NASA Evolvable Mars Campaign

Mars Surface Habitability Options

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Abstract— **This paper reports on current habitability concepts for an Evolvable Mars Campaign (EMC) prepared by the NASA Human Spaceflight Architecture Team (HAT). For many years NASA has investigated alternative human Mars missions, examining different mission objectives, trajectories, vehicles, and technologies; the combinations of which have been referred to as reference missions or architectures. At the highest levels, decisions regarding the timing and objectives for a human mission to Mars continue to evolve while at the lowest levels, applicable technologies continue to advance. This results in an on-going need for assessments of alternative system designs such as the habitat, a significant element in any human Mars mission scenario, to provide meaningful design sensitivity characterizations to assist decision-makers regarding timing, objectives, and technologies. As a subset of the Evolvable Mars Campaign activities, the habitability team builds upon results from past studies and recommends options for Mars surface habitability compatible with updated technologies.**

TABLE OF CONTENTS

1. INTRODUCTION 1
2. ASSUMPTIONS & REQUIREMENTS 3
3. HABITABILITY OPTIONS 4
4. RELATED STUDIES 6
5. FUTURE WORK 6
6. CONCLUSIONS 6
ACKNOWLEDGMENTS 6
REFERENCES 7
BIOGRAPHY 8

1. INTRODUCTION

Technologies and scenarios for planetary surface missions have been investigated by NASA, major aerospace contractors, universities, and individuals over the years, and continue to be influential on current studies. Design constraints for surface architecture have been suggested [1] describing the challenges of designing for partial gravity, dust, radiation, and transportation. Specific challenges have been addressed (too many to list here) for structures [2, 18], EVA suitports [3, 4], airlocks [5, 6, 7], mobility [21], as well as comprehensive design approaches [17] that are applicable to Mars surface outposts.

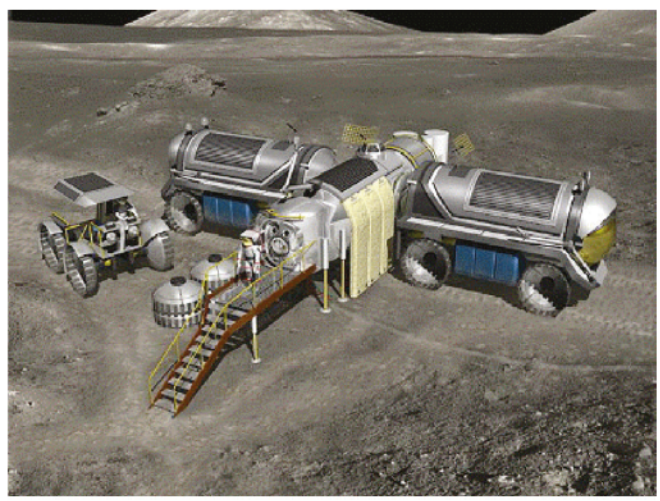

Figure 1: Mobile lunar outpost concept (Joosten & Guerra 1993)

Notable planetary surface habitability concept studies include Joosten & Guerra's [8] mobile lunar outpost (Figure 1), which has become a starting point for many of NASA's current habitability work. Recent efforts to re-evalutate surface habitability technologies include the Constellation Lunar Architecture Team, International Lunar Habitation Team, Habitat Demonstration Unit, Deep Space Habitat, and Mars Design Reference Architecture.

Constellation Lunar Architecture Team (LAT/CAT)

The Constellation Lunar Architecture Team studied many concepts in 2007-2008 (many of them not particularly new),

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including containerized frame mini-modules, integral lander habitats, "habitank" concepts (where propellant tanks are used or repurposed as habitable pressure vessels), toroidal inflatable outposts, mid-expandable modules (hard end cones spanned with inflatable tube cylinders), horizontal cylindrical modules, and vertical cylinder modules [9]. Final conclusions focused on horizontal cylinder and vertical cylinder type configurations [10], an example of which is shown in Figure 2.

