

Conceptual Design and Analysis of a Deep Space Habitat with a Venus Flyby

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Within the mission trade space for crewed Mars missions, opposition missions are considered as fast transit options to minimize the crewed duration in the deep space radiation environment. However, they tend to have much higher in energy requirements than conjunction class missions, and Venus flybys are often leveraged to lower the total ΔV as much as possible. While the conceptual design of deep space habitats is already a complex problem, the Venus flyby introduces a new environment of operation that adds layers of difficulty. A design point is presented that is capable of performing the crewed Mars mission and ensure the crew is safe flying in proximity to Venus and the Sun. Detailed thermal analysis of the design point is done to show the sensitivity of the thermal control systems to changes in mission parameters.

I. Nomenclature

<i>ALSSAT</i>	=	Advanced Life Support Sizing Analysis Tool
<i>AU</i>	=	Astronomical Units
<i>CLV</i>	=	Commercial Launch Vehicle
<i>CTB</i>	=	Cargo Transfer Bag
<i>DRA5</i>	=	Design Reference Architecture 5.0
<i>ECLSS</i>	=	Environmental Control and Life Support Systems
<i>EPCU</i>	=	Electric Power Converter Unit
<i>EVA</i>	=	Extravehicular Activity
<i>EXAMINE</i>	=	Exploration Architecture Model for IN-space and Earth-to-orbit
<i>LEO</i>	=	Low Earth Orbit
<i>MLI</i>	=	Multi-Layer Insulation
<i>MTH</i>	=	Mars Transit Habitat
<i>NRHO</i>	=	Near Rectilinear Halo Orbit
<i>NTO/MMH</i>	=	Nitrogen Tetroxide and Mono-methyl Hydrazine
<i>OML</i>	=	Outer-Mold Line
<i>SLS</i>	=	Space Launch System
<i>TMM</i>	=	Thermal Math Model

II. Introduction

Since setting Mars as the horizon goal for human space exploration, NASA has developed many deep space habitat concepts for crewed transport to the red planet. Designs have evolved through the years to meet changing requirements, goals, and capability needs. Crewed habitats beyond Low Earth Orbit (LEO) are sensitive to mission and transportation assumptions. Within the trade space for Mars trajectory analysis, there are two main classes of missions, conjunction and opposition. Venus flybys are considered for crewed Mars explorations missions to enable integrated demonstrations of in-space crewed interplanetary transit systems and as part of fast transit, short stay, opposition-class trajectories for

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crewed transit to the Mars sphere of influence.[1] By leveraging Venus flybys for higher ΔV opposition-class trajectories, it is anticipated that propellant loading on the transportation system can be reduced, thus reducing the size and cost of these vehicles to perform future missions.[2]

However, these flybys add environmental considerations and mission concept of operations that place very additional requirements on deep space habitat subsystems, operations, and performance. Although they reduce propellant loads on transportation systems, these requirements may create the need for new technology developments and increase the mass and cost of the deep space habitat, which can possibly consume some of those savings. To understand the habitat design challenges associated with crewed Venus flybys, there is a need to reassess previous conceptual deep space habitat designs and consider low-mass alternatives capable of supporting crew near Venus.

III. Mission Concept of Operations

Conjunction class mission opportunities are usually 200-300 days longer in duration, which drives habitat design differently, compared to opposition missions with a Venus flyby. This study considers both modes and their impacts on the habitat, but an emphasis is placed on the latter to ensure crew safety near Venus. Full trajectory design and optimization was not done for this study, but a notional depiction of the opposition mission is shown in Figure 1.

