so much attention that it is useful to address it here, if only to discount some of its constructs and claims. MarsOne constitutes a private/commercial initiative to send humans one-way to Mars where they would establish a permanent settlement, all playing out as a reality television series. The significance of MarsOneWay is that there is no plan for a return to Earth option.

The cargo- and crew-lander modules are supposedly based on the SpaceX *Dragon* capsule, enlarged from the first generation 11 m^3 to 25 m^3.[15] The lander modules connect through tunnels like beads on a string. In this

[15] SpaceX has not confirmed these assertions by MarsOne.

respect, the MarsOne habitat configuration derives its core geometry from Joosten's early MDRM 1.0 and from the Strategies for Mars habitat concept. However, MarsOne locates its two airlocks in the center of the string, as indicated by the ladder to the hatch (FIGURE 28), effectively cutting the base configuration in half whenever an airlock capsule is depressurized while crewmembers go EVA.

This arrangement displays a lack of awareness of a key lesson from the Skylab architecture, in which the EVA airlock lay between the Saturn Workshop and the Multiple Docking Adapter to which the Apollo Command Module docked. Before two Skylab crew members went EVA, it became necessary for the third crew member to evacuate the Saturn Workshop that contained the living environment and the main working environment to retreat to the Apollo Command Module for safety in case the airlock should fail. This lesson learned from Skylab is: do not allow the EVA airlock divide the spacecraft or habitat circulation path (Cohen, 1985, p. 4-16). Both Joosten and Strategies for Mars avert this problem by the placement of the EVA airlocks; Joosten placed them below each habitat and *Strategies for Mars* placed them at the distal ends of the string of beads.

MarsOne follows the strategy of prepositioning cargo and habitat landers articulated in the first NASA Mars Design Reference Mission (Hoffman, Kaplan; 1997). Following the automated/robotic setup of the MarsOne base, four crew members arrive at the next launch window 26 months later, and four more at every 26-months interval.

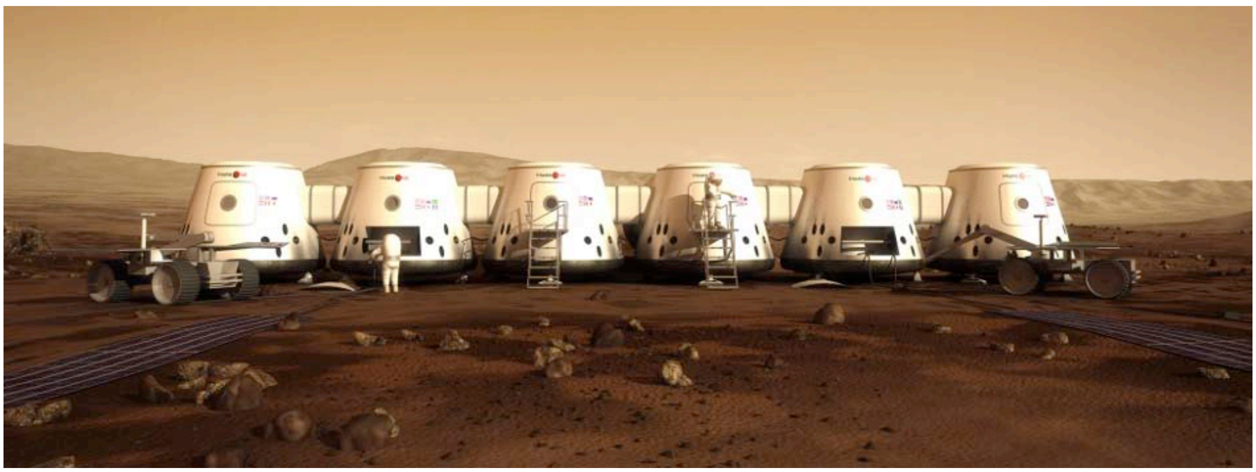

FIGURE 28. The MarsOne "2023 Roadmap" image shows the extremely bleak and desolate Martian landscape with the 25 m^3 cargo- and crew-landers linked together by extension tunnels. The spacesuited crewmembers give a sense of scale to these capsules (Credit: MarsOne).

FIGURE 28 shows the MarsOne base situated on a relatively featureless, dusty Mars terrain. While in these pressurized volumes, habitation accommodations are basic at best. The MarsOne plan to date considers food, dining, sleep, and hygiene essential – but not much else in terms of tangible support for the crew during the first several launch windows before it is possible to establish the large inflatable shown in FIGURE 29.

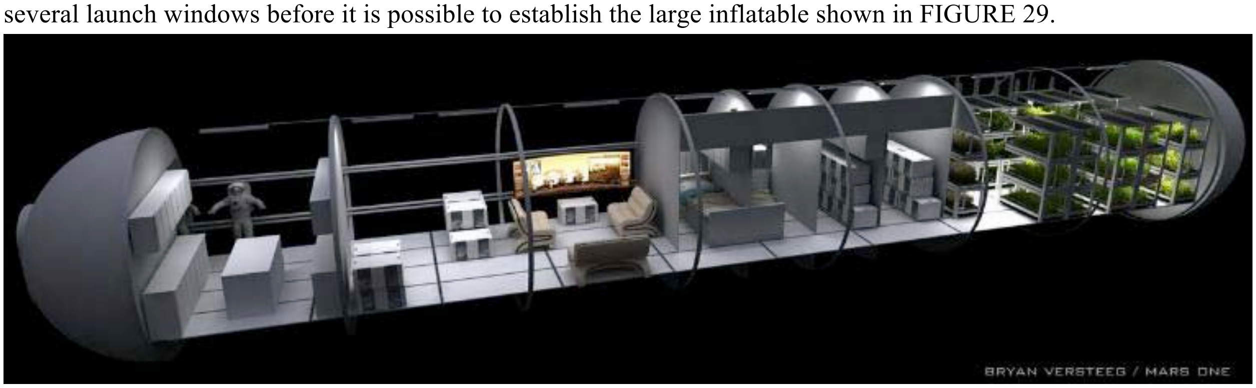

FIGURE 29. Longitudinal, cutaway view of the MarsOne 500 m3 habitation and plant growth inflatable module. (Credit: Bryan Versteed, MarsOne).