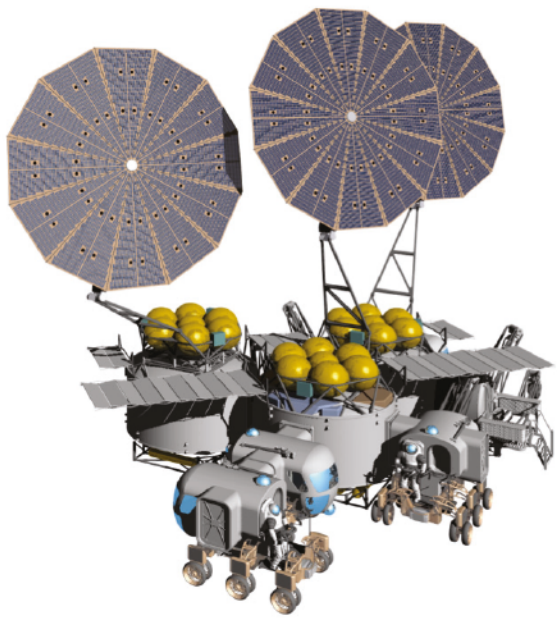

Figure 2: Constellation Lunar outpost -- 2009

International Lunar Habitation Team (ILHT)

The International Lunar Habitation Team (ILHT) was formed in late 2008 to support the International Architecture Working Group (IAWG) of the International Space Exploration Coordination Group (ISECG) in identifying the functions and operations required for conducting a collaborative campaign associated with a human return to the moon. The basis of the work was an example architecture and notional mission manifest for lunar human exploration, called the Global Point of Departure (GPoD) Lunar Architecture [11], that was developed by the IAWG. Habitation, provided within safe pressurized volumes, is an essential, required function to sustaining human life in any exploration mission regardless of destination, while incorporating technical sustainability wherever possible.

The team's primary responsibility was to use a systems engineering approach in identifying :

1. Those key mission drivers that determine the approach to Habitation
2. Top level requirements for Habitation for any exploration mission
3. Mission operations that result from meeting these drivers and requirements
4. Functionality that is needed to carry out these mission operations

The product of this approach was a Habitation Function Allocation Matrix that was then used to help define conceptual elements that were used within the study.

Habitat Demonstration Unit (HDU)

Assuming the vertical cylinder configuration that emerged from Constellation Architecture Team work (Figure 2), and developed in parallel with the GPoD research, it was decided to build a functional habitat that could be evaluated in mission contexts. The NASA Habitat Demonstration Unit (HDU) vertical cylinder habitat (Figure 3) was established as a exploration habitat testbed platform [12, 13] for integration and testing of a variety of technologies and subsystems that will be required in a human-occupied planetary surface outpost or Deep Space Habitat (DSH). The HDU functioned as a medium-fidelity habitat prototype from 2010-2012 and allowed teams from all over NASA to collaborate on field analog missions, mission operations tests, and system integration tests to help shake out equipment and provide feedback for technology development cycles and crew training.

Figure 3: Habitat Demonstration Unit (HDU) -- 2011

Deep Space Habitat (DSH)

NASA's Deep Space Habitat work initially built upon the HDU prototype (Figure 3), repurposing the unit to study deep space missions [14, 20] beyond Low Earth Orbit. With the exception of the Apollo missions, virtually all human space flight has occurred in low Earth orbits that are no more distant than the distance between Orlando and Miami. In other words, very close to the Earth. This is significant because NASA's goal is to explore Beyond low-Earth Orbit (BEO) and is building the Space Launch System (SLS) capable of sending humans to cis-lunar space, the surface of the Moon, asteroids and Mars.

Figure 4: Deep Space Habitat (DSH) – 2013

Unlike operations in low-Earth orbit, astronauts on deep space missions do not have rapid emergency return or frequent resupply opportunities and are exposed to potentially lethal radiation. To provide a low-cost deep space habitat within a short period of time, attention was concentrated on residual International Space Station (ISS) ground assets (Figure 4). For this approach, the Node 1 structural test article and a Multipurpose Logistics Module (MPLM) were considered the most favorable candidates. A Deep Space Habitat mockup facility was built at Marshall Spaceflight Center (Figure 5).