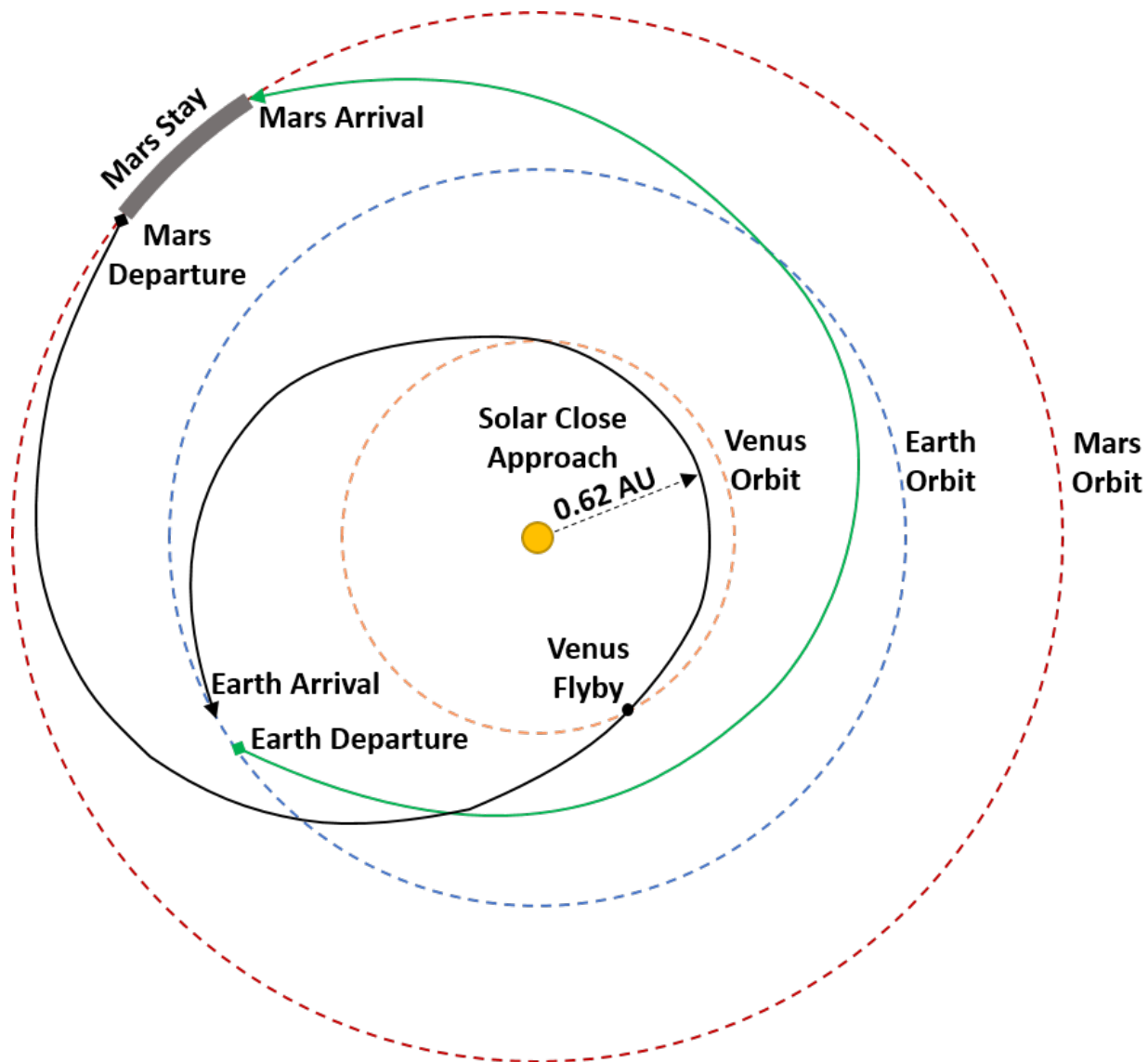


Fig. 1 Notional full crewed Mars opposition mission trajectory with a Venus flyby, not to scale.

Delivery of the habitat to NASA's cislunar Gateway in its Near Rectilinear Halo Orbit (NRHO) will be accomplished using a two CLV launch architecture and a boost stage.[3] Gateway will serve as the staging point for the habitat when it is not flying a mission, and outfitting will occur there. Although a separate transportation system will provide the means to get to Mars, the habitat is assumed to have free flying capability for operations near Earth and Gateway. After it has been outfitted and loaded with logistics for the Mars mission, the habitat will undock from Gateway and rendezvous with the Mars transportation system, which will have arrived at NRHO. The assumed opposition class mission will take about 2 years in total, with around 1-2 months in the Martian sphere of influence. The flyby will occur during the return leg to Earth and will take the habitat inside Venus orbit, with a baseline of 0.62 AU and a lower bound of 0.55 AU. Upon return from the Mars mission to NRHO, the habitat will redock to Gateway for re-outfitting.

For all potential missions, a crew of four will be supported. Although a total of about 760 days was used as the mission duration assumption for an opposition class mission, the habitat will be capable of 1100 day missions to account for conjunction opportunities if need be. To allow time for outfitting, shakedown, and analog or interim missions, the habitat will have a design lifetime of 15 years.

IV. Subsystems Design

A. System Mass

To provide the transportation system a limit for payload growth, a goal dry mass of 23 t dry was chosen. This on par with previous deep space habitat studies and should house all systems necessary to perform the mission described above.[4] The logistics mass will depend on the exact mission duration and profile, but a maximum loading for a 1,100 day duration is assumed.

B. Habitation Systems

To house the other subsystems and crew, a net habitable volume of at least 25 m³/crew member is needed, as recommended by NASA's Human Research Program.[5] A full set of crew support equipment, accommodations, and associated logistics required for long duration missions is provided similar to those provided in Simon et al.. This includes long duration accommodations such as private crew quarters, hygiene equipment, exercise, galley, medical equipment. There is assumed to be a closed-loop environmental control and life support systems (ECLSS) with an architecture that will allow for long dormant periods between crewed missions. These systems will be developed from existing technologies to provide low mass solutions with increased reliability and maintainability.[4] The atmosphere is assumed to be 14.7 pisa, with 21% O₂. The ECLSS subsystem was sized using the Advanced Life Support Sizing Analysis Tool (ALSSAT). It uses algorithms based on input levels of loop closure, mission scenario and combinations of subsystems used within. Crew support equipment and logistics will be provided as recommended by NASA's Space Flight Human Systems Standards and the Human Integration Design Handbook.[6–8]

C. Power Subsystems

Since the habitat will need to be able to free fly, an independent power subsystems is necessary. It is assumed to be a deployable solar array that can provide the habitat up to 20kW end of life (EOL) peak power at 1 AU. Beyond 1 AU, the transportation system will provide the additional power needed as the maximum solar array power generated drops from 20 kW moving away from the Sun. The solar arrays were modeled as a MegaROSA design, with 2 total panels and a cell efficiency of 0.33.[9] The power management and distribution (PMAD) systems uses a 28V electric power converter unit (EPCU) architecture.

D. Avionics

The habitat is assumed to have the necessary components to be a free flyer, which include the communications systems, command and data handling and guidance and navigation hardware. Overall subsystems size is determined through a master list of required components and their specific mass, volume and power. For each, an installation factor of 30% was included, as well as allocation for wiring based on the habitat's overall dimensions.

E. Extravehicular Activity

During the long duration crewed mission, EVA is assumed only for contingency cases. The airlock is integrated with the primary structure of the habitat and provides all the necessary services needed for one 2-person EVA every 3 months leveraging umbilicals and light-weight suits similar to Simon et al..

F. Propulsion

A critical capability needed for being a free flying element is a propulsion system. For this habitat, an integrated propulsion system with a ΔV capability of 180 m/s is assumed, which should cover any small maneuvers including NRHO insertion and rendezvous with either the Gateway or the Mars transportation system. The systems sizing is based off of an Aerojet R-42 thruster, with NTO/MMH propellant.[10] Storable propellant is assumed so that the habitat wouldn't need to carry any cryogenic fluid management hardware throughout its long duration missions. However, to fulfill its 15 year lifespan, a refueling capability is needed when it has returned to NRHO after its crewed Mars mission.

