The Single Habitat Module Concept for Exploration - Mission Planning and Mass Estimates

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The Single Habitat Module (SHM) concept approach to the infrastructure and conduct of exploration missions combines many of new promising technologies with a central concept of mission architectures that use a single habitat module for all phases of an exploration mission. Integrating mission elements near Earth and fully fueling them prior to departure of the vicinity of Earth provides the capability of using the single habitat both in transit to/from an exploration destination and while exploring the destination. The concept employs the capability to return the habitat and interplanetary propulsion system to Earth vicinity so that those elements can be reused on subsequent exploration missions. This paper provides an overview of the SHM concept and the advantages it provides. A summary of calculations of the mass of the habitat propulsion system (HPS) needed to get the habitat from Low Mars Orbit (LMO) to the surface and back to LMO and an overview of trajectory and mission mass assessments related to use of a high specific impulse space based propulsion system is provided.

Those calculations lead to the conclusion that the SHM concept can significantly reduce the mass required and streamline mission operations to explore Mars (and thus all exploration destinations).

Nomenclature

CCiCAP	=	Commercial Crew Integrated Capability
CLLS	=	Closed Loop Life Support
Cx	=	Constellation (Program)
DRM	=	Design Reference Mission
DSH	=	Deep Space Habitat
EVA	=	extravehicular activity
HAT	=	Human Architecture Team
HPS	=	Habitat Propulsion System
HLV	=	heavy-lift launch vehicle
ISP	=	Interplanetary Space Propulsion (system)
ISS	=	International Space Station
JSC	=	Johnson Space Center
K	=	Kelvin
LEO	=	low-Earth orbit
LLO	=	low-lunar orbit
LMO	=	low-Mars orbit
LSS	=	Lunar Surface Systems
MMSEV	=	Multi-Mission Space Exploration Vehicle (in this context, configured for in-space or surface mobility)

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MOX	=	liquid methane/liquid oxygen
NEA	=	near-Earth asteroid
NSO	=	Nuclear Safe Orbit
OAB	=	Orbiting Assembly Base
SEV	=	surface exploration vehicle
SHM	=	Single Habitat Module
SLS	=	Space Launch System

I. Introduction

When humanity goes to Mars and other exploration destinations, the approach employed will affect the success of the endeavor. Combining the best ideas for the technology with an efficient approach is most likely to result in mission success.

Deep space missions require that the crew be supported in transit and at exploration destinations for long durations. The Single Habitat Module (SHM) concept (Fig. 1) recognizes that crew support requirements for transit and while at a destination are roughly the same and thus could be addressed with a single module. Assuming the heritage of recent decades of human space operations in low-Earth orbit (LEO), the SHM concept starts with assembly of the exploration vehicle at a location near Earth using the capabilities humanity has developed and demonstrated in creating and operating the International Space Station (ISS). The SHM vehicle will include habitation to address crew support requirements and an efficient Interplanetary Space Propulsion (ISP) system to address propelling the vehicle to and from an exploration destination. Assembling and fueling the integrated vehicle near Earth provides the capability to start exploration missions fully fueled to meet the requirements of the mission. Being fully fueled at the start of each mission makes it possible to leave the vicinity of Earth with enough fuel to return a habitat from an exploration destination. Employing only one habitat can dramatically simplify mission conduct and make it possible to reuse mission assets.

The end of a SHM exploration mission results in the ISP system and habitat being returned to the near-Earth staging site. Those core elements are to be refurbished and refueled in space, then reused for subsequent exploration missions.

Such an approach to space exploration would focus development on the fewest possible number of exploration elements (the habitat and ISP) and enable reuse of those elements to provide a human exploration infrastructure that can address many exploration goals. A campaign of exploration missions using the SHM approach should be more quickly achievable and much more affordable (versus independent missions) since fewer elements are required.

This paper provides a description of the SHM concept, including ideas on how the concept could be implemented using a combination of new technologies and past exploration program concepts.

During late 2012 the Habitat Propulsion System (HPS) characteristics were established and the mass of the HPS was calculated. That provided the information needed to finish the first complete mission mass calculation for the SHM concept. The completion of the mass calculations enabled the first direct comparison of the SHM concept with the comparable Mars mission addressed in the 2009 Constellation Program (Cx) Mars Design Reference Architecture (DRA)[1]. While the mission duration of the SHM concept and the Mars DRA are calculated to be roughly the same, the mass for a Mars surface exploration mission using the SHM approach is calculated to require much less Initial Mass in LEO (IMLEO) (over 40% less (over 330 metric tons)) than using the Mars DRA.

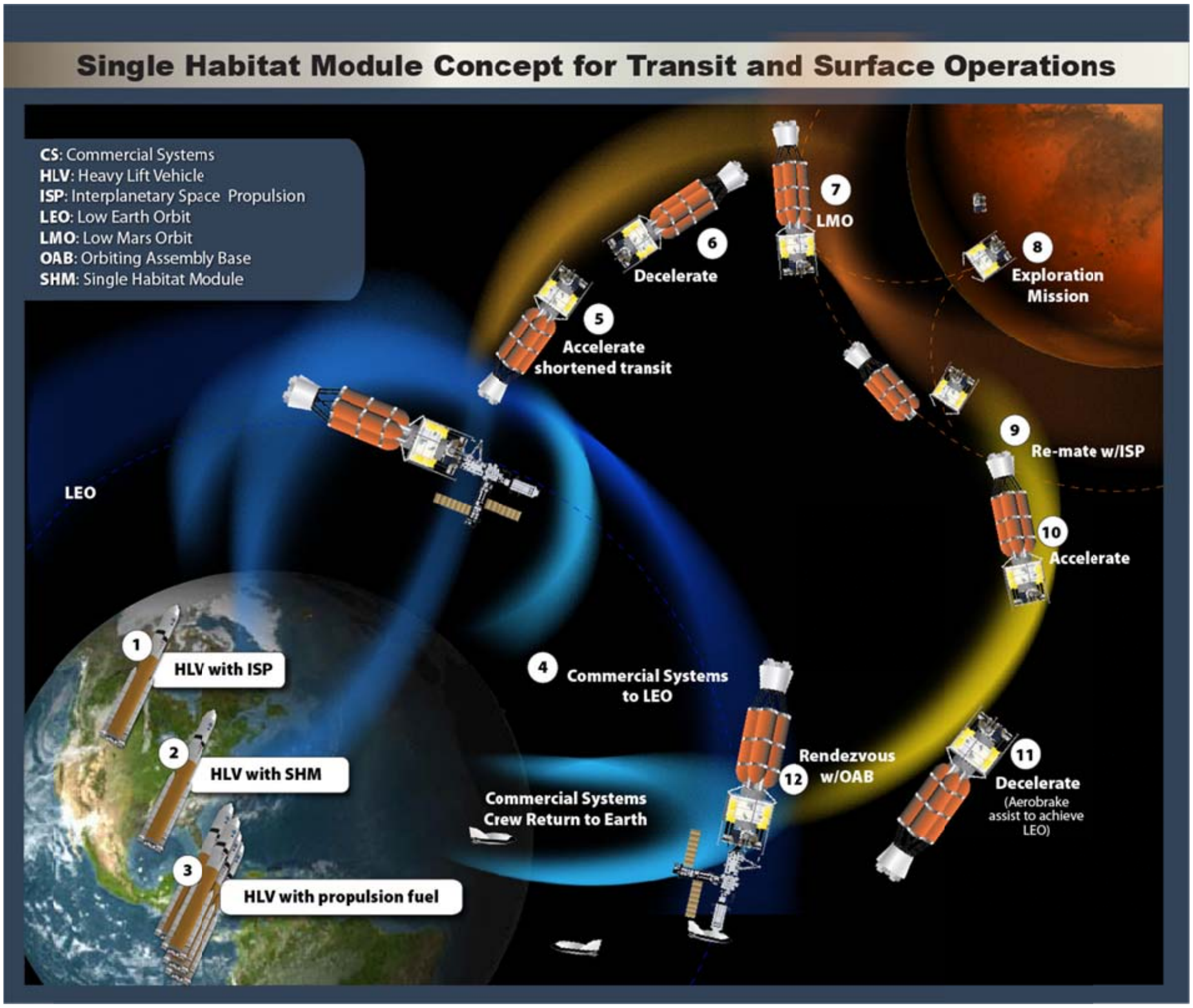


Figure 1. The SHM concept for a Mars surface mission (the design driving mission).