FIGURE 29 shows a longitudinal section of the 500 m^3 inflatable environment that serves as the "greenhouse" to grow plants for food. MarsOne states that they dedicate 50 m^3 of "shelves" to growing plants for food. However, the MIT review team led by Sydney Do found that to grow all the food for a crew of four would require at least 200 m^3. Unfortunately, a life-threatening problem arises when trying to raise all the food for humans in a closed atmosphere. The plants produce a surplus of oxygen, which can create oxygen toxicity for the crew and a fire hazard (Do et al, 2014).

Harry Jones in the Bioengineering Branch at NASA Ames Research Center (2006) explains that in terms of raising vegetables and fruit for food as part of a bioregenerative life support system, the optimum balance is about 50% grown on site, and 50% resupply of dry food. The reasons are that plants producing 50% of the food to feed one person generate 100% of the oxygen he or she will need. Growing more food means producing excessive O_2 that poses problems in two ways: First, it creates a toxicity and fire hazard to live in a too-rich oxygen atmosphere. Second, dumping the excess O_2 means breaking the closure of the life support system to run more open loop. One possible but hardly ideal solution would be to oxidize the excess biomass from the plants, thereby consuming the excess O_2. Then the CO_2 produced could provide respiration for the plants. This method requires more equipment, power, and poses a different potential fire risk.

FIGURE 29 also shows what appear to be galley, dining, and lounge areas for the crew. It is not clear where the crew would sleep, in the inflatable module or back in the lander modules. According to the MarsOne website, shower and toilets are in the landers, which does not enable or enhance recycling such as tertiary waste water processing through the agricultural systems. In the inflatables there are stowage areas for supplies and some work areas. What do not appear are the exercise equipment and perhaps sports facilities. A spacesuit appears on the left end near the back wall, suggesting perhaps that area serves for EVA maintenance and repair. Or, would the crew have need sometimes to enter the inflatable module in their pressure suits? That scenario might become necessary case of elevated oxygen toxicity. The MarsOne website states that the inflatable module includes an airlock, which would allow suited ingress and egress.

Although the MarsOne concept provides much greater volume than does Inspiration Mars, it still must make a persuasive case that the quality and quantity is sufficient to support a permanent human colony from which there is no return to Earth, permanently cut off from the natural world. The highly controlled and contained agricultural plant growth chambers hardly qualify as the "natural world," although their presence would be better than no plants at all. MarsOne faces an intensifying controversy over their largely unsubstantiated assertions of all kinds. The MarsOne team would help their cause by publishing scholarly, scientific, and technical articles that explain their design reasoning and engineering calculations.

XI. Evolvable Mars Campaign

The Evolvable Mars Campaign (EMC) constitutes NASA's current effort to conduct a "Pre-Phase A," pre-design decision study on sending humans to Mars.

Greg Williams and Jason Crusan (2015) state the EMC Goal:

> Define a pioneering strategy and operational capabilities that can extend and sustain human presence in the solar system, including a human journey to explore the Mars system starting in the mid-2030s.

FIGURE 30. Evolvable Mars Campaign: frustoconical monolithic "large habitat" with four radial ports inside the dynamic envelope of an SLS payload shroud that is sized to match the diameter of an Orion (Courtesy of Matthew Simon, NASA LaRC).

With respect to habitat architecture, they describe it as:

> Multi-use, evolvable space infrastructure, minimizing unique major developments, with each mission leaving something behind to support subsequent missions

EMC appears to take a two-scale approach to developing Mars mission habitats, a large "monolithic" family of habitats and a small, modular family. The driving difference between these two families is that the large habitat is intended to protect the crew for long, full-mission durations ranging from 300 to 1100 days. The small habitats would protect the crew for about one to two weeks for short duration excursions. Within each family, EMC takes a "kit of parts" type approach to maximize the commonality and minimize the different "major developments."

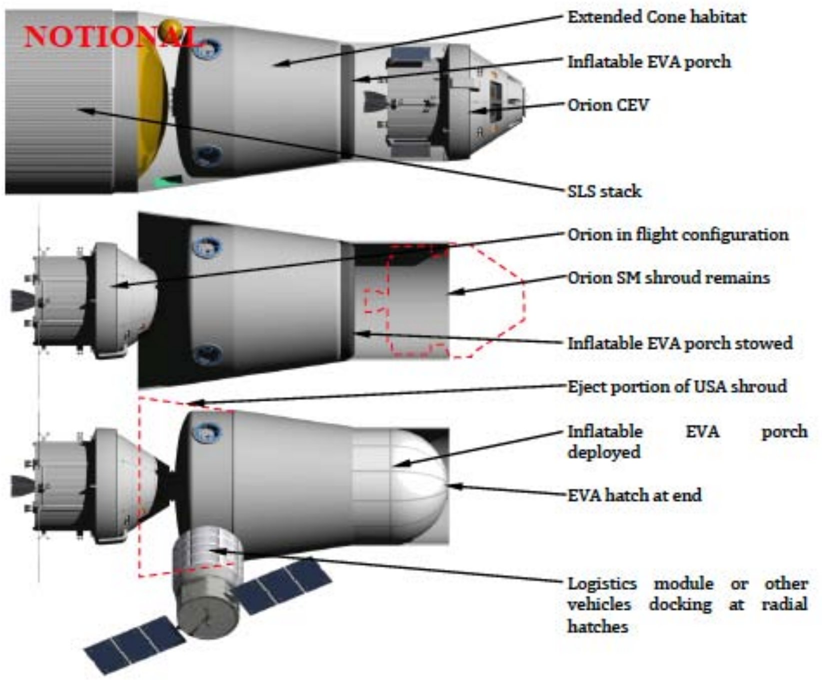

FIGURE 31. Evolvable Mars Campaign: Three variations of the extended cone "large habitat" within the Universal Shroud Adapter (USA) fairing. (Courtesy of Matthew Simon, NASA LaRC).