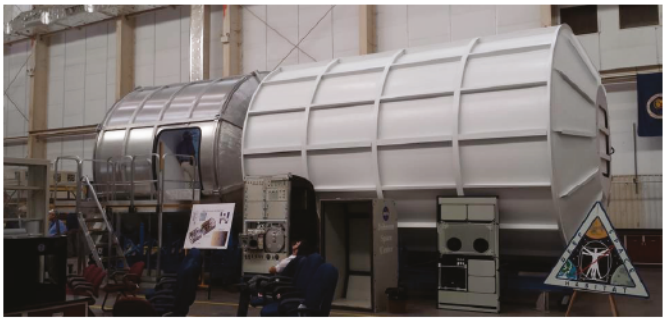

Figure 5: ISS-derived Cis-lunar Deep Space Habitat mockup at NASA Marshall Spaceflight Center

Mars Design Reference Architecture 5.0

NASA human Mars mission scenarios (Figure 6) have been studied, with a current baseline centering around Mars Design Reference Architecture (MDRA) 5.0 [16]. The essential aspects of MDRA 5.0 are as follows:

- Mars Descent/Ascent Vehicle (MDAV) and Habitat Lander are pre-positioned at Mars via multiple cargo missions
- MDAV is delivered to surface of Mars and begins In-situ Resource Utilization (ISRU) propellant production
- Crew and Mars Transit Habitat are launched via multiple missions after MAV propellant tanks have been filled
- Crew descends to surface in Habitat Lander
- Mars surface mission
- Crew ascends to orbit in MAV
- Crew returns to Earth in Mars Transit Habitat

Figure 6: Mars Design Reference Architecture (Drake 2009) showing scenario depicted by Rawlings 1997

The NASA Human Spaceflight Architecture Team (HAT) Evolvable Mars Campaign (EMC) habitation work described in this paper has come out of the MDRA 5.0 baseline. Habitability work at this early stage was to determine how a complete outpost could be divided up into multiple manifests, and thereby minimize the number of cargo and crewed launches required.

2. Assumptions & Requirements

Though a variety of scenarios were explored, a set of common assumptions were baselined in order to compare options in a fair manner.

The base assumptions were as follows:

- 500 day surface stay mission
- 4 crew members
- 2 pressurized rovers
- Maintenance airlock (internal or external)
- Crew lander and MAV delivered separately
- Surface power and exploration equipment delivered separately

Logistics, stowage, consumables, and subsystem requirements were determined from models incorporating rules of thumb, published data [18, 19], or tools [17] derived from spaceflight missions on the International Space Station (ISS). Common base assumptions across all habitability options were also assumed for Structure & Mechanisms, Avionics, Thermal Control, Maintenance & Spares, Reserves, Protection, Power, Environmental Control & Life Support, Crew Equipment & Accommodations, Logistics, and Extra-Vehicular Activity (EVA).

Crew Functions

Crew functions were not the main drivers at this stage in the investigation. However, it was important that some sort of parametric rules of thumb be considered for outpost sizing so that important functions of hygiene, health maintenance, crew dining, group activities, vehicle maintenance, command activities, translations/ingress/egress, mission operations, emergency operations, logistics operations, and science operations were represented. These functions were included in the models based on published work [18] and previous experience.

3. Habitability Options

Over the course of investigations, the EMC propulsion team proposed a range of lander capacities to work from. For example, if a 15 ton capacity lander were chosen, it would take eleven missions to deliver the same amount of surface assets that could be delivered by four missions using a larger 40 ton capacity lander. The lander capacities that were proposed were 15,000kg, 18,000kg, 27,000kg, and 41,000kg. While evaluating the different habitablity options, part of the trade was to see if a particular habitability option would be a driver for lander capacity selection.

The EMC habitability working group narrowed down habitability options to Monolithic Baseline, Modular Vertical, SLS/EUS-derived, and Small-diameter Modular Horizontal.

Note that in the following habitability options, masses shown are only a portion of the entire surface outpost mass for each concept. Outpost power would be supplied by a centralized surface power strategy, so arrays shown are for contingency and / or initial setup only.