A. Single Habitat Module Concept Mission Operations

As illustrated in Fig. 1 for a Mars mission, each SHM mission would implement the following mission scenario:

1 thru 3 – Assemble and fuel the mission elements near Earth
  Check out each element at the in-space assembly station

4 – Exploration crew to man the via Orion or Commercial Crew Integrated Capability (CCiCAP)

5 and 6 – Transit to the deep space destination via the ISP system
  Accelerate roughly ½ the way to destination then decelerate the rest of the transit to achieve low orbit at destination (use aerocapture assist to decelerate at Mars to aid in achieving low orbit)

7 – Separate the habitat with its propulsion system from the ISP system

8 – Use the HPS to descend and land at the exploration site on the destination surface
  Conduct surface operations using the SHM as the base of operations (this is what it is all about)

9 – Ascend to low destination orbit via the HPS and rendezvous with the ISP system
  Discard the HPS after re-mating with the ISP system to reduce return mass
  (possibly discard only the prop tanks to retain the engines for reuse)

10 and 11 – Use the ISP system to return to Earth vicinity orbit
  Accelerate roughly ½ the way to Earth then decelerate the rest of the transit to Earth vicinity

12 – Rendezvous with the in-space assembly base

13 – Transfer crew to Orion (or CCiCAP) and use Orion (or CCiCAP) to return crew and samples to Earth

Those operations would result not only in the conduct of an exploration mission but also in the return of the most critical of mission assets (the interplanetary propulsion system and the habitat module) to near-Earth orbit. Returning those elements to near Earth provides the capability to reuse them for the next exploration mission.

A logical progression of missions using the SHM concept would be to develop the SHM habitat and ISP designed to conduct the most challenging Mars surface mission. Those elements would be used for a sequence of progressively more challenging exploration missions. The first would be to conduct a Near-Earth Asteroid (NEA) rendezvous mission. After returning the SHM to the Earth vicinity, refurbish and resupply the ISP and SHM then conduct a lunar surface mission to test and demonstrate SHM capabilities to conduct a surface mission. Then refurbish and resupply the ISP and SHM again at the near-Earth site, then conduct a Mars mission. The exploration sequence could be repeated to other destinations until the life limits of the SHM are reached.

B. Background

The Presidential Budget proposal for fiscal year 2011[2] contained several concepts that (if realized) can be used to improve the way deep space missions are conducted. It also directed NASA to focus on deep space missions including a mission to a NEA and ultimately to conduct a human mission to Mars.

The SHM concept of a different approach to crew accommodations and mission conduct puts the new concepts together in a way that can make exploration more efficient and less costly, and would nearly eliminate the waste of mission resources. SHM combines the following concepts: CCiCAP (or Orion) access of crew to LEO; heavy-lift launch vehicle (HLV) launch of large payloads (now funded as the Space Launch System (SLS) Program); fueling (later refueling) (and assembly) in space; Closed Loop Life Support (CLLS); interplanetary space propulsion (probably nuclear powered); green technology (reuse mission assets and likely use of liquid methane as the SHM propellant); possible aerocapture; and ISS utilization. As of 2012, NASA is pursuing all of those new technology and vehicle efforts as currently funded projects or in future plans. The CCiCAP, Orion, and SLS projects are well under way.

The SHM concept was first communicated to the NASA Human Exploration Framework Team via an email in June 2010. It was proposed as a game-changing concept to the NASA Office of the Chief Technologist in September 2010. It was presented at the NASA JSC Innovation Day in May 2011 and at a Knowledge Capture forum in June 2011 at JSC. During those presentations, the concept was referred to as the Single Crew Module concept. (The change to SHM was made to eliminate confusion with mission concepts others have proposed involving a single crewmember).

The SHM concept was described at the 2012 ICES conference[3]. At the AIAA Space 2012 conference progress in understanding the mission that would employ advanced technologies to implement the SHM concept was described[4]. Progress on the SHM concept was presented to the JSC knowledge capture forum on October 17, 2012.

In November and December 2012 calculations for the mass of the HPS system needed to deliver the single habitat and Multi-Mission Space Exploration Vehicle (MMSEV) to the surface of Mars and return them to LMO to rendezvous with the IPS were completed. Knowing the HPS mass and the mass of the habitat/MMSEV lead to the second iteration of the trajectory and mission mass assuming nuclear powered electric propulsion. Thus the first complete mass estimate of the SHM concept was completed. That allowed comparison to the Mars DRA mission mass and initial assessment of the quantified mission characteristics.

This paper will summarize the earlier paper results then focus on the way calculation of the HPS them complete SHM mission mass was addressed.

II. Single Habitat Module Essentials

To achieve the goal of the SHM concept to efficiently conduct an exploration mission and enable reuse of the critical elements of an exploration mission, the elements to be reused must be designed to meet the needs of the most difficult exploration mission envisioned. The most difficult mission currently envisioned is the surface exploration of Mars. The vehicle that addresses the Mars surface exploration mission would be capable of missions to NEAs or the moon and would thus be reusable for those types of exploration missions.

The design driving case includes a Mars landing and surface exploration followed by return to Earth. Mars surface exploration requires that the habitat be equipped with propulsion capability to descend from LMO to land at a designated exploration site, support crew operations while on Mars, then ascend back to LMO to rendezvous with the ISP.

For the SHM approach, it is critical to return the habitat module and the MMSEV (for either in-space and/or surface mobility) to destination orbit then back to Earth since both the module and the MMSEV are essential for crew support and/or to address potential contingencies.

The habitat module of the SHM concept will need to address all life support and crew habitability and command functions for each entire exploration mission. It must provide enough resources for the crew to function during the long zero gravity (or very low acceleration of the ISP) of the to-and-from transit phases and also be compatible with the long-duration surface exploration phase in the partial gravity of Mars or the moon.

Cabin atmosphere leak or contamination and other contingencies must be addressed.

Extravehicular activity (EVA) and mobility capabilities are required to enable exploration at the destination.

III. Single Habitat Module Concept Implementation

If implemented, the SHM concept will have a program to develop the best design for the variety of elements. Design development of the SHM would consider many aspects of the mission to use the technology available during the design period to accomplish the SHM goals. The Constellation (Cx) Program and technology development efforts have provided many options for how to implement such a concept. Many options are possible for the technologies involved in specific parts of each deep space mission. The new Advanced Exploration Systems (AES) Program and Office of Chief Technologist (OCT) efforts will verify that new technology candidates are ready to make the new vehicles robust and efficient in accomplishing mission goals. Mass minimization and safety will be key design considerations.

The features described in the following section and in Fig. 2 make sense for potential design solutions for the SHM concept, and take into consideration technology options that are or are expected to be available and vehicle element concepts. This basic concept for SHM implementation was used in mission IMLEO mass calculations that will be presented. A later section will address options that will probably lead to less mass to Mars surface and thus much less mission mass.