A. EMC Large Habitat

The first design integration gateway that EMC confronts consists of how to fit a habitat unit on top of a launch vehicle, particularly the Space Launch System (SLS), the new "super rocket" that NASA is developing that will offer a maximum initial mass in LEO of 130 metric tonnes. The SLS could carry payloads in a range of shroud diameters from 5 to 10 m.

FIGUREs 30 to 32 show some of these "notional" concepts, where *notional* appears to mean that the EMC team is not preferring any one over the others, but they are merely illustrating what could be possible. FIGURE 30 shows a "monolithic" *habitation element* with four radial ports in the manner of the 1995 Strategies for Mars habitat, but much smaller than its ~10 m diameter. The habitat assumes a frustoconical shape to fit within the "dynamic envelope" of an imagined universal shroud adapter (USA), with the top base at about 5 m diameter and the bottom base of about 5 to 7 m diameter.

FIGURE 31 shows an alternate configuration, the "extended cone habitat." This difference from FIGURE 30 suggests that the shape of the USA fairing remains quite malleable. The radial port section is cylindrical, making for a much more practical connection to exterior pressurized modules on the presumably level Mars surface. At the top end of the habitat appears an "inflatable EVA porch" with its own hatch. This EVA porch must be exclusively for μ-G use because on the planetary surface it would sit at least 10 m above the ground, with no apparent means for the crew to descend.

FIGURE 32 shows three more examples of payloads within the fairing atop an SLS. The left and center examples show the 5 m fairing dynamic envelope, with "short duration" habitats. The right example shows what appear to be two more small habitat-size modules, perhaps logistics modules, with a much larger payload above, perhaps a monolithic habitat.

However, while making some progress at creating the pair of "erector sets," EMC has yet to place a habitat – even as an artist's impression -- on the Mars surface or describe how it might function within the larger mission operations. The EMC team's reticence to develop a point design may make sense for a pre-Phase A study. This posture allows the team considerable freedom to consider a wide range of possibilities without being driven to settle on a configuration-specific construct. However, ultimately, it will be impossible to evaluate how well an EMC habitat or combination of elements might perform as a planetary base or operations outpost until the team formulates one or more specific configurations for in-space or missions on the surface.

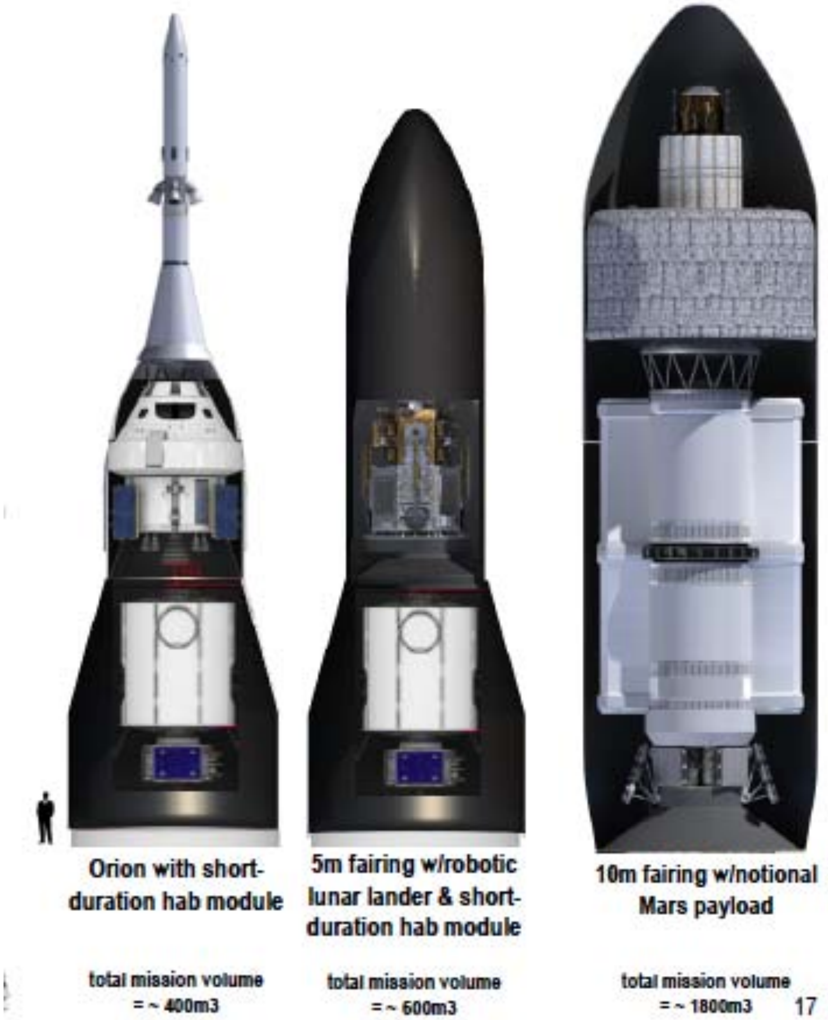

FIGURE 32. Three examples of payloads within the SLS USA fairing (Courtesy of Douglass Craig, 2015). The two longitudinal sections to the left for the nominal 5 m fairing diameter would probably be the choice for launching a "small habitat" unit alone. However, a nominal 10m fairing might be able to accommodate five to six "small habitats."

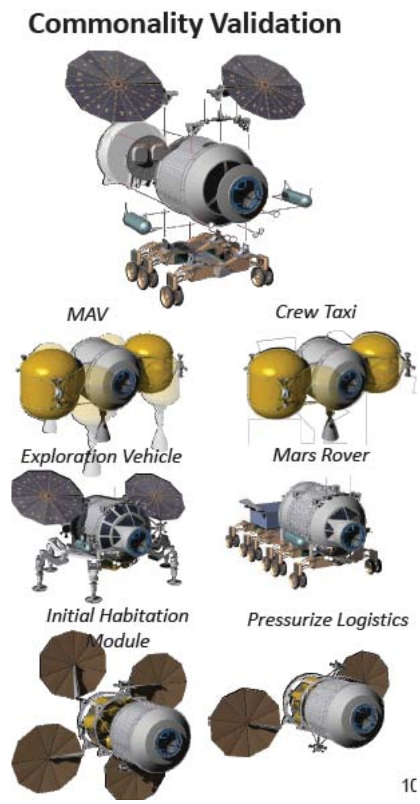

FIGURE 33. Examples of spacecraft incorporating the common small habitat from the Evolvable Mars Campaign. Courtesy of Brand Griffin, 29 July 2015 FISO Telecon, http://spirit.as.utexas.edu/%7Efiso/telecon/Griffin_7-29-15/