G. Protection Systems

One of the main reasons the opposition class mission is assumed is to reduce the crew duration in the radiation environment. However, to reduce the dosage further, the habitat will be lined with the logistics packaged in cargo transfer bags (CTBs). To protect from micrometeoroids and orbital debris (MMOD), a multi-layer configuration was modeled as the skin of the inflatable, consisting of Nextel ceramic fabric, low-density cored polyurethane foam, and Kevlar rear wall.[5]

H. Habitat Design Trade Space

Beyond the above assumptions for other subsystems, the Table 1 shows the trade space considered for this study and this section describes the down-selection performed to reach the final architecture.

Table 1 Habitat design trade space considered for this study.

Design Strategy	Modular	Monolithic	
Structure	Metallic	Inflatable	
Thermal Control	Radiators	Insulation	Solar Shield

1. Design Strategy

Although most deep space habitat concepts have been proposed as monolithic architectures, a modular approach has the potential to offer many benefits. Monolithic habitats contain all of the necessary functional requirements within one, enclosed system. This type of habitat is much simpler to design and develop, compared to other solutions. Since all of the necessary functions are contained within itself, there are no structural mass inefficiencies associated with it. However, these habitats tend to be designed for a single mission duration and crew, and are significant in unit mass and volume. This places strain on the launch and delivery strategy. Previous examples of monolithic deep space habitats are NASA's own Mars Transit Habitat and TransHab concepts.[4, 5]

Modular habitats, on the other hand, distribute these requirements over several, smaller, units. Since each single unit is smaller in comparison to a monolithic one, they can be launched on commercially available launch vehicles, rather than relying on the large volume capability of NASA's Space Launch System (SLS).[4] Capabilities of modular habitats can be slowly built up over time and expanded upon after initial completion. A significant example of a modular habitat is the International Space Station (ISS), built up over time by the Space Shuttle. Modular elements can also simplify logistics and spares resupply operations as a full logistics module can be replaced rather than relying on the crew to physically move cargo between two separate elements. Each single unit can also share design traits, thus reducing manufacturing costs.[11]

Although the benefits seem plentiful, modular architectures are not without penalties. To separate the functional responsibilities of a habitat over smaller modules, there exists a mass penalty brought by the duplicate systems and structural inefficiencies on each module to ensure a single, working system. This is in addition to the risk associated with launch and assembling many elements. To reduce the load on the transportation systems as much as possible, a monolithic habit was chosen for this mission.

2. Structures

Historically, metallic habitat concepts have been proposed for their relative simplicity and strong structural properties. Metallic structures are very capable in protecting against MMOD as well as handling loads from transportation elements. They can be designed specifically to fit within existing launch vehicles to make delivery a much simpler process. Additionally, it allows for the internal layouts to be pre-outfitted, without having to rely on later outfitting flights. However, to accommodate the recommended 25 m³ habitable volume per person, metallic habitats tend to be very massive on launch, usually requiring super-heavy class launch capabilities.[11]

Inflatable structure habitats are much more recent, with Bigelow's Expandable Activity Module (BEAM) demonstrating not only their feasibility, but viability for long duration missions.[12] Their larger concept, the BA330 is expected to launch in 2021 and have 330 m³ of pressurized volume.[13] These habitats have shown the possibility of very large habitable volumes, on the order of 100s of cubic meters. In addition, they can be launched on smaller launch vehicles, as they can be inflated after being placed into orbit, allowing an additional SLS flight for heavier elements within the campaign. However, internal layouts need to be established after launch. To maintain structural rigidity, inflatables are usually designed with a central, metallic core, which also handles any thrust loads, as well as carries any required docking ports.

Since an SLS launch is assumed to be unavailable, either one or more CLVs need to be used to deliver the habitat. With the habitable volume requirements, a solid, monolithic habitat would not fit within a CLV and it would be difficult to launch a solid, modular habitat on the same number of CLVs that an inflatable can be delivered in. As a result, the inflatable option is chosen for this conceptual design. However, with the whipple shield assumption, further refinement is needed to assess if an inflatable habitat could be designed with one.

3. Thermal Control

Since the Venus flyby will take the crew and habitat very close to the sun, an emphasis was placed on assessing additional options for thermal control strategies beyond the traditional radiator and MLI setup. Prior to this study, a rough order of magnitude assessment of the sink temperature at 0.62 AU showed that radiator assembly would grow to about 3 t to reject the required heat loads within the habitat. This drove the need to assess other low mass solutions to ensure the dry mass of the habitat does not grow beyond the limit. However more detailed analysis shows that radiators are able to reject all of the heat loads by themselves, without growing significantly, which is described in the Thermal Analysis section of this paper.

The habitat will use a doubled pumped-fluid loop heat rejection model, with external and internal loops. The internal loop will use 40%/60% Prop Glycol and water, while the external loop will use HFE-7200. A heat exchanger is used to transfer heat between the two. There are total of 16 radiator panels with an absorptivity to emissivity ratio of 0.17:0.92, with a design lifetime of 15 years. As a baseline, the radiators were sized to sink temperature of 215 K and a heat rejection load of 14.5 kWt. It also assumed that they have the capability to track to the coldest temperatures throughout the mission to ensure heat rejection.

V. Habitat Design Point

Using the above assumptions and design decisions, a parametric model of the habitat was created using the Exploration Architecture Model of IN-space and Earth-to-orbit (EXAMINE). EXAMINE is a design framework that houses a collection of subsystem sizing models that users can leverage to build and integrate different architecture elements. High level design traits and inputs were set based upon the mission and habitat design assumptions to generate a design point. A mass breakdown is shown in Table 2

This dry mass exceeds the goal mass limit, it does include 30% allotment for growth. It sized as a cylindrical habitat, with the inflatable section being 7.8 m diameter and 8.5 m in length, shown notionally in Figure 2. The central core is 3.0 m in diameter and 16.2 m in length. This gives a total of about 197 m³ of pressurized volume in the inflatable section, including the central core.

Table 2 Habitat design point mass breakdown.