The CLLS, thermal control, EVA, and command and habitation capabilities (needed to support the crew during the entire mission) need to be as efficient as possible to minimize mass of both equipment and consumables. Long-duration missions have been shown (in exploration trade studies) to greatly benefit from regenerating resources. The longer the mission, the more beneficial regeneration of resources becomes. A single habitat and command module will take advantage of the benefits of regeneration for the entire duration of the mission. The most reliable solution will be employed, combined with appropriate redundancy and sparing.

The CLLS will minimize waste products, which will partially address planetary protection issues. The CLLS implemented will have to address the most demanding of the environments, whether that occurs in transit or during surface operations.

Thermal control radiators must address the peak heat loads in transit and at Mars. Radiators that work efficiently in deep space may also work well in a convective Martian atmosphere.

EVA capabilities will be required at the exploration destination. EVA interfaces would need to be robust to address the dust environment and provide the isolation needed for the crew from potential Martian contamination. The suit port concept[5] would provide very efficient EVA capability and would address the dusty environment. The same EVA system can address potential contingencies during transits and at the destination.

The inclusion of an MMSEV would address the exploration mobility and EVA capability needed at the destination. The MMSEV would also be very capable of addressing many potential cabin contingencies since it can function for an extended period of time as an independent spacecraft. It also offers efficient, independent EVA capabilities.

Landing gear is required for the lunar and Mars missions. The landing gear could be detached and left on the surface to reduce return mass.

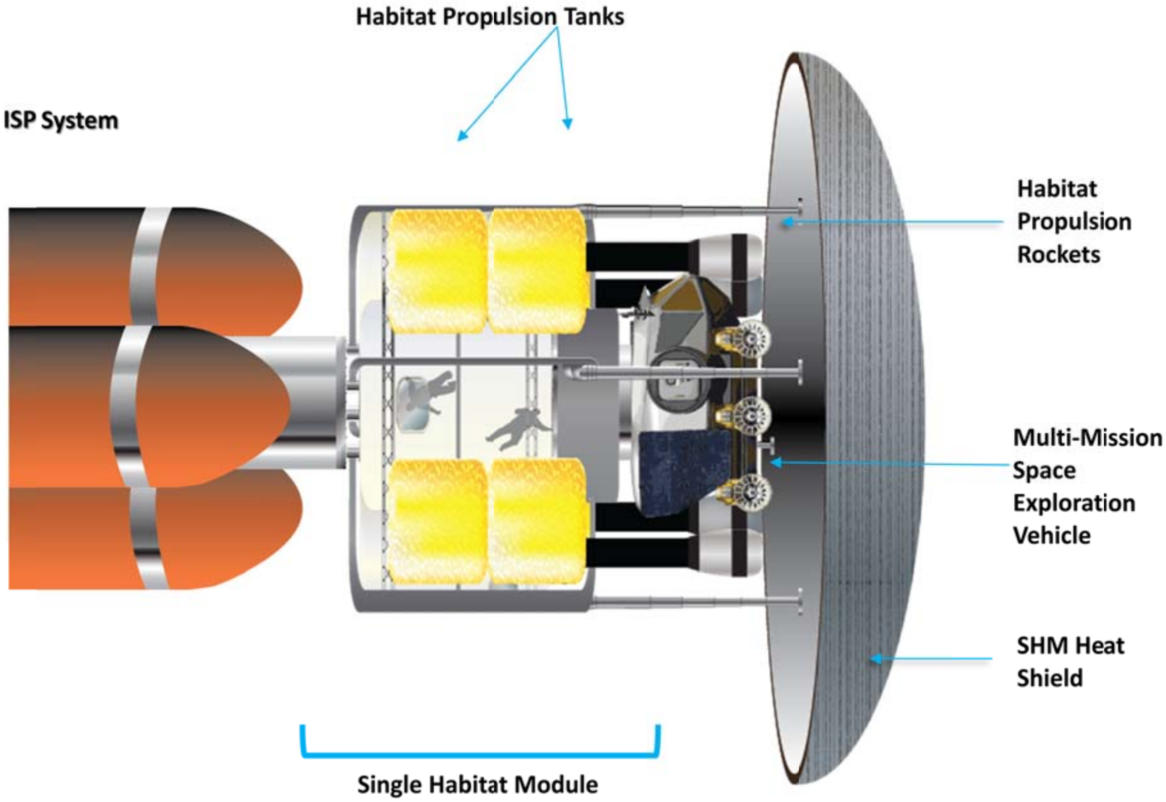


Figure 2. SHM propulsion, MMSEV, and ISP provide radiation protection for the habitat.

It must be emphasized that the SHM portrayed in Figure 2 is only one way that the SHM concept could be implemented. The architecture of Figure 2 does address several areas that have been identified to be concerns for long duration exploration missions. Surrounding the habitat with propulsion propellant provides a substantial amount of radiation protection during the transit from Earth to Mars. Having the propulsion system around the habitat rather than under it takes advantage of the capability to assemble elements in space and results in the MMSEV being positioned such that access for surface exploration does not require removing large modules from the top of a vehicle. The use of Aerocapture at Mars reduces the time required to enter LMO and the propellant needed to land the habitat on the surface. Inclusion of the MMSEV for all mission phases provides a contingency habitat capability. The MMSEV also provides efficient EVA capability that can be used not only for exploring at a destination but during transit (if needed). The MMSEV provided EVA capabilities could also be used during assembly of the SHM and during refurbishment and resupply between exploration missions.

Assembly of the SHM, reuse of mission assets, trajectory and IMLEO initial iteration calculations were presented in the AIAA Space 2013 paper[4]. The SHM concept assumes that the capabilities developed during the assembly and operation of the ISS can be used to address assembly of exploration vehicles. Assembly at ISS for the habitat parts of the vehicle is possible but final assembly and departure need to be from a Nuclear Safe Orbit (NSO) orbit of at least 5,000 km altitude. NASA, commercial and international assets can be employed in the assembly of the SHM and in providing parts of the SHM itself. Reuse of the IPS and habitat elements is to be done after return of those elements to the orbiting assembly station.

IV. Calculation of the Mass of the SHM Concept as Implemented for a Mars Mission

The approach to calculating the mass of the SHM concept was addressed in the 2012 ICES paper[3]. That process has been implemented and has resulted in the calculation of the HPS and IPS masses which combined with the habitat, MMSEV, landing gear and aerocapture heat shield complete the calculation of the IMLEO for the SHM as implemented in Figure 2. To summarize that sequence of calculations for a design driving mars surface mission:

1) The mass of a habitat, MMSEV and landing gear was established for a long duration surface mission based on deep space habitat AES and earlier Cx studies with consumables mass calculated based on an assumed set of CLLS equipment and calculation of the length of a NEP propelled mission duration
2) The mass of the aerocapture heat shield was estimated based on 20% of the total SHM vehicle mass (based on preliminary heat shield design concepts)
3) The mass of the HPS system required to land and then relaunch the habitat/MMSEV was calculated assuming a MOX propellant system
4) The trajectory and IMLEO mass was recalculated using the combined habitat, MMSEV, landing gear, heat shield, HPS mass to be delivered to LMO then returning the habitat/MMSEV from LMO to LEO
    a. It was assumed that Orion delivers the crew to the SHM at the end of its spiral leading to departure from Earth; then Orion rendezvous' with the SHM at the start of its spiral toward return to LEO

A. Habitat Propulsion System Implementation

Prior Cx exploration scenarios to the moon[6] or Mars[1] required a propulsion system that was to deliver a long-duration habitat for crew occupation to the surface. The SHM concept requires that the habitat not only be delivered to the surface but also be returned to orbit to rendezvous with the ISP. The propulsion system of planned Cx missions (which has been assessed to be feasible) had significant capability. The primary difference between the Cx and SHM concepts is in the amount of fuel the HPS requires to perform the ascent. Considering that the landing gear is probably left on the surface, and given enough propellant, a system capable of launching the habitat from the .377 g Mars gravity well should be feasible.