B. EMC Small Habitat

FIGURE 33 shows the EMC approach to developing a "small habitat" with a strong emphasis on commonality for it to serve at multiple different mission purposes. FIGURE 27 shows a selection of six permutations, with the top, center image portraying the complete kit of parts. The "Evolvables" define these purposes variously as the Exploration Augmentation Module (EAM), Exploration Augmentation Module Logistics Module (EAMLM), Initial Habitation Module (IHM), Mars Ascent Vehicle (MAV), Mars Moon Crew Taxi (MMCT), Mars Moon Excursion Vehicle (MMEV), Mars Pressurized Rover (MPR, but not a Moon Rover), Mars Moon Exploration Vehicle (MMEV), Mars Logistics Module (MLM), Phobos Taxi, Phobos Hab, and the Pressurized Logistics Vehicle (PLV). Beyond creating an abundance of new acronyms, it is not clear how these common small habitat applications enable an exploration mission design concept or a concept of operations. Agreed that it should be feasible to adapt one pressure vessel to a variety of spacecraft with habitat modules, it is still not clear how such a small module can support a long duration "campaign." Beyond very short-term operations, there does not appear to be any provision for contingencies or emergencies that might maroon one of these vehicles or modules, forcing the crew to rely upon system redundancies and additional supplies to survive until repair or rescue. Unless the intention is misunderstood, these small habitats do not apply to the deep space habitat for an interplanetary vehicle or a 600 day Mars surface habitat for a conjunction-class mission.

C. EMC Path Ahead

The evolvable Mars campaign offers the potential for NASA to accomplish a set of goals that it has often advocated, but never come close to achieving: true commonality, flexibility, and modularity. Sometimes the ISS is held up as an example of modularity, but in fact, it is almost the opposite. Just because the pressure vessels are about the same size and most (excluding the Russian ones) have the standard 1.25 m square hatch does not make them "modular." In fact, over about ten years, NASA and its partners produced five different modules and three nodes on at least six production lines. As a consequence, the ISS program did not benefit from economies of commonality, modularization, or scale.

However, with the EMC approach, NASA may anticipate achieving benefits of commonality, flexibility, and modularity, if the spacecraft and habitat designers can adhere to the design principles they set forth. The decomposition into small and large modules provides an important discriminator that recognizes the time of use – the mission duration – should influence the module size, specifically its pressurized volume. One temptation will be to add too many minor variations (aka bells, frills, and whistles) that may tend to obscure the clarity and directness of the root conception. Another, almost opposite temptation will be to run out of patience that there are so many modular variations and demand that only one or two be established as "common."

One advantage of the approach that starts from the component level and builds to the system level is that it becomes possible to avoid prejudging what is possible and what is not possible based on the limitations of preconceived chunks of hardware. Instead, by starting a series of exercises in applying the EMC modular designs to actual Mars mission scenarios, it will be possible to explore and comprehend the true utility and potential operational advantages of the EMC design approach.

XII. Conclusion

We are now in the second decade of the 21st century, but no national or international space agency, no major aerospace corporation, nor any "NewSpace" enterprise offers a coherent, technically achievable, and sustainable plan – much less a mission architecture -- for human exploration beyond low Earth orbit (LEO). Space habitat designers and architects have advanced a range of creative solutions for the Mars surface habitat and for its supporting facilities. However, the architectural and engineering disciplines remain far from achieving a successful solution for the Mars habitat that answers all the programmatic, functional, and operational requirements that an exploration program will levy upon it. Part of the difficulty seems to be the resistance to recognizing important lessons that others learn – whether they are in a competing organization or from an earlier "generation" of effort.

A leading reason for this lack of closure and success in Mars habitat architecture is that the requirements remain ambiguous in many cases, and constantly in flux. The requirements seem to expand and contract in reaction to various speculative future budgets and the strategies that exploration program or project managers employ to anticipate the hard financial realities 20 to 30 years in the future.

During the hiatus from 1993 to 1997 in preparing MDRM 1.0 for publication, the question was: could NASA learn anything new that might modify its preconceptions? The MDRA 5.0 in 2009 answered partly in the affirmative, showing that NASA could progress toward a viable First Mars Habitat architecture. Still, it begs the question: can NASA remember and retain what it already knows? To wit: Where is Hoffman and Kaplan's pre-positioning landing and verification of the first Mars habitat on the launch opportunity before sending the crew? Where are the "two of everything" or two failure/fail-safe redundancies for reliability?

A deeper analysis suggests that the wide disparities among habitat architecture approaches arise from situations that have almost nothing to do with actually designing and building a Mars habitat. The root cause of these contradictions is that none of the exploration concepts or programs to date provided a well defined, comprehensive, and consistent design problem definition. In the absence of this definition and the validation that it would need, these differences in design concept reflect that for the designers, *each design solution conveys their hypothesis of what the design problem is.* When measured by this metric, most of these space architects have made progress toward showing the world what may be possible to accomplish on Mars.

However, none of these design concepts – no matter how excellent – can define what is the problem that it solves. That design problem definition can come only through an honest, inclusive, and open process of participation about what to achieve on Mars and how to accomplish it. These words *honest, inclusive, and open* are radioactive in some of the design and planning situations described above. It should not be necessary to explain these words to a sophisticated readership, but they have been honored so often more in the breach than the observance, that it is necessary to make this review complete.

Honest means that the assertion of numbers includes a clear statement of the assumptions, methods, and results. It also means being forthright about the underlying agendas or purposes of design reasoning. It means no secret addenda, requirements, or revisions. *Open* means that the creators provide the data honestly to all the participants and to the public to understand and evaluate the design decisions and how they interact. *Open* means entering technical reports and submissions into databases that are accessible to all the participants so that they can respond timely to the new inputs, instead of being surprised at critical junctures by changes being enacted without prior notice. *Openness* of this sort is the only sunlight tonic that can ensure *honesty* because people will know that all can review their work.