Subsystem	Mass (kg)
Avionics	368
ECLSS	6,433
EVA	811
MMOD	2,644
Power	1,710
Propulsion	1,649
Structure	5,147
Thermal Control	846
Basic	19,607
Growth (30%)	5,882
System Mass	25,489

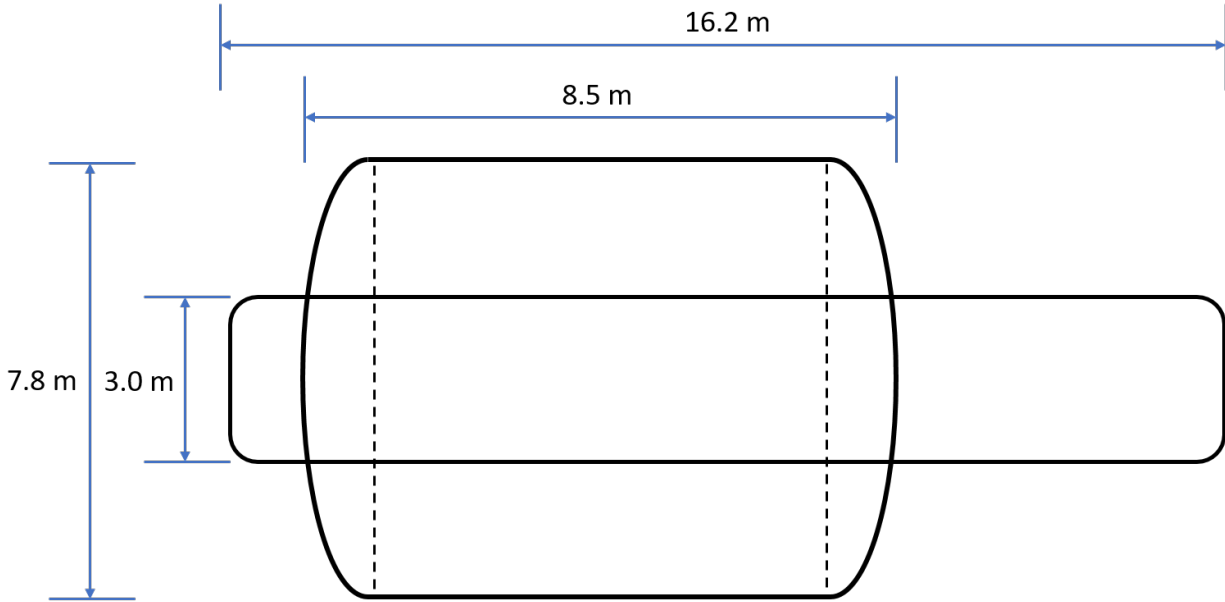


Fig. 2 Notional wireframe drawing and dimensions of the habitat including the inflated section and central core.

Although a detailed layout analysis is necessary, the inflatable section houses the habitable living areas and crew. The core maintains the structural rigidity and houses the airlock and docking ports for mating with other vehicles. The deployable solar arrays and radiator assembly is mounted on the longer end of the core, which allows for maximum docking corridors for visiting vehicles. It is assumed that the Mars transportation system will either dock at one or both ends of the habitat, depending on its design.

VI. Thermal Model Development

A description and configuration of the habitat thermal math model (TMM) is provided in this section. This includes intended use of the model, simulated phases, identification of model version/revision, dependencies, a detailed technical model description, Outer-Mold Line (OML) geometry, optical properties, trajectory/orbital cases evaluated, and various other material properties and assumptions.

A. Technical Description of Vehicle Model

1. Analytical Tools

The preliminary Thermal Math Model (TMM) representing the habitat flight configuration concept was developed using Thermal Desktop® 6.1 Patch 5 by Cullimore and Ring Technologies.[14] SINDA/FLUINT 6.1 Patch 3 by Cullimore and Ring Technologies was used as the thermal analyzer.[15] AutoCAD 2018 was utilized for geometric modeling.

2. System of Units

In presentation of data, SI system of units were used in the analysis and are summarized in Table 3.

Table 3 Thermal Model Units

Parameter	Units
Model Length	meters (m)
Temperature	Kelvin (K)
Energy	Watts (W)
Time	Hours (hr)
Mass	kilogram (kg)
Orbital Length, distance, or altitude	Kilometers (km), and Astronomical Units (AU)
Angle	Degrees
Conductivity	$\frac{Watts}{m \cdot K}$
Conductance	$\frac{Watts}{m^2 \cdot K}$
Density	$\frac{kg}{m^3}$
Flux	$\frac{Watts}{m^2}$
Power	Watts (W)

3. Coordinate System

The model coordinate system convention used for this analysis and applied to TMM model axes alignments was based on reference coordinate systems prominently utilized by the vehicle and systems designs for future NASA Deep Space Habitat, Gateway, and M2M Programs. In these analyses, the centerline of the habitat vehicle positive X direction initially points, in flight nose-velocity-vector (VV) convention, down the habitats primary longitudinal vehicle axis. The positive Y direction points to the right of centerline of X, and the positive Z direction satisfies the right-hand rule. An overall depiction of habitat is seen in Figure 3. The general habitat coordinate system orientation is seen in Figure 4.