Monolithic Baseline

The Monolithic Habitat includes most or all of the required pressurized volume for a Mars surface outpost into a single vertical cylinder (Figure 7). The Monolithic Habitat concept maximizes its diameter at 7.2m to fit into the Space Launch System (SLS) shroud, and parametrically sizes the height to attain the required volume.

Because of the large size of the single habitat element, the only lander capacity that would be available for carrying the Monolithic Habitat would be a 41,000kg capacity lander.

Element	kg	m^3
Monolithic Habitat	28440.0	159.7
PEV Rover	6809.0	12.0
PEV Rover	6809.0	12.0
Total	**42058.0**	**183.7**

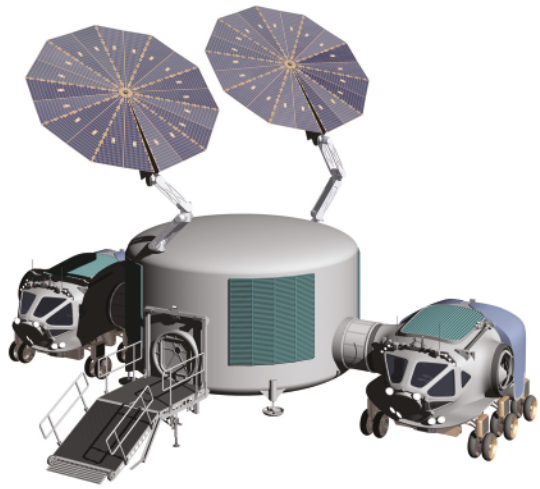

Figure 7: Evolvable Mars Campaign monolithic outpost configuration

Modular Vertical

The Modular Vertical Habitat option began with a core volume dedicated as a "machine room" for full Environmental Control & Life Support System (ECLSS) functionality, then supplemented the remainder of required volume using modules of identical size (Figure 8).

Element	kg	m^3
Vertical Core "machine room"	12482.0	52.8
Vertical Hab / Inflatable	17732.0	123.8
PEV Rover	6809.0	12.0
PEV Rover	6809.0	12.0
Inflatable Airlock	3464.0	10.6
Total	**47296.0**	**211.2**

Figure 8: Evolvable Mars Campaign vertical modular outpost configuration

The Modular Vertical concept also added an inflatable dome concept, similar to the Habitat Demonstration Unit (HDU), that could be collapsed during tranport and deployed in-situ.

The Vertical Core "machine room" module was 5.4m in diameter with a height of 2.7m, and the same identical hard module was used as the base of the Vertical Hab / Inflatable element. Due to the mass of the largest element being 17,732kg, the Modular Vertical outpost eliminated the possiblity of a 15,000kg capacity lander, but was able to be accommodated by all the other lander options.

SLS/EUS-derived

Launch vehicle derived habitats are a common consideration since large propellant tanks are pressure vessels that could be used for habitability. This approach promotes commonality through the use of propellant tank design and manufacturing processes for the primary habitat pressure vessels.

Element	kg	m^3
SLS/EUS-derived Habitat	35966.0	319.0
PEV Rover	6809.0	12.0
PEV Rover	6809.0	12.0
External Airlock / Dock Node	1559.0	10.0
Total	**51143.0**	**353.0**

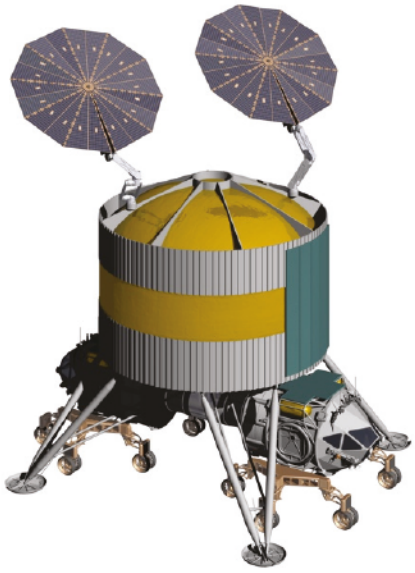

Figure 9: Evolvable Mars Campaign SLS/EUC-derived propellant tank outpost configuration

Previous papers have reported on studies that utilized hydrogen tank components from the Space Launch System (SLS) to construct large habitats for deep space missions including Mars transit habitats supporting crews of 6 for 1000 days [15, 20]. Current studies for surface habitat landers have also considered launch vehicle derived components.