Finally, *Inclusive* means that the design process brings in the participation of the disciplines essential to designing and engineering the mission from the beginning. That means starting from the scientific exploration purposes, methods, and processes that the crew will carry out. It means starting the design of the habitats from the exigencies of the life support systems that will be critical; it does not mean saying "we allocated three racks to life support: make it work." More important, what *inclusive* does not mean is parceling out the work among the "stakeholders" to ensure a piece of the pie for all of them before there is an optimal recipe for creating the pie itself. Finally,

NASA has seen a great many human spaceflight program starts followed by sudden stops. It is time put in place an open, honest, and inclusive design methodology that can create, sustain, and complete a successful human exploration of Mars.

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Appendix

The Appendix displays tables and drawings from the MDRM 1.0. Although these are not the most recent estimates and sketches, they were conducted with a somewhat rigorous approach, and show the relationship between the Mars outpost master planning and the flight manifests. This Appendix reproduces the site plans and flight manifests for the first three landing opportunities, based upon the corresponding three launch windows from Earth.

FIGURE A1 shows the first three payloads on the first three launch windows for the prepositioning flights. It also shows on the far right the first crew vehicle with the transfer/entry descent and landing/surface habitat. TABLES A1 and A2 show the preliminary mass estimates for the prepositioned Hab/Lab module and the first Crew Transfer /Surface Habitat as shown on the right of FIGURE A1. These mass estimates involved an effort to make honest and consistent calculations, although radiation shielding was not a topic of serious contemplation.

The site plans for the first three launch window landing opportunities appear next, each followed by its flight manifest. In the early 1990s, when the MDRM 1.0 was in preparation, the team worked to a requirement for a 10 km separation between the LZ and the base, with a concomitant requirement of a pressurized rover that could travel at 10 km/hr across an unprepared Mars surface. This rover would bring the newly arrived quickly and safely to the base habitat.

However, when the MDRM 1.0 was published in November, 1997, the site plans shown below came as a complete surprise. In place of the 10 km distance appeared a dimension of less than 1/20th the original. Depending on the location of the habitats in relation to the landing ellipse, the distance between them could be as small as 300 m. The reasons were quite obscure for this choice of a 500 m safety separation between the nearer focus of the landing ellipse and the base facilities that could be obliterated by a bad landing. At the time, it was not possible to obtain an explanation for where or how it originated, or whether any analysis backed it up.

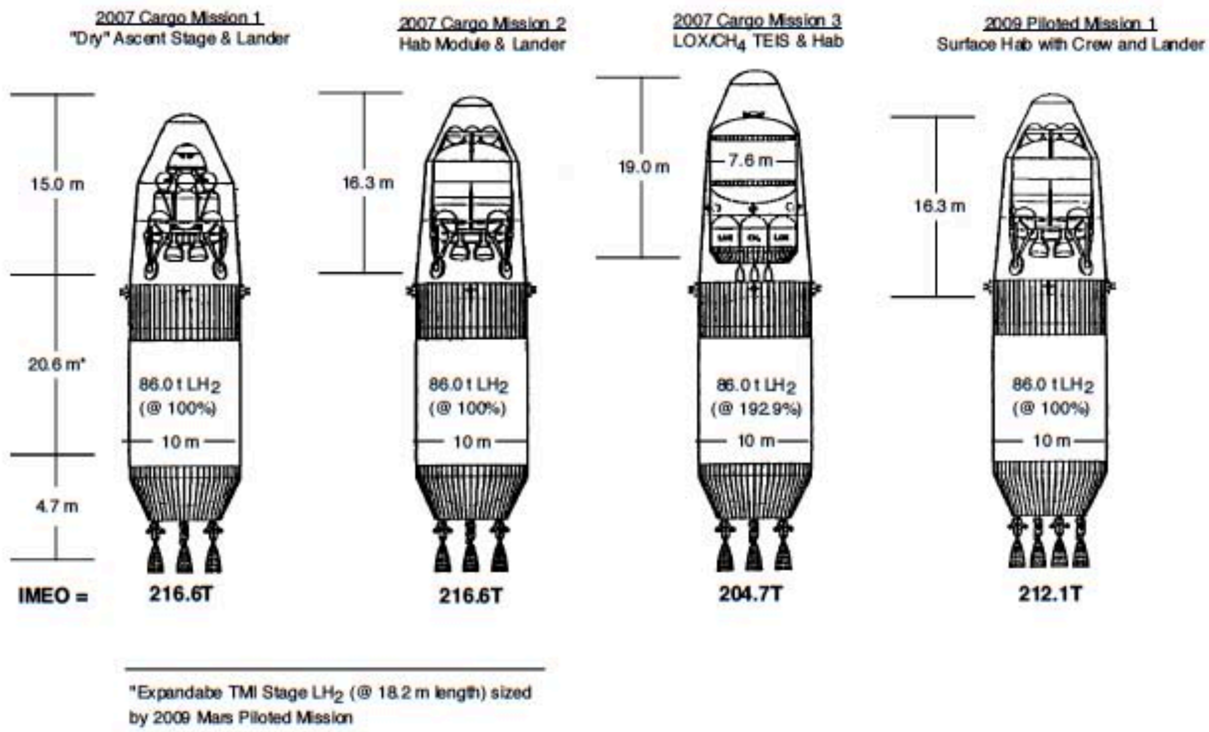

FIGURE A1. Packaging of the cargo payloads to Mars for the first launch window showing the two surface pre-positioning launches in the two fairings to the left, the MAV and the Habitat module. On the far right, the first crew would land in the second surface habitat module.

One theory to explain this discrepancy in separation distance is that the Ames members of the team stated that the safety radius from the Ames static test stand was 600 m for aircraft engines being tested and possible thrown rotor blades. They advocated that with tons of rocket fuel instead of a few hundred liters of jet fuel, the safety radius should be at 10 times greater, or about 5 km. The editors took this argument under advisement and settled on a compromise of 500 m. It was not possible at that time to obtain an explanation from the JSC team members of where this 500 m to the focus originated, and none has been forthcoming. None of the subsequent MDRM/MDRA revisions or their addenda have offered a new model site plan.