The earlier SHM paper[4] described the way a HPS could be implemented such that propellant tanks provide radiation protection for the habitat during the transit to Mars. That system would employ a liquid methane/liquid oxygen (MOX) propulsion system that would provide redundancy during descent and ascent. The use of MOX propulsion addresses the need for long term storage of propellants while in transit to Mars. Cryo-coolers may be required to address propellant storage thermal conditioning while at either the moon or Mars.

Summer 2012 trajectory assessments have confirmed that aerocapture makes sense to enter Mars orbit, then to provide braking prior to landing. An aerocapture/heat shield will be used below the MMSEV to aid in the deceleration of the entire SHM to enter Mars orbit. The same aerocapture/heat shield is then used (after habitat separation) to decelerate the habitat during Mars descent. The aerocapture/heat shield is to be detached prior to landing to enable habitat landing. The HPS is required to complete the maneuvers to land on Mars then to launch the habitat to rendezvous with the ISP in Mars orbit.

<u>Propulsion system and fuel mass calculations</u>

The trajectory assessments provided calculations[4] of the velocity changes (DV) needed to land on Mars (800 feet per second (fps) and the DV needed to ascend and rendezvous with the IPS (3900 fps). Those DVs were combined with the habitat/MMSEV mass estimates at descent (39,400 kg) and ascent (37,400 kg) to calculate the mass of the propulsion system (HPS).

Calculations were done in reverse to focus on parts that could be quantified. Thus the ascent habitat/MMSEV mass was used to calculate the fuel and propulsion system (HPS) mass to lift and accelerate that mass by the 3900 fps required. Using that ascent HPS mass and the descent mass of the habitat, MMSEV and landing gear; the mass of the fuel required for the descent DV of 800 fps was calculated.

Using a MOX engine performance (a little less specific impulse than a LOX/Liquid hydrogen engine but much more tolerant of the long duration deep space and Mars surface environments) and using propulsion system mass experience (to estimate the size of the propulsion system for the habitat and propellant mass) the mass of the propulsion system (the rockets, infrastructure and tankage) was calculated to be 13,100 kg. That propulsion system would be used for both descent and ascent.

The mass of propellant needed to provide the 3900 fps DV needed to ascent from Mars and rendezvous with the ISP was calculated to be 93,400 kg resulting in a total ascent mass of 143,800 kg.

All the ascent/rendezvous mass plus the landing gear was included in calculation of the descent mass. To provide the 800 fps DV on descent was calculated to require 38,100 kg of MOX propellant.

Combining the masses; the SHM concept requires that the ISP provide transit from Earth to Mars for a combined 197,000 kg. That mass includes the habitat, MMSEV, HPS and landing gear. On return from Mars to Earth, the IPS needs to provide transit of only the habitat/MMSEV or 37,400 kg. The landing gear is left on Mars (or the Moon) and the HPS is assumed to be left in Mars orbit since it is not required for the return transit. The HPS and landing gear elements would be replaced during the refurbishment and refueling operations near Earth before the next exploration mission.

The habitat/ MMSEV, landing gear, and HPS masses summarized in Table 1 include the first HPS mass calculations for the SHM concept.

Mass of elements of the SHM concept

		Mass (kg)
Ascent from Mars to rendezvous with the ISP		
Habitat		30,900
MMSEV		6,500
HPS		
	System	13,100
	Propellant at launch	93,400
Descent from LMO to landing on Mars		
Habitat		30,900
Landing Gear		2,000
MMSEV		6,500
Aerocapture/Heat Shield		67,000
HPS		
	System	13,100
	Propellant at start of Descent	131,500
Total ISP payload Mass at start of mars Mission (IMLEO)		309,000
Total ISP payload mass at start of return from Mars to Earth		37,400
Total SHM Mass in LEO at start of Mars Mission		512,000
Total mass of SHM at Return to LEO		117,000

Table 1 (TBS) Masses calculated for a Mars surface mission implemented using MOX propulsion

C. Interplanetary Space Propulsion System Implementation

ISP system efficiency is critical to the feasibility of deep space exploration. Chemical propulsion can work, but the mass required would be very high. Due to the dramatic specific impulse achievable via electric propulsion, a factor of 10 less propellant might be required (versus Space Shuttle vintage chemical propulsion).

High power is required to achieve both the high specific impulse and moderately high thrust desired for deep space human sized mission transit. To provide the high power levels needed probably requires that nuclear (versus solar electric) power be employed. Studies by NASA on nuclear powered propulsion systems have developed concepts for up to 5 megawatt Nuclear powered Electric Propulsion (NEP)[7] systems illustrated in Figure 3. The feasibility of the NEP concept leads to the mission mass of a SHM that employs a 5 MW system to power the ISP as the basis for trajectory and mass calculations for a mission to the surface of Mars.

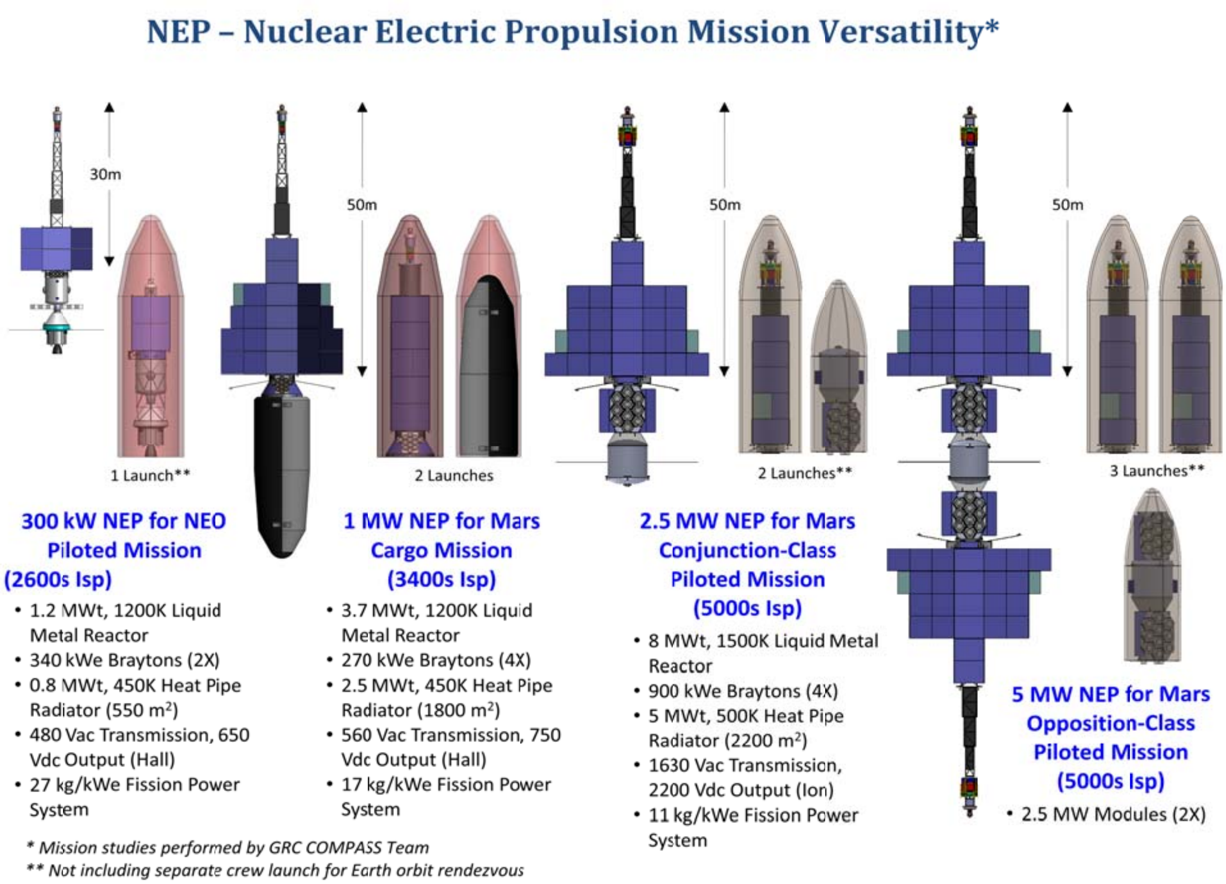


Figure 3 – Nuclear Propulsion Study Architectures Leading to a 5 MW NEP Powerplant