Figure 9 is one of several configurations illustrating the use of the hydrogen tank for habitation derived from the second stage of the SLS known as the Exploration Upper Stage (EUS). This SLS/EUS habitat lander utilizes a sky crane landing concept to drop off the lander similar to the one used for the Mars Curiosity Rover; so, no propulsion system remains. However, mass-wise the SLS/EUS option could be delivered only by the 41,000kg capacity lander if such an option were chosen. The primary habitat is from the SLS/EUS hydrogen tank design outfitted with solar arrays above and an external airlock below to accommodate docking of pressurized rovers between the landing legs and EVA egress.

The SLS/EUS habitat lander is 8.4 meters in diameter matching the diameter of the SLS core stage and EUS upper stage. It is about 8 meters high providing interior volume for three floor levels. The interior volume includes crew quarters and waste and hygiene compartments on the top level; work stations, galley, and wardroom on the central/main level; and utility and EVA systems on the lower level with direct access to the external airlock and rover docking ports below. The volume appears to be adequate to support a crew of 4 with storage and life support systems volume for 500 day surface missions.

Small-diameter Modular Horizontal

The Small-diameter Modular Horizontal habitation option was based on the concept of a common cabin 3m diameter for not only all habitat modules, but also the same diameter for rover cabins as well (Figure 10).

Element	kg	m^3
Horizontal Core "machine room"	9827.0	45.9
Horizontal Hab Module	11280.0	60.0
Horizontal Hab Module	11280.0	60.0
PEV Rover	6809.0	12.0
PEV Rover	6809.0	12.0
Inflatable Airlock	3464.0	10.6
Total	**49469.0**	**200.5**

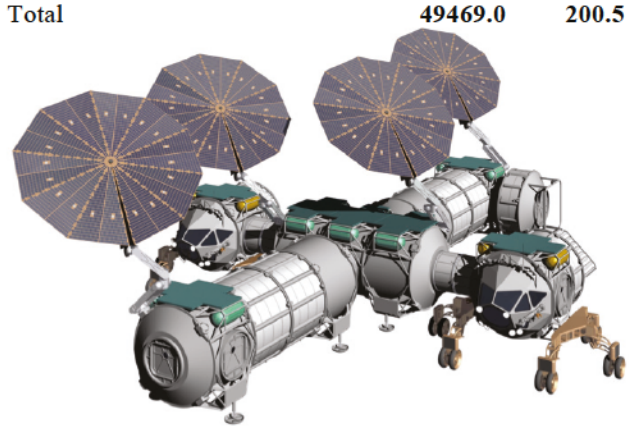

Figure 10: Evolvable Mars Campaign small-diameter modular horizontal outpost configuration

Using the same 3m diameter for all pressure vessels, but taking a modular parametric approach for length, a single factory manufacturing line on Earth could manufacture all elements derived from function-specific bulkheads. Similar to the Modular Vertical option, the Modular Horizontal option establishes a core "machine room" with supplemental habitat volumes. Additional volumes could pattern themselves after the Core Hab, or could consist of mid-expandable "midex" membrane cylinders spanning between

end cones or short pressurized compartments. In addition, 3m diameter pressurized hard shell modules can function as cores for TransHab-like large-volume inflatable habitats, opening up a door for a possible connection between surface and transit habitat architectures.

Because of the smaller module size and masses, the Modular Horizontal outpost elements could be carried by any of the entire proposed range of lander capacities, from 15,000kg to 41,000kg, in some cases two or three at a time.

4. Related Studies

The Phobos exploration mission concept includes a crew taxi for transfers between a Mars 1-Sol orbit where the primary Mars transit habitat is located and Phobos orbit where a smaller habitat will be attached to the surface. The size and accommodations required for the taxi are similar to those needed for the Mars crew ascent vehicle, which supports a crew of 4 for a few hours to days depending on planned propulsion and trajectory options. Future studies will explore this commonality even further to consider similar designs for the initial Exploration Augmentation Module (EAM) planned to support the Asteroid Retrieval Mission in the early to mid 2020's.