TABLE A1. MDRM 1.0 Mass estimates for the first launch window prepositioning Habitat/Lab Module.

Table 3-18 Mars Surface Habitat/Laboratory Mass Breakdown

Subsystem	Subsystem Mass (tonnes)	Consumables Subtotal (tonnes)	Dry Mass Subtotal (tonnes)
Physical/chemical life support	4.00	2.00	2.00
Plant growth	3.00	1.00	2.00
Crew accommodations	7.50	7.50	0.00
Health care	0.00	0.00	0.00
Structures	10.00	0.00	10.00
EVA	1.50	1.00	0.50
Electrical power distribution	0.50	0.00	0.50
Communications and information management	1.50	0.00	1.50
Thermal control	2.00	0.00	2.00
Power generation	0.00	0.00	0.00
Attitude control	0.00	0.00	0.00
Spares/growth/margin	5.50	0.00	5.00
Radiation shielding	0.00	0.00	0.00
Science	3.00	Uncertain	3.00
Crew	0.00	0.00	0.00
Total estimate	**38.50**	**11.50**	**27.00**

TABLE A2. MDRM 1.0 Mass estimates for the Transit/Descent and Landing/Surface Habitat Module.

Table 3-13 Mars Transit/Surface Habitat Element

Subsystem	Subsystem Mass (tonnes)	Consumables Subtotal (tonnes)	Dry Mass Subtotal (tonnes)
Physical/chemical life support	6.00	3.00	3.00
Plant growth	0.00	0.00	0.00
Crew accommodations	22.50	17.50	5.00
Health care	2.50	0.50	2.00
Structures	10.00	0.00	10.00
EVA	4.00	3.00	1.00
Electrical power distribution	0.50	0.00	0.50
Communications and information management	1.50	0.00	1.50
Thermal control	2.00	0.00	2.00
Power generation	0.00	0.00	0.00
Attitude control	0.00	0.00	0.00
Spares/growth/margin	3.50	0.00	3.50
Radiation shielding	0.00	0.00	0.00
Science	0.90	0.00	0.90
Crew	0.50	0.50	0.00
Total estimate	**53.90**	**24.50**	**29.40**

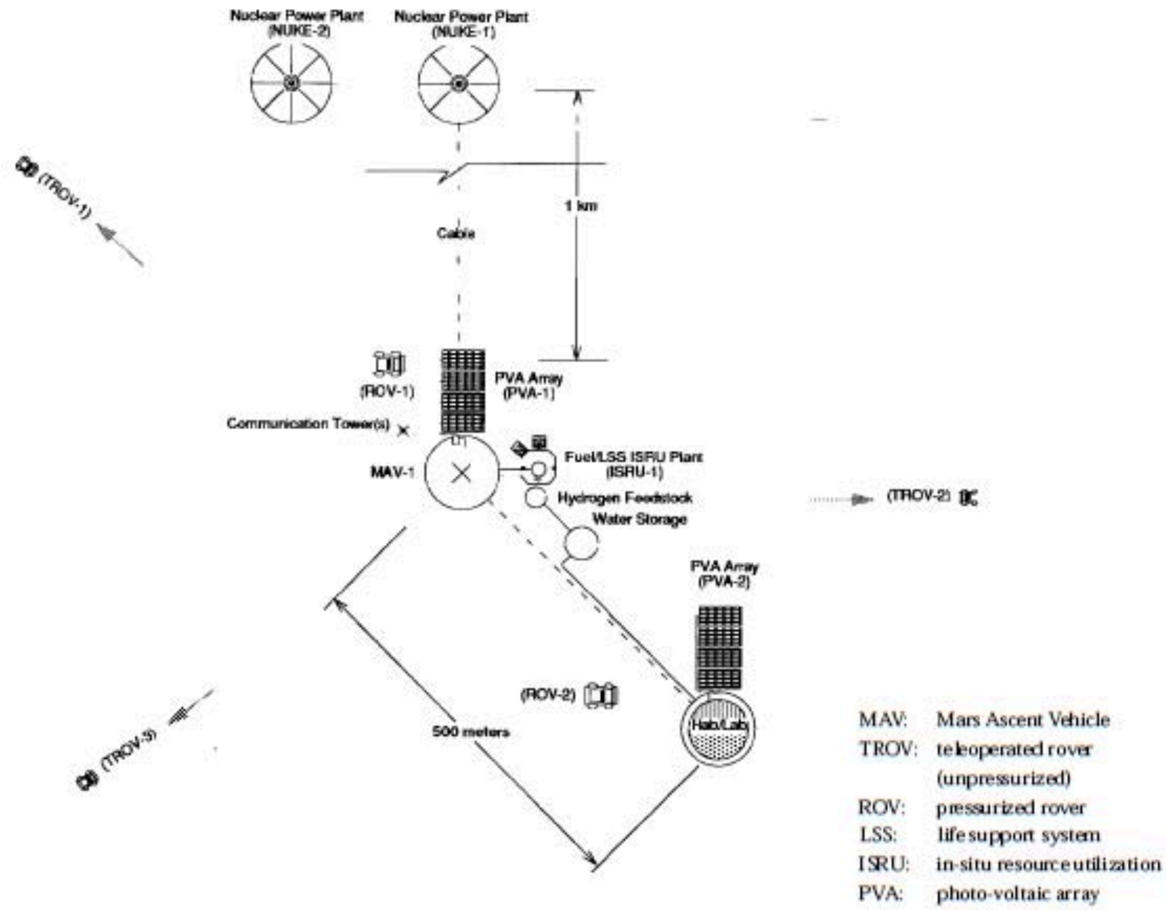

Figure 3-8 Mars surface outpost after deployment of payloads from first two cargo landers.

FIGURE A2 Site plan of the Mars base after the first launch window pre-positioning landings. The MAV sits about five to six habitat diameters from the Hab/Lab, on the order of 40 to 50m. This close proximity poses an unnecessary safety risk to the entire outpost. An MAV may crash on landing or explode on takeoff, wiping out the entire base. For this reason the Strategies for Mars site plan placed the landing zone at least 5 km from the outpost.