Calculation of Initial SHM Mass in LEO (IMLEO)

The first iteration of SHM IMLEO calculation[4] established the mission parameters needed to calculate the length of mission, the related habitat size, consumables required and velocity changes required for a NEP powered mission. That information allowed calculation of the HPS mass which was estimated to be 144,600 kg. The HPS mass combined with the rest of the SHM elements (197,000 kg) was then used to perform the second iteration of the total mission trajectory, mission duration and IMLEO. **The second iteration is viewed as the initial estimation of the mass of the SHM concept in IMLEO since it uses the combined mass of all the elements of the mission.**

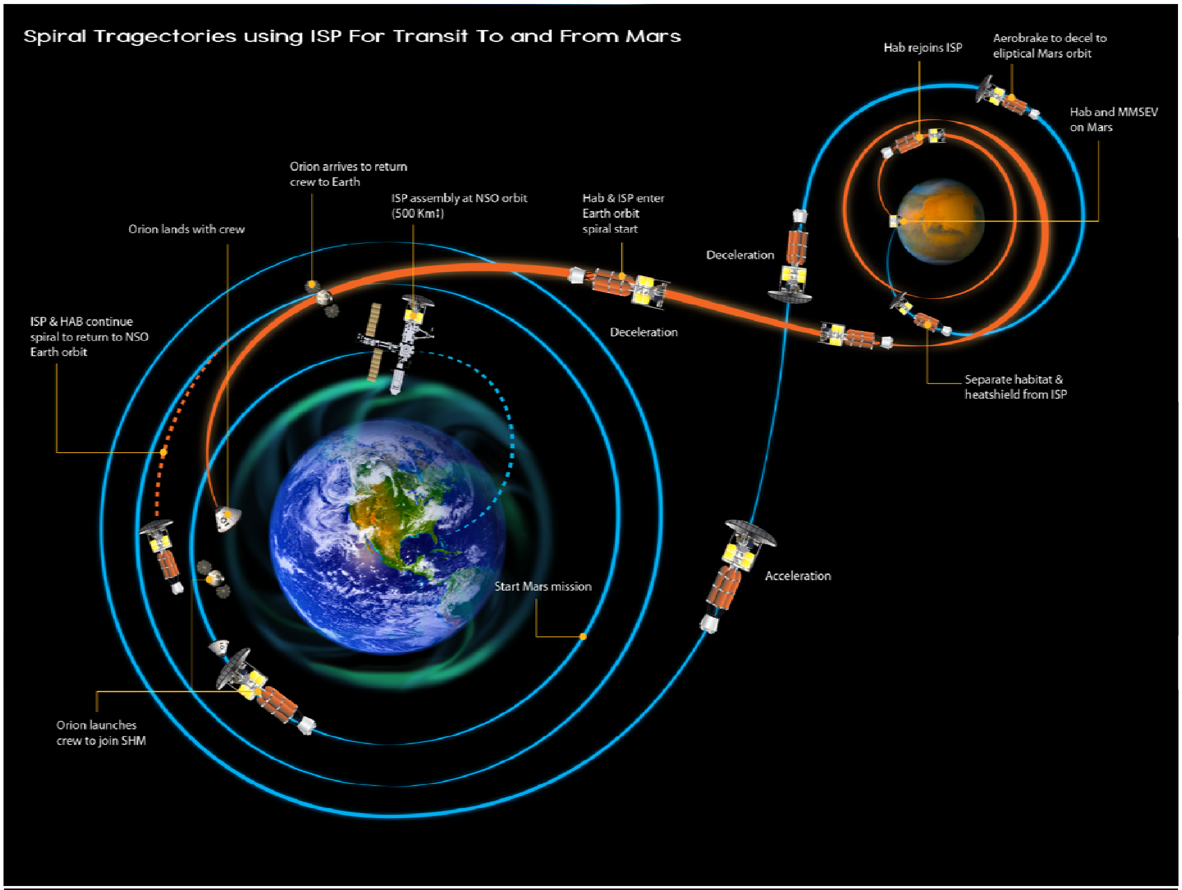


Figure 3 - The spiral trajectory resulting from the implementation of a high specific impulse ISP system

Two cases were assessed to evaluate the effect of added nuclear power on mission mass and mission time. The first used a 5 MW NEP powerplant, whereas the second assumed a 10 MW powerplant. Both cases assumed a starting point at a NSO of 500 km circular LEO, a power delivery efficiency of 0.8, powerplant specific mass of 6 kg/kw and structures and heliocentric tank mass of 15% of the vehicle mass.

Mission Parameters Used in Case Studies

Both cases assume that the SHM starts uncrewed from the NSO and spirals from Earth increasing velocity until escape from Earth gravity and the transit to Mars. To minimize exploration crew time; it is assumed that the crew is launched to the SHM on an Orion vehicle that rendezvous' with the SHM just prior to escape from the vicinity of Earth. The details of the Orion delivery of the crew and the use of the Orion after crew delivery are details that are future work. It is possible that a crew flies the SHM to that point then hands over SHM control to the exploration crew and then uses the Orion vehicle to return to Earth. Each case also assumes the use of an aerocapture/heat shield to aid in deceleration of the SHM entire vehicle using the Martian atmosphere as a brake. The same heat shield is used after the habitat elements are separated from the ISP for the Martian descent and landing. The aerocapture/heat shield is use to provide most of the deceleration of the habitat, then it is discarded and the habitat HPS is used to propulsively land on Mars.

Starting the missions was determined to be best at a time when Earth and Mars alignments provided minimal DV requirements for the transit. For missions using NEP the transit times are different than for those using more historic propulsion systems thus the Hohman transfer timing is a little different. Considering those parameters each of the case studies is started on 1/2/2028. Since the transfer of the vehicle to mars requires more propellant than the return transit this approach minimized mass required for the Mars bound transit.

To target a realistic mission on Mars an estimate of the amount of time needed to conduct exploration near the landing site was made. It was assumed that MMSEV aided exploration of the selected site could be done in 2 months. That would allow time for 3 or 4 MMSEV exploration excursions each followed by MMSEV resupply and refurbishment at the landing site. It should be noted that the MMSEV is returned to Earth with the habitat because it serves as not only a surface mobility aid but also as a contingency vehicle to address potential cabin contingencies.

A crew of 4 was selected for the SHM mission analysis. That crew size is viewed as near minimum for an exploration mission. The Cx Mars DRA assumed a crew of 6.