5. Future Work

In addtion to connection back with the proposed EAM module development, future work will see how Mars surface habitability, Phobos outpost, Mars Transit Habitat, and EAM can be developed in parallel, with requirements from each unique environment informing the design and development of each other to arrive at a common architecture.

Commonality

Evaluating the various habitability options, the EMC team will look at using only two pressure vessels: large volume for habitat, and small for cabins. More effort will be expended to emphasize re-use and modularity [21, 22]. The team will elaborate on the "machine room" concept, with the goal of identifying the smallest volume required for a package ECLSS system that can be attached to habitats, rovers, or in-space vehicles using simple docking technologies.

Packaging

More investigation on packaging will be part of future work. This will include how to package large habitat elements on landers (appropriate for the lander capacity chosen), lander off-loading, and habitation element mobility. Another main thrust of future work will include an investigation of small-profile hab elements that can fit in the Space Launch System (SLS) / Orion trunk, and deploy into larger volumes.

In-Situ Resource Utilization (ISRU) Construction

A third major investigation will consider possible uses of ISRU regolith-based construction that may require a small investment in regolith handling equipment [24] but have a return many times greater if the result is an ultimate mass savings. For example, JPL's All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) mobility system is one of the main options for surface mobility and relocating habitat elements [23]. The ATHLETE can also carry a multitude of mission-specific functions, such as construction and in-situ manufacturing capacity. One technology that might be applicable is using ATHLETE as a large-scale 3D printer to harden powdered regolith into prefabricated panels or blocks to construct in-situ structures (Figure 11) – these compressive structures can be prepared in advance and lined with lightweight membrane pressure liners to significantly reduce mission mass that must be lifted out of Earth's gravity well [25].

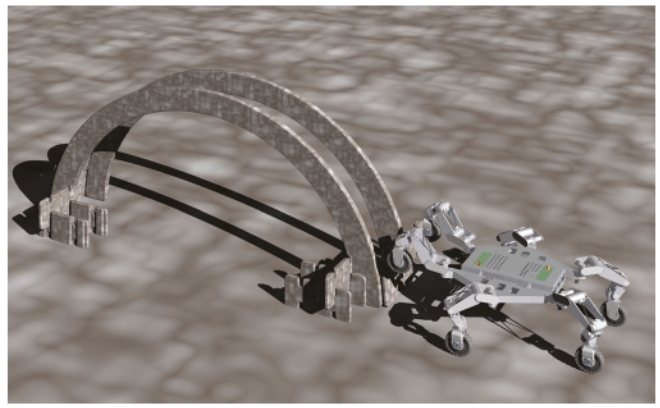

Figure 11: Regolith-based construction using ATHLETE as a large-scale 3D printer and constructor – Freeform Additive Construction System (FACS)

6. Conclusions

As of this writing, of the four main habitability options, Monolithic Habitat, Modular Vertical, SLS/EUC-derived, and Modular Horizontal, the EMC team leaned toward the Modular Vertical option because it breaks up the mass of a monolithic concept, yet does not add many small elements and their resulting risks for docking and mating. However, since entry, descent, and landing challenges are not completely resolved it was also determined to continue developing the other options as well, since the larger lander options may prove impractical. Also, other habitation options may be more appropriate for future work efforts listed above.

Acknowledgments

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BIOGRAPHY

A. Scott Howe *is a licensed architect and robotics engineer at NASA's Jet Propulsion Laboratory. He earned PhDs in industrial and manufacturing systems engineering from Hong Kong University and in architecture from University of Michigan. Dr. Howe spent 13 years of practice in Tokyo, Japan, and taught for 6 years at Hong Kong University. He specializes in robotic construction and currently is on the NASA development team building long-duration human habitats for deep space and permanent outposts for the moon and Mars. Dr. Howe is also a member of the JPL All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robotic mobility system development team, Asteroid Redirect Mission (ARM) capture mechanism team, and Mars Sample Return (MSR) Orbiter design team.*