TABLE A3. MDRM 1.0 Flight manifest for the three pre-positioning launches at the first launch window, and land in accordance with the FIGURE A2 site plan.

Table 3-3 General Launch Manifest: 2007 Launch Opportunity

Flight 1: Cargo	Flight 2: Cargo	Flight 3: Cargo
	Surface Payload	
• None	• Ascent Capsule • Empty Ascent Stage • LOX/CH_4 Production Plant • LH_2 Propellant Seed • Power Supply (nuclear-160 kW) • Utility Truck • Pressurized Rover • Additional Payload	• Surface Habitat/Laboratory • Nonperishable Consumables • Power Supply (nuclear-160 kW) • Utility Truck • Spares • Teleoperable Science Rover
	Mars Orbit Payload	

• Earth-Return Vehicle
  • Fueled (LOX/CH_4) TEI Stage
  • Transit Habitat
  • Earth-Return Capsule
	• None	• None

	Space Transportation Vehicles	
• NTR Transfer Stage • LOX/CH_4 TEI Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake

TEI: Trans Earth Injection
NTR: Nuclear Thermal Rocket
LOX: liquid oxygen
CH_4: methane
LH_2: liquid hydrogen

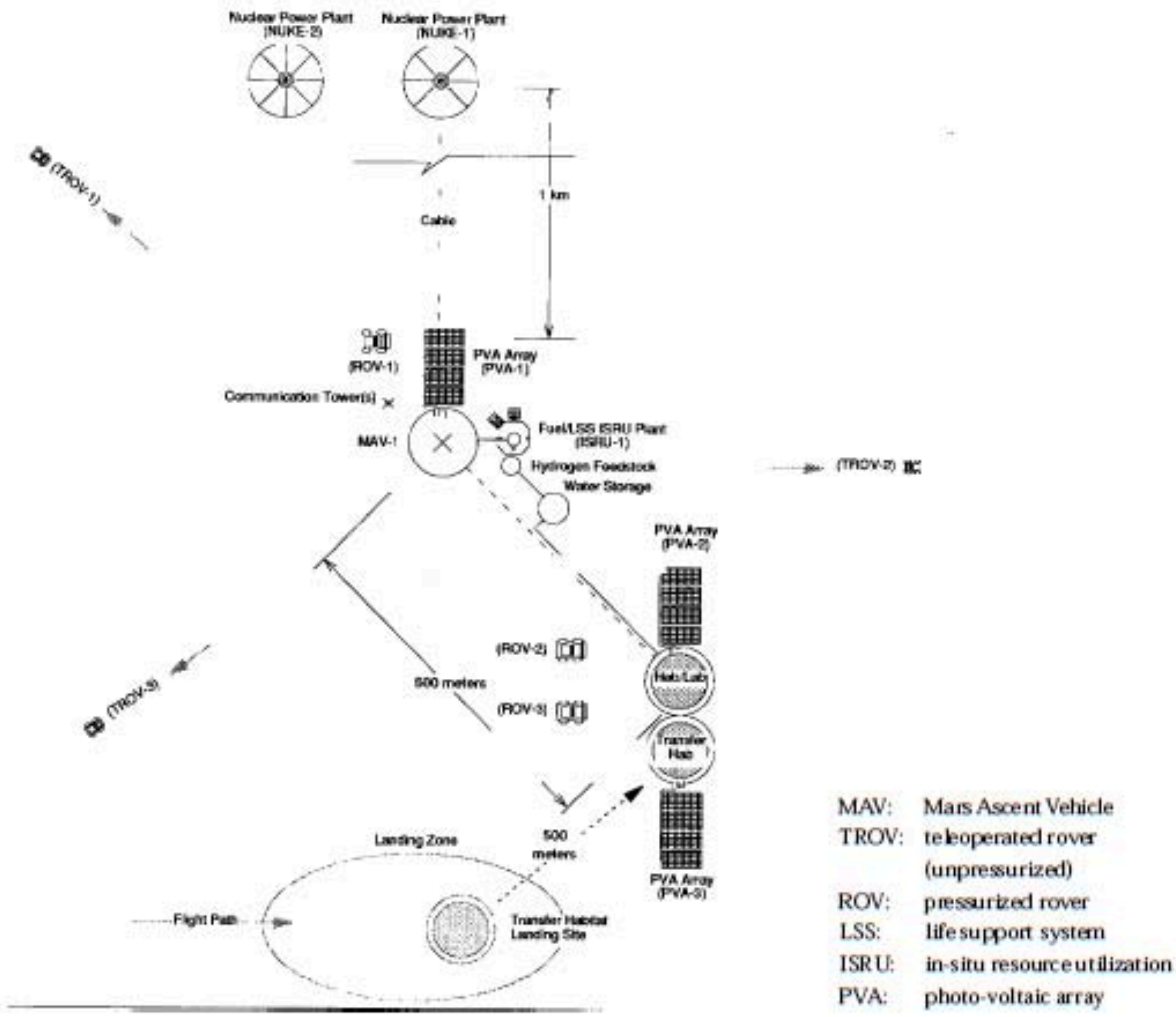

Figure 3-9 Mars surface outpost at the end of first flight crew's stay.

FIGURE A3. Mars base showing the placement of the two landed payloads that the first crew brings with them on the second launch window, the "backup" MAV and the first Transfer Habitat that lands in a separate landing zone ellipse than the MAVs. In this version of the site plan, the separate landing ellipse for the MAVs is visible, with a notation that apparently the nearer focus of the ellipse is 500 m from where the MAVs relocate for takeoff from the surface.

TABLE A4. Flight manifest for the payloads and crew that arrive at Mars on the second launch window, and land in accordance with the FIGURE A3 site plan.