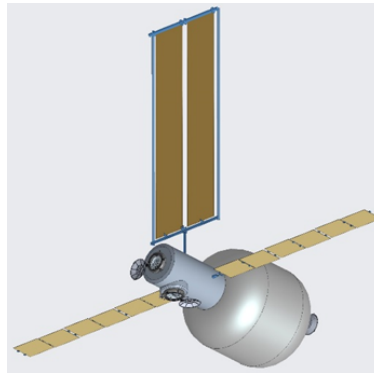


Fig. 3 Notional depiction of the habitat

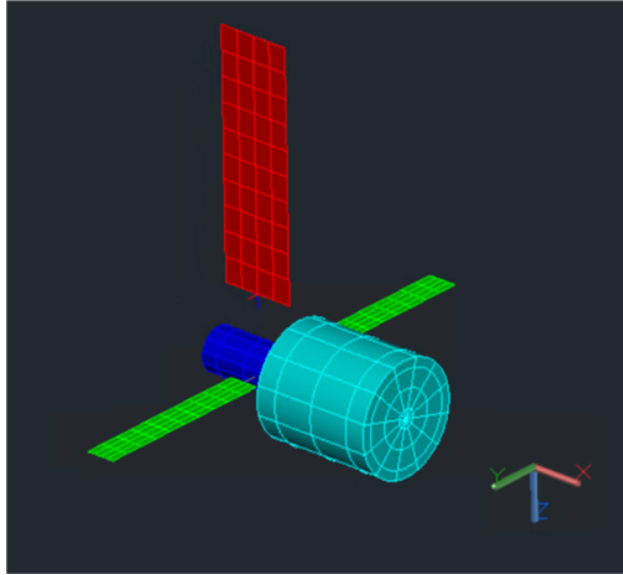


Fig. 4 Notional depiction of the habitat

4. Model Description

This section describes the Thermal Math Model used for the habitat Thermal Analysis. Subsections will be dedicated to the description of the individual submodels/components. A complete Thermal Desktop representation of the model with relevant surfaces to illustrate prominent radiative influences and temperatures are shown notionally for the solar close approach in Figure 5 and near Venus eclipse approach in Figure 6. Currently, the habitat concepts are in initial design stages, thus the thermal approach applied involved a simple representation of a portion of the habitat Outer Mold-line (OML geometry).

To assess overall radiative effects of all pertinent and viewable surface interactions, habitat module (with Aft vestibule, the extension of the core structure, plus (2) Y-opposed/deployed thermal radiator arrays), and a single Z-solar photo-voltaic array were included in the TMM. The habitat vestibule thermal radiators were evaluated in two positions: flat (0° roll) in the xy-plane and rolled 45° about the y-axis towards the aft section. The solar array was evaluated in two positions: edge-on to planet/sun (0°) and broadside to planet/sun (90°). Only relevant surfaces for external radiative effects were added in the model for core view-factor and optical property influences, with most forward and aft-most vehicle projected sections not included due to negligible thermal impacts at this time. Dimensional characteristics of the TMM model illustrate the following geometric OML of Figures 7 and 8.

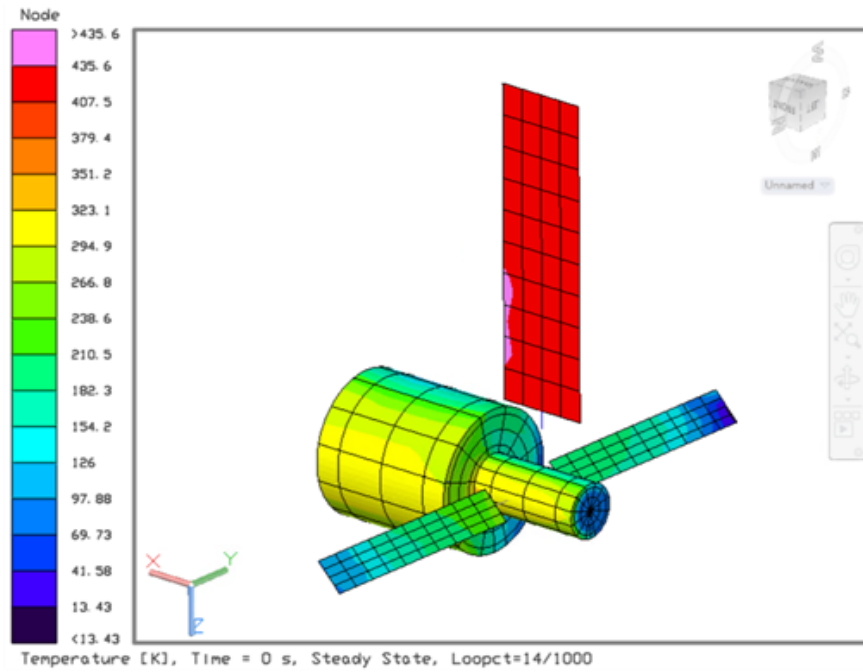


Fig. 5 Habitat Thermal Math Model: 0.62 AU Solar Approach with Solar Array broadside to sun and thermal radiators rolled 45deg.

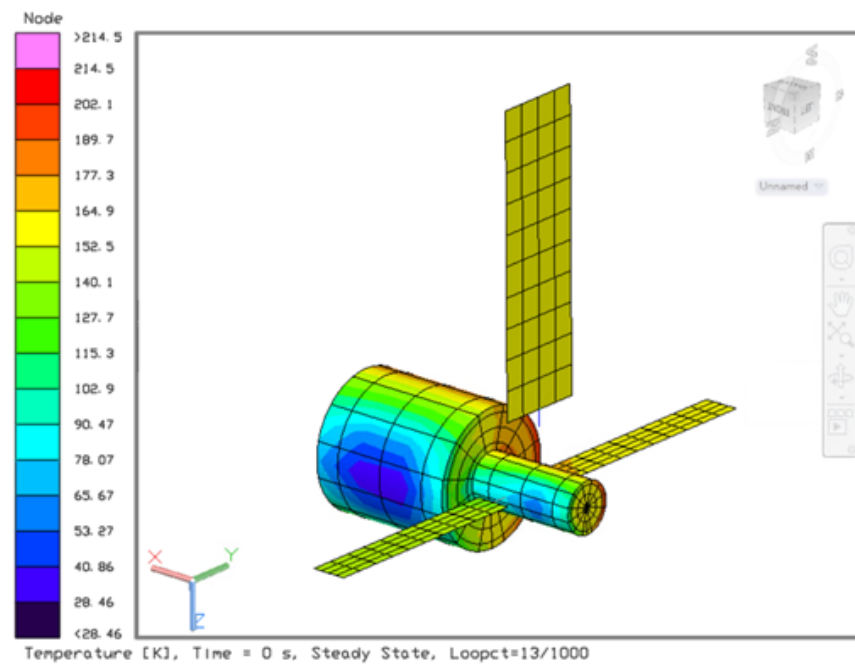


Fig. 6 Habitat Thermal Math Model: 832km Venus eclipse approach with Solar Array edge-on viewing Venus and thermal radiators flat, rolled 0deg.