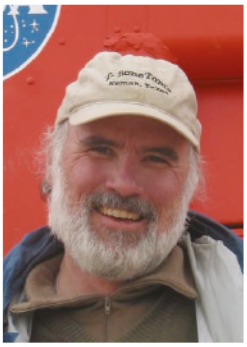
Matthew Simon *has been a member of the Habitation team within NASA's Human Spaceflight Architecture Team (HAT) for 3 years. This team designs and evaluates alternative space mission architectures to support strategic planning decisions at NASA Headquarters for future human space exploration missions. As a member of this team, he is primarily responsible for designing conceptual habitation systems and providing crew systems and support expertise throughout mission design. In addition, Mr. Simon supports multiple other projects on spacecraft design, radiation protection, exploration medical capability, strategic decision analysis, and technology portfolio characterization. He is currently pursuing a doctorate in Aerospace Engineering from Georgia Tech to be completed later this year. His research focuses on improving the generation and assessment of habitat interior layout designs in early design phases.*

David Smitherman *is an architect and technical manager of future space projects for the Advanced Concept Office at NASA's Marshall Space Flight Center in Huntsville, AL. His work focuses on space habitats, space and surface systems, space transportation infrastructures, and overall mission architectures. He worked as an architect in the 1980's, as a planner for the redesign of the space station and various space station payloads in the 1990's, and since*

1998 has been a study lead for various advanced concepts studies including Space Business Parks, New Space Industries, Space Elevators, Solar Power Satellites, Propellant Production Depots, and Deep Space Habitats. Mr. Smitherman has a Master of Science degree in Space Architecture from the University of Houston (2008), a Bachelor of Architecture degree and a Bachelor of Science degree in Environmental Design each from Auburn University (1980), and is a registered architect in the State of Alabama with NCARB certification.

Robert Howard *has a bachelor of science in general science from Morehouse College, a bachelor of aerospace engineering from Georgia Tech, a master of science in industrial engineering North Carolina A&T State University, and a Ph.D. in aerospace engineering from the University of Tennessee Space Institute. He also holds a certificate in Human Systems Integration from the Naval Postgraduate School and is a graduate of the NASA Space Systems Engineering Development Program. Currently Dr. Howard works for NASA at Johnson Space Center in Houston, TX, where he is the lab manager for the Habitability Design Center. There, he leads a team of architects, industrial designers, engineers and usability experts to develop and evaluate concepts for spacecraft cabin and cockpit configurations. He has served on design teams for several NASA spacecraft study teams including the Orion Multi-Purpose Crew Vehicle, Orion Capsule Parachute Assembly System, Altair Lunar Lander, Lunar Electric Rover / Space Exploration Vehicle, Deep Space Habitat, Waypoint Spacecraft, Exploration Augmentation Module, Asteroid Retrieval Utilization Mission as well as Mars surface and Phobos mission studies.*

Larry Toups *attained a Bachelor of Architecture Degree from the University of Houston. After practicing architecture, he received a Masters Degree in Space Architecture from the University of Houston, Sasakawa Institute for Space Architecture. From June 1988 – January 1994 he was a Senior Engineer with Lockheed Engineering and Sciences Company at Johnson Space Center. In this role, he provided technical support for JSC's New Initiatives Office in the area of Systems Engineering of habitats and planetary systems and contributed to numerous NASA studies. From 1998-2003, Mr. Toups assumed the role of Habitability Systems Lead in the ISS Vehicle Office. He is currently in the Exploration Mission Systems Office at Johnson Space Center.*



Stephen Hoffman *received a B.S., M.S., and Ph.D. in Aeronautical and Astronautical Engineering from the University of Illinois in 1978, 1980, and 1984 respectively. Dr. Hoffman is a Senior Systems Engineer with 35 years of experience working in civilian space programs performing tasks involving program management, interplanetary mission planning, preliminary spacecraft design, orbit mechanics, and planetary analog missions. Dr. Hoffman is currently supporting the Exploration Missions and Systems Office at the NASA Johnson Space Center. He supports a variety of mission studies and concept assessments associated with human exploration beyond low Earth orbit for this office.*