Table 3-4 General Launch Manifest: 2009 Launch Opportunity

Flight 4: Cargo	Flight 5: Cargo	Flight 6: First Crew
Surface Payload		
• None	• Ascent Capsule • Empty Ascent Stage • LOX/CH_4 Production Plant • LH_2 Propellant Seed • Bioregenerative Life Support Outfitting Equipment • Science: 1 km drill • Science Equipment • Additional Payload /Spares	• Crew • Surface Habitat • Consumables • Spares • EVA Equipment • Science Equipment
Mars Orbit Payload		

• Earth-Return Vehicle
  • Fueled (LOX/CH_4) TEI Stage
  • Transit Habitat
  • Earth-Return Capsule
	• None	• None

Space Transportation Vehicles		
• NTR Transfer Stage • LOX/CH_4 TEI Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake

TEI: Trans Earth Injection
NTR: Nuclear Thermal Rocket
LOX: liquid oxygen
CH_4: methane
LH_2: liquid hydrogen

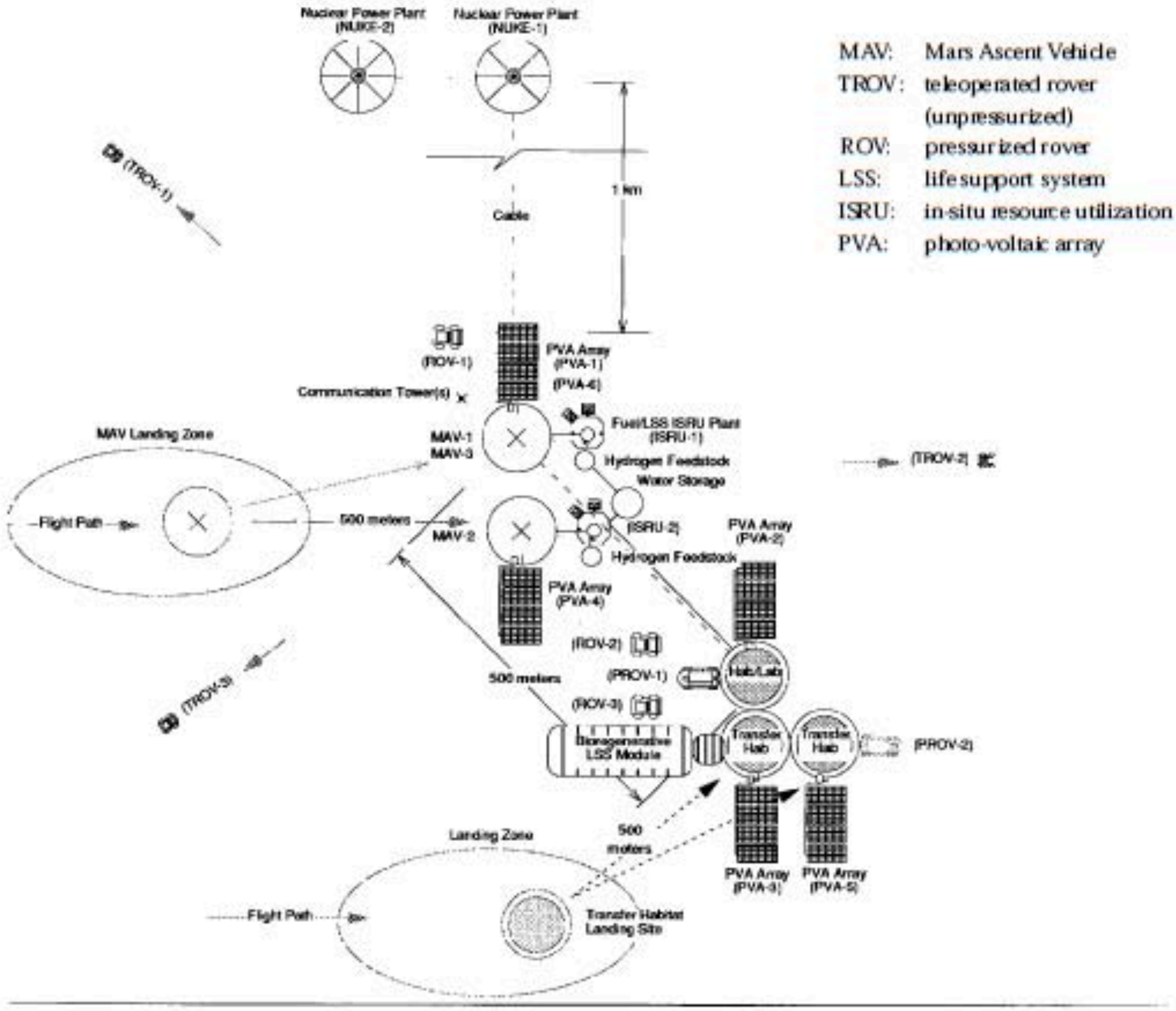

Figure 3-11 Mars surface outpost at the end of second flight crew's stay.

FIGURE A4. Site plan of the Mars base on the third launch window, showing three landed habitats clustering together and two MAVs. In this version, the separate landing ellipse for the MAVs is visible, with a notation that apparently the nearer foci of the ellipse is 500 m from where the MAVs relocate for takeoff from the surface. A bioregenerative life support module appears attached to one of the Transfer Habitats, with what appears to be an inflatable airlock node/tunnel connecting them.

TABLE A5. Flight manifest for the payloads and crew that arrive at Mars on the third launch window, and land in accordance with the FIGURE A4 site plan.

Table 3-6 General Launch Manifest: 2011 Launch Opportunity

Flight 7: Cargo	Flight 8: Cargo	Flight 9: Second Crew
	Surface Payload	
• None	• Ascent Capsule • Empty Ascent Stage • LOX/CH_4 Production Plant • LH_2 Propellant Seed • Pressurized Rover • Science Equipment • Additional Payload/ Spares	• Crew • Surface Habitat • Consumables • Spares • EVA Equipment • Science Equipment
	Mars Orbit Payload	

• Earth-Return Vehicle
  • Fueled (LOX/CH_4) TEI Stage
  • Transit Habitat
  • Earth-Return Capsule
	• None	• None

	Space Transportation Vehicles	
• NTR Transfer Stage • LOX/CH_4 TEI Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake	• NTR Transfer Stage • LOX/CH_4 Descent Stage w/Mars Aerobrake

TEI: Trans Earth Injection
NTR: Nuclear Thermal Rocket
LOX: liquid oxygen
CH_4: methane
LH_2: liquid hydrogen