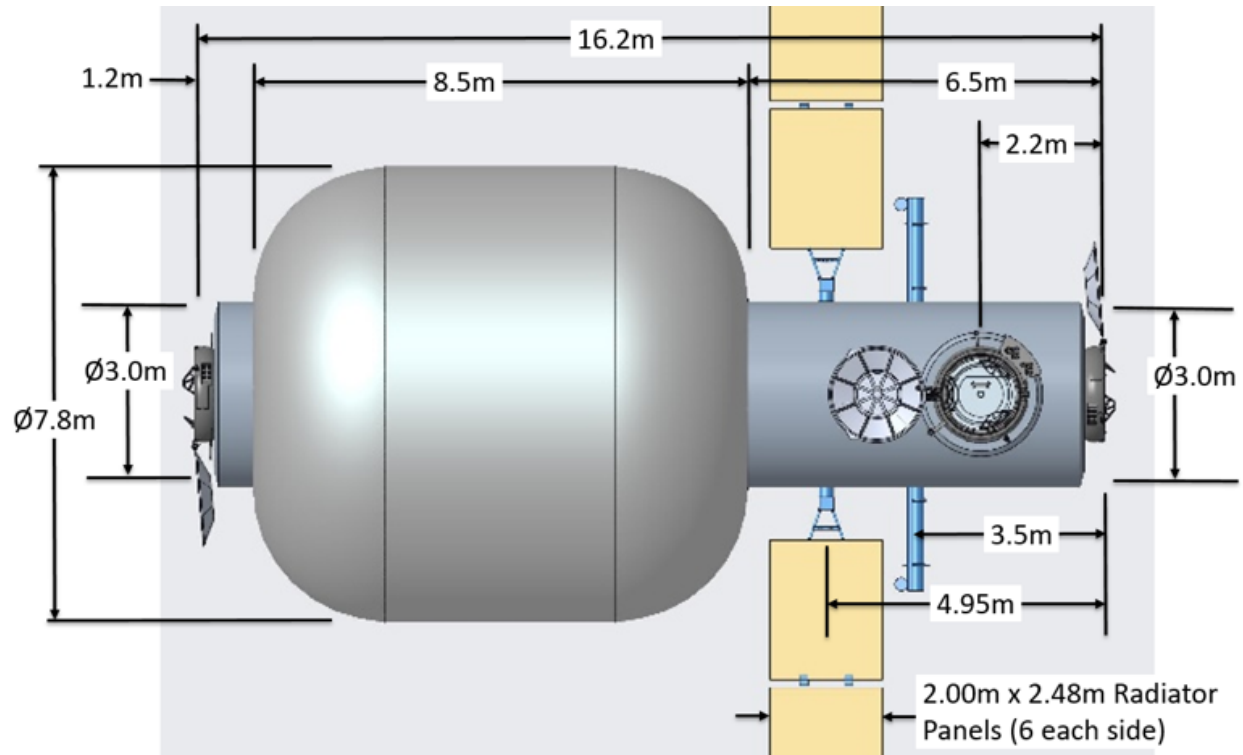


Fig. 7 General habitat TMM OML geometric characteristics.

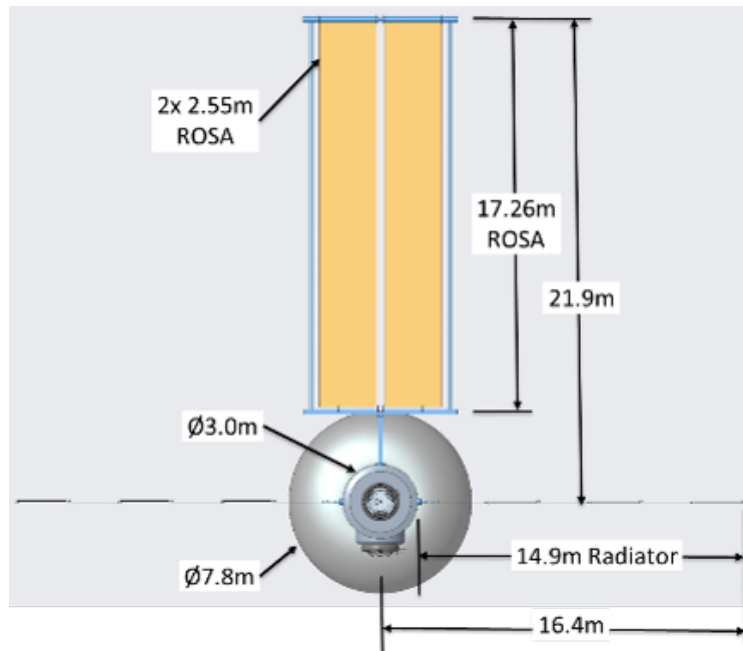


Fig. 8 General habitat TMM OML geometric characteristics, with solar array dimension.

This TMM model contains the following geometry and optical properties with appropriate rendering of prominent external adiabatic surfaces in Figure 4 and evaluates only the orbital flight phase scenarios deemed as most rigorous as worst hot thermal case-based attitudes and positioned in static trajectory positions (for quasi-steady results). Salient

surface dimension and radiative optical properties (α - solar absorptivity and ϵ - IR emissivity) used are:

- Habitat radiators (green)
 - 2 (+/- axis) opposed x 2 m x 13 m effective $\rightarrow$ 52 m² (deployed/articulating)
 - $\alpha/\epsilon = 0.17/0.92$ (single-sided)
- Solar Array (red)
 - 5.1 m x 17.26 m $\rightarrow$ 88 m²
 - $\alpha/\epsilon = 0.93/0.85$
- Habitat (light blue) + Vestibule (dark blue)
 - Inflatable Section: 7.8 m diam. x 8.5 m $\rightarrow$ 304 m²
 - Vestibule: 3 m diam. x 6.5 m $\rightarrow$ 75 m²
 - $\alpha/\epsilon = 0.123/0.868$

Cases for points throughout the trajectory were evaluated for extreme worst case thermal excursions in transit, including:

- Closest approach of 0.55 AU and 0.62 AU to the sun
 - Broadside Habitat & Vestibule cylinder (plus shaded side)
 - Habitat radiators edge-on to sun
 - Solar Array plane viewing solar vector
- Venus eclipsed or shadow side, closest approach to Venus planet transit within 500km, 832km and 1500km altitudes
 - Vehicle warmest habitat broadside-facing side to planet
 - Coldest and opposite side of habitat surfaces away from planet

These locations analyzed are seen schematically in Figure 9 and Table 4 at two points in the current trajectory, Pos 0deg (sub-solar pt) and Pos 180deg, eclipsed by Venus in near pass. Trajectory path is not to scale.