The spiral away from Mars takes around 22 days (in Case 1, 18 days for Case 2) and it is assumed to start when the crew launches and rendezvous' with the ISP. For the return transit, the landing gear is assumed to be left on Mars and the HPS system is assumed to be left in Mars orbit since it has completed its function of returning the habitat and MMSEV to the IPS.

The return from Mars to Earth is thus timed by the near optimum transit to Mars and the duration of the stay on Mars that was selected based on the amount of time needed to conduct exploration at a single site. Return starting at that time is not necessarily optimum but the return mass is much less that the transit to Mars thus compromising mission efficiency a little to reduce exploration crew time. In Case 1, the return transit was nearly optimal as shown in Figure 5 below. In Case 2, the timing was not optimal leading to a much longer return and much greater propellant use. More optimum mission timing would improve Case 2 results significantly.

At the end of the mission both cases assume that the deceleration of the SHM will be done propulsively using the ISP. However, the crew will egress the SHM to board an Orion at the start of the inbound Earth spiral to return to Earth while the SHM elements continue to spiral toward the assembly station at the NSO. Since nuclear power is employed the use of an aerocapture/heat shield to decelerate at Earth is not acceptable (otherwise it would be very beneficial).

Case 1 and 2 results are summarized the following data.

Case 1 Results Summary

- IMLEO = 512 mt
  - Does not include descent, ascent, or rendezvous propellant (for Orion)
- Earth escape spiral
  - Assumed Isp = 7000 sec
  - Propellant mass = 51 mt
  - Time = 345 days
- Earth-Mars heliocentric transfer
  - Departs 12/12/2028
  - Variable Isp
  - Propellant mass = 32 mt
  - Time = 640 days
- 60 Mars surface stay
- Mars escape spiral
  - Assumed Isp = 3000 sec
  - Propellant mass = 18 mt
  - Time = 22 days
- Mars-Earth heliocentric transfer
  - Departs 12/7/2030
  - Variable Isp
  - Propellant mass = 39 mt
  - Time = 216 days
- Earth capture spiral
  - Assumed Isp = 7000 sec
  - Propellant mass = 13 mt
  - Time = 86 days

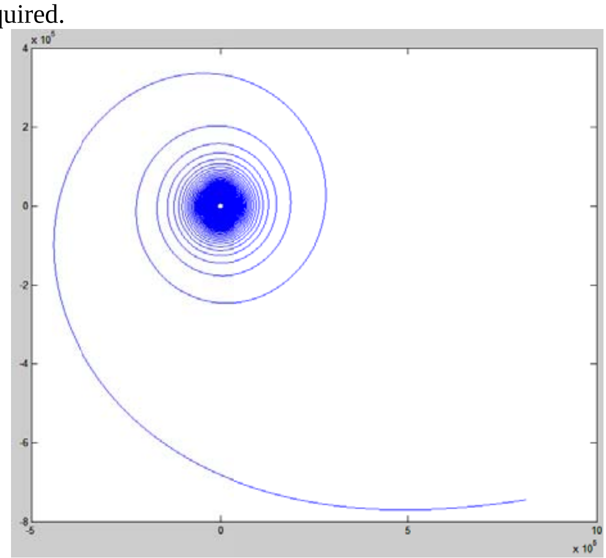
Total Crew Time = 944 days
Total Vehicle Time = 1375 days

Case 2 Results Summary

- IMLEO = 731 mt
  - Does not include descent, ascent, or rendezvous propellant (for Orion)
- Earth escape spiral
  - Assumed Isp = 8000 sec
  - Propellant mass = 64 mt
  - Time = 283 days
- Earth-Mars heliocentric transfer
  - Departs 12/12/2028
  - Variable Isp
  - Propellant mass = 67 mt
  - Time = 430 days
- 60 Mars surface stay
- Mars escape spiral
  - Assumed Isp = 3000 sec
  - Propellant mass = 29 mt
  - Time = 18 days
- Mars-Earth heliocentric transfer
  - Departs 5/7/2030
  - Variable Isp
  - Propellant mass = 87 mt
  - Time = 372 days
- Earth capture spiral
  - Assumed Isp = 8000 sec
  - Propellant mass = 16 mt
  - Time = 72 days

Total Crew Time = 886 days
Total Vehicle Time = 1241 days

Results show that the time required to conduct a Mars surface mission can be reduced by increasing the power of the nuclear powerplant by 58 crew days (134 for the total mission). However, the IMLEO increases from 512 to 731 mt with the increase in powerplant power. Thus a trade of higher mission mass versus shorter mission length is required.



- Earth escape spiral (crew not on-board)
  - Initial mass = 512 mt
    - Powerplant = 30 mt
    - Structure = 55 mt
    - Aero shield = 67 mt
    - Propellant used = 51 mt
    - Payload = 309 mt
  - Begins spiral 1/2/2028
  - Assumed constant Isp, 7000 sec
  - Time = 345 days

Figure 4 – The Earth Escape Spiral to depart from a 500 km Altitude NSO

The Spiral away from Earth is shown in Figure 4 below to illustrate the mission concept and show added detail for that part of the mission.

The Orbital mechanics for using a high ISP approach for a Mars surface mission are shown in Figure 5.

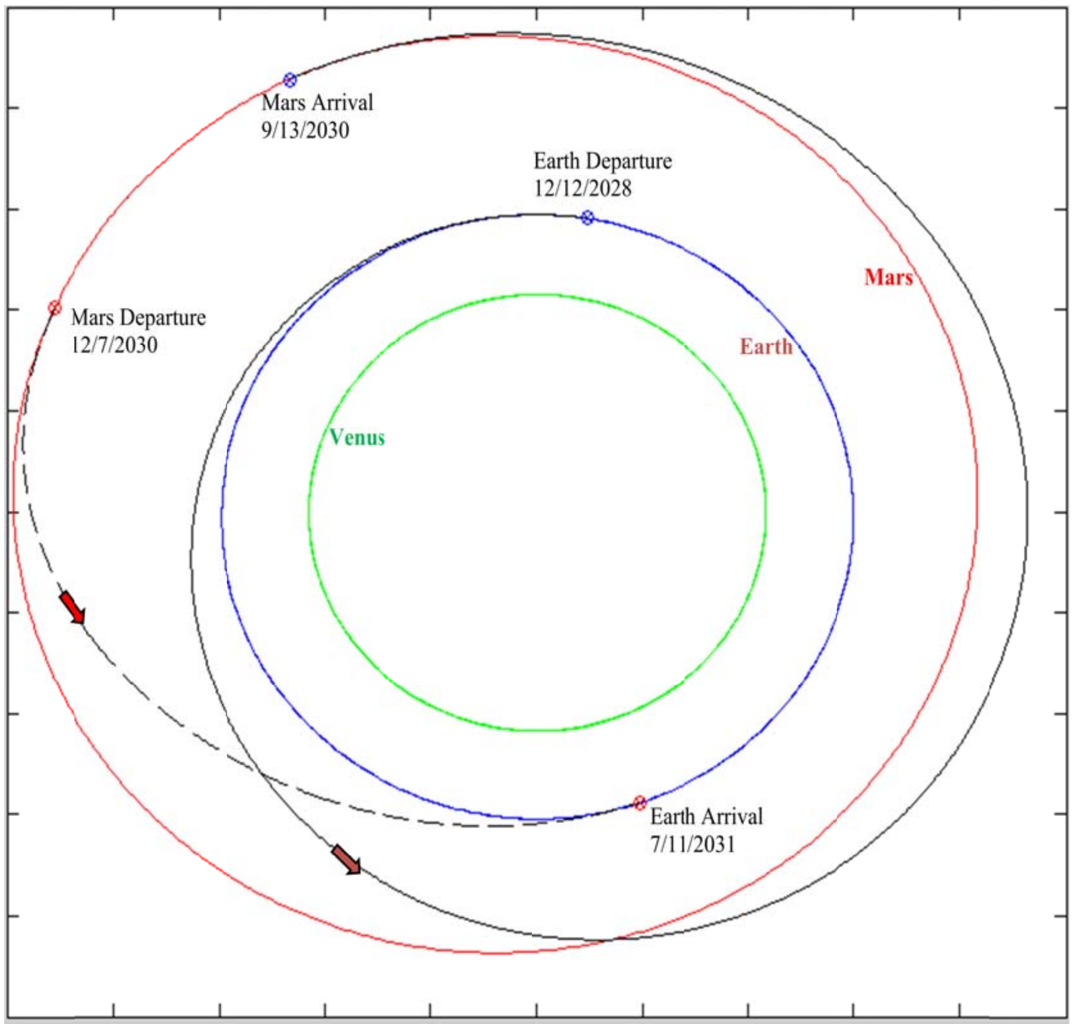


Figure 5 - Case 1 - Heliocentric View for a 5 MW Powerplant Powering the ISP for a SHM Mission