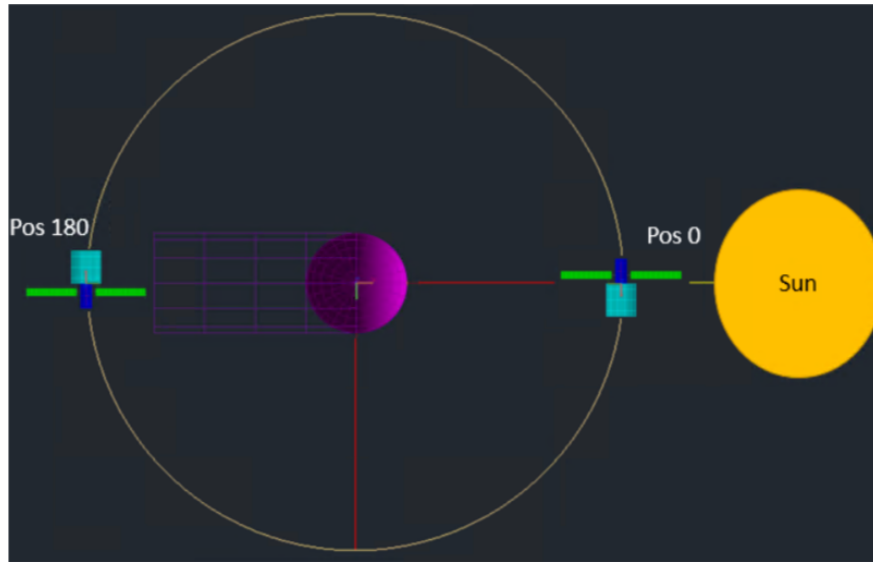


Fig. 9 Depiction of the locations analyzed using the thermal model, not to scale.

Table 4 Position key for locations analyzed in the thermal model.

	Thermal Case	Vehicle Attitude
Pos 0 (Solar Close Approach)	0.55 AU, 0.62 AU	Sun -Y side, Velocity Vector +X
Pos 180 (near Venus eclipse)	500 km, 832 km, 1500 km altitudes	Venus +Y, Velocity +X

B. Thermal Modeling Results

The first set of results summarize the predicted temperatures at the surface of the habitat, arrays and radiators at 0.62 AU from the Sun during the solar close approach. These temperatures are shown in Table 5; the first set showing results with the radiators at 0 deg and the second set with the radiators at 45 deg. At a worst case, the sink temperature on the radiators reach up to 243 K and feathering 45 deg only reduces it to 240 K. Table 6 shows the results for the vehicle at the same attitudes and radiator angles, but at a solar close approach distance of 0.55 AU. distance was chosen as a potential lower bound for future trajectory analyses. The sink temperature increases to 258 K at the worst case and again, feathering does not appreciably change the result. Although only a single vehicle attitude was assessed, there is potential for the transportation system to be able to change entire orientation of the vehicle if needed and it is not thrusting during the approach. This way, the habitat could more easily point its radiators to coldest sink temperatures as well as be shadowed by the transportation system itself.

Table 5 Summary table of predicted surface temperatures, in Kelvin, results from thermal analysis for the case: .62 AU, Pos 0, PV = 90 deg and Rads = 0 deg, 45 deg.

	Rad = 0 deg			Rad = 45 deg		
	Min	Max	Avg	Min	Max	Avg
Habitat Rad 1 (+Y)	80	212	179	31	203	152
Habitat Rad 1 (-Y)	143	243	203	103	240	176
Radiator Avg	-	-	191	-	-	164
Solar Array	432	435	434	432	435	434
Habitat Inflatable	12	307	177	13	309	175
Vestibule	51	317	191	30	326	193

Table 6 Summary table of predicted surface temperatures, in Kelvin, results from thermal analysis for the case: .55 AU, Pos 0, PV = 90 deg and Rads = 0 deg, 45 deg.

	Rad = 0 deg			Rad = 45 deg		
	Min	Max	Avg	Min	Max	Avg
Habitat Rad 1 (+Y)	28	226	189	32	217	161
Habitat Rad 1 (-Y)	149	258	215	110	254	188
Radiator Avg	-	-	202	-	-	175
Solar Array	458	462	460	458	462	460
Habitat Inflatable	12	325	188	14	328	186
Vestibule	54	336	202	64	346	205

Table 7 summarizes the surface temperatures during the Venus flybys, at following three altitudes, 500 km, 832 km and 1500 km, all in eclipse. These three points were chosen to show the sensitivity of temperature to a range of altitudes. As expected, these temperatures are, in general, much lower than the ones shown previously, supporting the idea that the solar close approach will be the most thermally constraining point in the mission. Between the altitudes, the worst case temperature does drop, but not significantly. Interestingly, the difference between the two radiator assemblies are much smaller than that of the previous set of results, most likely due to the absence of direct sunlight.

Table 7 Summary table of predicted surface temperatures results from thermal analysis for the case: 500 km, 832 km, 1500 km flyby altitudes, Pos 0, PV = 90deg and Rads = 0 deg, 45 deg.