B. Comparison of Single Habitat Module Elements to Those of Apollo and Constellation Exploration Plans

The SHM concept is not directly comparable to past exploration approaches since it employs technology advances that were not considered in the past, and since it reuses mission assets. The SHM approach of developing an exploration capability that can be employed for any exploration destination results in a significantly different compliment of mission assets than other approaches.

The Mars DRA[1] requires 942 crew days to complete. Thus the 5 MW SHM concept crewed mission duration is almost equal to that of the Mars DRA; however the IMLEO for the SHM concept is 512 mt compared to 848 mt for the Mars DRA. Based on these preliminary calculations implementing the SHM concept versus the Mars DRA concept could save 336 mt (over 40%).

However, as noted at the start of each of the Case summaries, the mass associated with the Orion vehicle (approximately 11 mt) and the propellant mass associated with Orion transit from LEO to rendezvous with the SHM is not included in the SHM mass estimate. Also the mass of the Orion and its propellant that rendezvous' with the SHM at the end of the return transit is not included in the SHM mass. The mass of the Orion vehicle is included in the Mars DRA mass estimates. Thus the difference between the concepts will be less than 336 mt. Calculation of those added masses associated with the SHM concept is viewed as future work; however, it is expected that most of the 336 mt difference will be saved if the SHM concept is employed.

Comparing Case 2 versus the Mars DRA shows that 56 days of crew time and 117 mt could be saved if a 10 MW powerplant is employed. However, the 10 MW powerplant is beyond the current nuclear power feasibility studies thus higher risk would be incurred if that level of power is planned.

Qualitative Comparison of the SHM approach versus Cx and HAT approaches

SHM could be compared directly to the Cx Mars Design Reference Architecture (DRA) to compare assets and thus understand the benefits. Alternatively, SHM could be compared to the elements required to conduct a lunar sortie mission. Those comparisons would address the benefits of the mission simplification associated with the SHM single habitat. However, such comparisons would be somewhat misleading since one of the benefits of the SHM concept is the reuse of mission assets and, when compared to a single mission, those benefits are not considered.

The most appropriate comparison of past approaches and SHM is to compare the combination of NEA, lunar landing, and Mars surface missions. The Cx DRMs require the following: separate crew accommodations for transit, descent, ascent, and surface operations; new vehicles for every mission; prepositioning mission assets at exploration locations; (for the Mars DRA) in-situ resource utilization to provide propellant for the return mission. The SHM simplifies the mission compliment of elements.

Top-level comparison of elements required to depart from Earth for exploration missions comparing the SHM compliment to Human Architecture Team (HAT) NEA mission, Cx Lunar Sortie and the Cx Mars DRA:

SHM for the three missions	Habitat, MMSEV, ISP plus two refurbishment and refuel operations, plus probably several Orion Multi-Purpose Crew Vehicle (MPCVs).
HAT NEA	Orion, DSH, MMSEV, Solar Electric Propulsion. MPCVs
Cx Lunar Sortie mission	Orion, Altair (Lander, Ascent).
Cx Mars Surface mission	Orion, DSH, Surface Habitat, two Nuclear Thermal Rockets, SEV, Combined Descent and Ascent Vehicle, Mars Ascent Vehicle.

Comparing elements required for the approaches leads to an appreciation of the ways that the approaches are different. Qualifications to such comparisons are that the masses of the SHM habitat and ISP propulsion systems still need to be refined, and the SHM refurbishment and refuel process will require launch of materials from Earth. The author speculates that NEA and Cx Mars DRA missions would also require some level of assembly near Earth prior to departure. The SHM approach of decelerating the ISP and SHM to return to Earth vicinity will require more propulsion capability than the direct atmospheric reentry planned for the HAT NEA and Cx lunar sortie and Mars DRA but enables reuse of those critical elements.

F. Why Single Habitat Module is Expected to Reduce Cost and Time Required to Explore

The SHM concept was calculated save a significant amount of mass-to-destination when the entire mission is considered. Part of that savings is because prepositioning a habitat and separate descent and ascent vehicles is not required for the SHM concept. In addition to the mission mass savings, fewer exploration elements are required using the SHM concept (versus the Mars DRA) thus a program using the SHM approach should be more streamlined and focused. Development of fewer vehicles should reduce the schedule to start exploration. Efficiencies in development organizations needed and the cost to conduct missions will be realized because fewer project organizations are needed.

Reusing mission assets for subsequent missions will dramatically reduce the cost and schedule for other exploration missions.

The in-space assembly base (perhaps ISS, but more likely ISS-derived) could be used to support Earth orbit and other Earth vicinity (Lagrangian or lunar) NASA or commercial activities between exploration missions.

V. Summary of Single Habitat Module Approach Benefits

The benefits of the SHM approach center around the single vehicle needed to conduct exploration. Supporting the crew through the entire mission in one habitat simplifies the total mission and enables reuse of mission assets. The SHM approach can make exploration more affordable and can focus missions on exploration instead of vehicle development. SHM approach benefits include:

1) A single module that addresses crew functions for all mission phases.

   a. This eliminates modules that in Cx approaches are required for transit to a destination (Multi-Purpose Crew Vehicle), transit from orbit to destination surface (Altair descent vehicle), a surface habitat, and an ascent vehicle to return to orbit
   b. Reducing the number of exploration elements reduces the number of projects required for exploration thus reducing the size of the organization needed to implement exploration
2) Elimination of the need to develop new vehicles for subsequent missions
3) Transportation of significantly less mass to destination since fewer elements are required
4) Use of regenerative technologies that minimize mass via use for the entire mission
5) Elimination of the need for short-duration non-regenerative technologies
6) No requirement for the prepositioning of assets
   a. Reduces landing accuracy requirements
   b. Crew arrives at an exploration site that has not been explored robotically via prepositioned assets (thus crew exploration is all new and not partially redundant)
7) Use of a high-power ISP that can shorten mission duration to 944 days versus the Mars DRA mission duration of more than 942 crewed days
   a. Would reduce the amount of consumables required
   b. Would partially address radiation protection by shortening crew exposure time
8) Vehicle dimensions that are not constrained by launch vehicles
   a. Allows architectural freedom to arrange mission elements
9) The positioning of propellant around the habitat protects the crew from radiation
10) Exploration flexibility by allowing the exploration community to use exploration resources to get to new destinations instead of building new vehicles

VI. Summary and Conclusion

The SHM concept has merits and could significantly simplify the conduct of exploration missions. The reuse of mission assets for subsequent exploration missions could dramatically reduce the cost of exploration and could significantly reduce the time required to develop and conduct a Mars mission. Assessment of the use of high specific impulse propulsion has led to a better understanding of the implications that using such technology has on mission planning. The infrastructure in the Orbital Assembly Base could be used to conduct other near-Earth NASA or commercial operations between exploration missions.