	500 km, Rad = 0 deg			832 km, Rad = 0 deg			1500 km, Rad = 45 deg		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Habitat Rad 1 (+Y)	165	179	169	156	171	160	142	157	146
Habitat Rad 1 (-Y)	147	161	157	137	152	148	123	139	134
Radiator Avg	-	-	163	-	-	154	-	-	140
Solar Array	164	171	166	155	162	157	143	148	144
Habitat Inflatable	72	213	161	28	214	144	26	204	136
Vestibule	60	220	157	56	214	150	49	205	138

C. Radiator Sizing Sensitivity Analysis

Trajectory designs are always evolving throughout the conceptual design process to ensure that the system is flying its optimal mission and minimize the ΔV as much as possible. Although a reference mission profile was chosen for this habitat design, it is important to assess its sensitivity to changes in key mission parameters to understand how much room there is to grow or shrink. Specifically, the radiator mass and area should be assessed to changes in the Venus flyby altitude and solar close approach distances, as they are the most thermally constraining points in the mission. However, running many thermal math model cases to identify the sink temperature is computationally expensive. Instead, since the radiator size is driven primarily by sink temperature and the heat rejection load, a multivariate sweep was conducted to show the sensitivity. Sink temperature was varied from 3K to 280K for 5 different heat rejection loads. These results are shown in Figures 10 and 11. All other design parameters are held constant for this sweep.

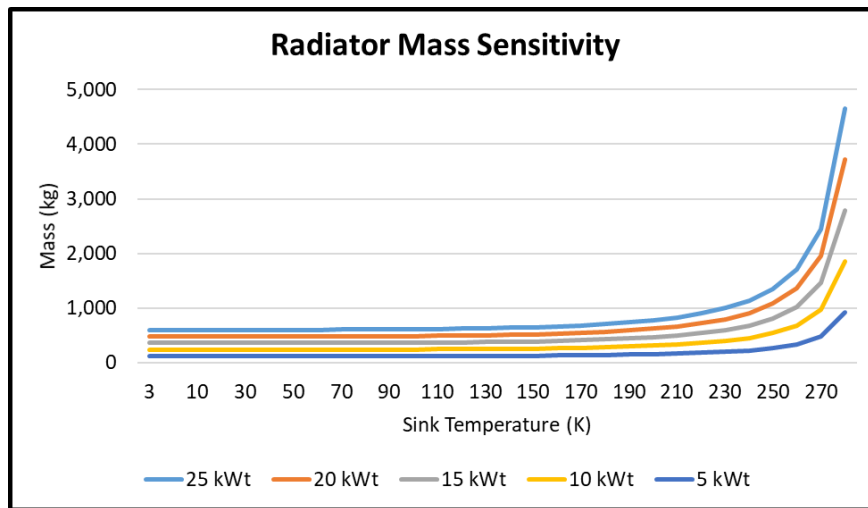


Fig. 10 Mass growth sensitivity of radiators to sink temperature and various heat rejection loads.

Although rejecting to a 3K sink temperature is ideal, these plots show that these radiators stay relatively constant in both mass and area up until about 220K, where they start to grow significantly. These trends are the same for all heat loads, though the absolute values are different. At the baseline 215K, the radiator mass is about 525 kg, but is approaching the growth area. From the previous detailed thermal analysis for the solar close approach at 0.55 AU, the worst case sink temperature seen was about 258K. This means, at that current distance, the radiator mass grows to nearly 1 t for a 15 kWt heat rejection load and up to 2 t for 25 kWt. Although a thermal math model is needed to identify the exact sink temperatures, if the habitat were to get any closer to the Sun, the radiator mass and area grow significantly and become showstoppers. However, if the rejected heat load can be lowered at the current sink temperature, then the mass of the radiator could be decreased by up to 50%. This could be achieved by entering a lower operating power

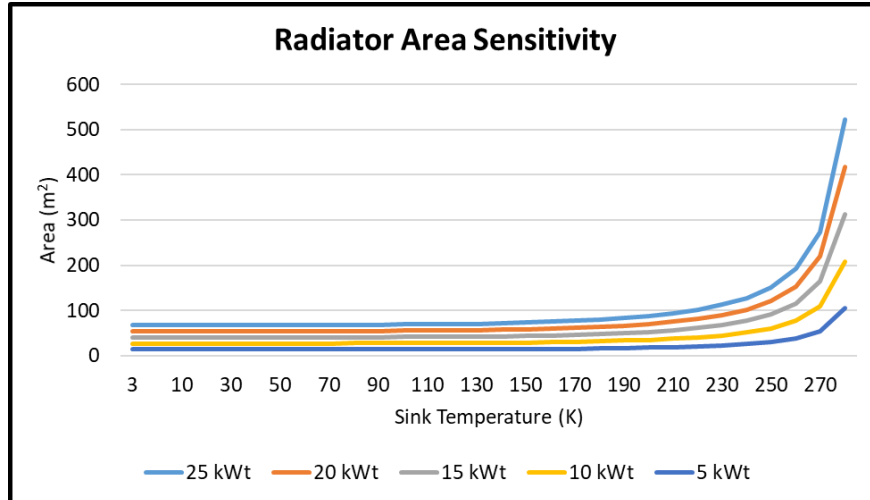


Fig. 11 Area growth sensitivity of radiators to sink temperature and various heat rejection loads.

mode during the solar close approach, turning off any non-mission critical hardware needed for crew survival. The opportunity also comes with the threat of a 40% increase in required area and mass if the heat load increased.

VII. Conclusion

Opposition class trajectories for crewed Mars missions are considered for their fast transits to reduce exposure to deep space effects on the crew. However, they come at the cost of high energy requirements and propellant loads for transportation systems, making Venus flybys a key enabler for these missions. Conceptual design of deep space habitats for Mars missions is a difficult problem and the inclusion of a Venus flyby adds further complexities, especially for thermal control systems. To ensure these concepts don't grow to become too heavy for transportation systems, a new habitat concept has been developed through trade space exploration and down-selection and detailed thermal analysis was conducted near Venus and during a solar close approach. Although it was initially predicted to be a multi-ton mass driver, thermal and sensitivity analysis show that a ISS-type radiator based thermal rejection system is capable of performing this mission. However, closer approaches to the Sun will increase the mass significantly. Future studies will not only refine mass estimates of the habitat, but will consider more points along the mission and other vehicle attitudes. For example, another potentially constraining case would be a Venus flyby on the inside of Venus, where vehicle will be in view of the Sun and be exposed to albedo.

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