The completion of the first estimation of the mass of the vehicle employing the SHM concept has confirmed that the concept is likely to provide substantial mass savings versus the Cx Mars DRA approach for one crewed mission to the surface of Mars.

NASA Leaders should consider the SHM concept as an alternative approach for exploration and start a program to implement SHM. Such a program organization should be the advocate for current technology development leading to those technologies being available for use in a SHM program. Exploration programs should initiate development of the assembly station (or address repurposing of the ISS as the assembly station).

More detailed studies be should be conducted to refine the SHM concept, specifically to assess the option of the SHM concept presented below as forward work.

VII. Forward Work

The SHM concept will be presented to NASA engineering management to provide them with an understanding of the concept and of the work done to date. It is expected that give the results of studies performed to date; management will decide to pursue additional detailed development of the SHM concept leading to organization of a program to implement the SHM approach to exploration. Such a program will provide the “pull” reason to continue development of technologies that will make the SHM concept work.

In mid and late 2012 several engineers have commented that it would be important to minimize the mass of the elements that are used to conduct a surface mission. Others have commented that using 2 MMSEVs to conduct surface exploration is beneficial in several ways. Those changes would impact the SHM concept significantly and may further reduce the IMLEO of the SHM concept.

The most promising architecture is shown in Figure 6 wherein all the habitat functions, supplies for transit and waste generated during the Earth to Mars transit are left in LMO and only the required functions are located in a part of the habitat that serves only to support MMSEV exploration of the surface. Using 2 MMSEVs provides habitation volume for the crew, command of descent and ascent functions, and addresses contingencies during long roving operations. The part of the habitat that accompanies the MMSEVs to the surface would be dedicated to providing consumables needed by the crew during the surface stay including those required by the MMSEVs to conduct surface exploration. Most of the CLSS systems needed for the entire mission are required to support the MMSEVs and the crew during the 2 month surface exploration. The part of the habitat that is used on the surface will be primarily the regenerative life support systems, the volume needed to access those systems and to house the consumables needed during the surface exploration. This concept will require two extra hatches (one to interface between the surface habitat and the transit habitat and the other to interface with the second MMSEV). The MMSEV hatches and interface with the surface habitat would be on the side which is consistent with current MMSEV designs. The added mass for those hatches is expected to be much less than the mass saved by employing this approach to minimize the mass to the surface.

It is anticipated that this approach will result in the mass of parts of the SHM complex that are used for surface exploration being significantly less than the 39,400 kg habitat/MMSEV mass of the SHM concept addressed earlier. Reducing that mass will significantly reduce the HPS mass and that will then reduce the mass of the entire complex IMLEO.

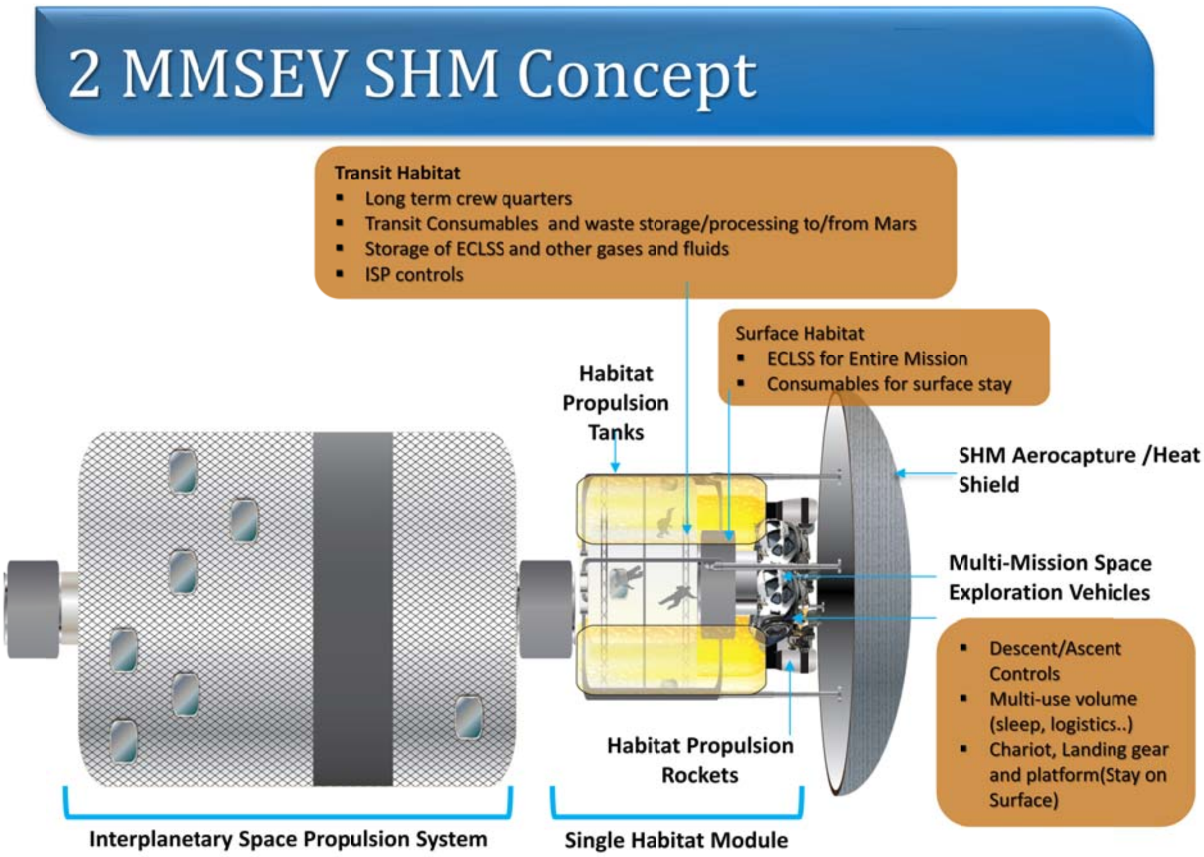


Figure 6 – Using 2 MMSEVs as the habitat while on the surface may significantly reduce the mass of the SHM

The author will continue to pursue SHM alternatives with those changes to determine how those changes can improve the concept (if resources permit).

Other forward steps include the normal development activities of evaluating technology options to minimize mass and improve functionality of mission elements. Technology and operational options that could lead to reduction of vehicle mass or reduced cost include:

1) Using an inflatable habitat structure to reduce structural mass
2) Using the ISS as an assembly site (eliminates the need for a separate near-Earth assembly base, but decreases the mass each launch can deliver to space because of the high inclination)
3) Considering advanced Environmental Control and Life Support System technologies to save more than 1000 kg (2205 lb) versus ISS-derived technologies (for 1 year)

4) Jettison landing gear at destination surface (requires refurbishing the SHM with new landing gear for the next mission)
5) Jettison SHM propulsion prop tanks and maybe the engines (requires resupply of those elements for the next mission) (refueling required in any scenario)
    a. Consider using a set of propulsion tanks for descent and another for ascent and rendezvous and leave the descent tanks at Mars (to reduce ascent mass)
6) Segmenting the ISP prop tanks and discarding tanks when empty (refueling required in any scenario)
7) Leaving the SEV on the surface (compromises contingency capabilities during return)
8) Leaving one of the two MMSEVs in the 2 MMSEV concept (introduces symmetry issues for ascent)
9) Conduct further studies of the trajectory of the SHM concepts that better optimize the transit times

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