THE HYBRID PROPELLANT MODULE (HPM): A NEW CONCEPT FOR SPACE TRANSFER IN THE EARTH'S NEIGHBORHOOD AND BEYOND

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ABSTRACT

The safe, affordable and effective transfer of ever-larger payloads and eventually personnel beyond Low Earth Orbit (LEO) is a major challenge facing future commercial development and human exploration of space. Without reusable systems, sustained exploration or large-scale development beyond LEO appears to be economically non-viable. However, reusable systems must be capable of both good fuel efficiency and "high utilization of capacity", or else economic costs will remain unacceptably high. Various options exist that can provide high fuel efficiency – for example, Solar Electric Propulsion Systems (SEPS) – but only at the cost of low thrust and concomitant long transit times. Chemical propulsion systems offer the potential for high thrust and short transit times – including both cryogenic and non-cryogenic options – but only at the cost of relatively low specific impulse (Isp). Nuclear thermal propulsion systems offer relatively good thrust-to-weight and Isp – but involve public concerns that may be insurmountable for all except the most-critical of public purposes. Fixed infrastructures have been suggested as one approach to solving this challenge; for example, rotating tether approaches. However, these systems tend to suffer from high initial costs or unacceptable operational constraints. A new concept has been identified – the Hybrid Propellant Module (HPM) – that integrates the best features of both chemical and solar electric transportation architectures. The HPM approach appears to hold promise of solving the issues associated with other approaches, opening a new family of capabilities for future space exploration and development of near-Earth space and beyond.

This paper provides a summary overview of the challenge of Earth neighborhood transportation and discusses how various systems concepts might be applied to meet the needs of these architectures. The paper describes a new approach, the HPM, and illustrates the application of the concept for a typical mission concept. The paper concludes with a discussion of needed technologies and a possible timeline for the development and evolution of this class of systems concepts.

INTRODUCTION

There are many challenges confronting mankind's exploration of space, and many engineering problems that must be solved in order to provide safe, affordable and efficient in-space transportation of both personnel and equipment. Many of these challenges directly impact the commercialization of space, with cost being the single largest obstacle. One method of reducing costs is to develop reusable transportation systems, both Earth-to-orbit systems, as well as in-space infrastructure. Without reusable systems, sustained exploration or large-scale development beyond Low Earth Orbit (LEO) appears to be economically non-viable. However, reusable in-space transportation systems must be capable of both good fuel efficiency and "high utilization of capacity", or else economic costs will remain unacceptably high. Fixed infrastructures have been suggested as one approach to solving this challenge; for example, rotating tether approaches. However, these systems tend to suffer from high initial costs or unacceptable operational constraints. Another significant challenge is minimizing the in-space travel time for crewed missions. The risks associated with human missions can be significantly reduced by decreasing the time that the crew is in transit. Besides nuclear thermal propulsion systems, and the inherent public concerns that accompany the use of these systems near the Earth, the propulsive system that provides a reasonably high thrust and short transit time is one that uses chemical propellants. One significant drawback to chemical systems is the relatively low specific impulse (Isp) of this form of propulsion, which requires large propellant quantities of to provide the velocity changes that are required to complete a mission. Solar Electric Propulsion Systems (SEPS) can provide high fuel efficiency but only at the cost of low thrust and transit times that are not compatible with crewed missions. An innovative concept that integrates the best features of both chemical and solar electric transportation architectures has been proposed. This concept appears to hold the promise of solving the issues associated with other approaches, and may provide a new family of capabilities for future space exploration and development of near-Earth space and beyond.

BACKGROUND

A reusable Hybrid Propellant Module (HPM) has been proposed as a concept for the fundamental building block for an efficient, reusable in-space transportation system for both crew and un-crewed missions. The HPM provides long term storage of both chemical and electric propellants, and when combined with modular orbital transfer/engine stages, provides an integrated propulsion system. It is anticipated that an HPM based in-space transportation architecture can be implemented in the near future (next 10-15 years), and can be augmented and adapted as new technologies become mature. The HPM would provide chemical propellant for time critical transfers and utilize electric propellant for pre-positioning or to return the HPM for refueling and reuse. In theory, the HPM concept can be scaled to meet the delta-V requirements for any mission. However, for practical purposes, the HPM design and analyses performed so far have been focused on sizing the HPM to provide the propellant storage required to satisfy the requirements for a set of exploration NASA Design Reference Missions (DRMs) and future LEO commercialization scenarios. The HPM concept features a high level of reusability and is assumed to be supported by inexpensive launch of propellant and logistics payloads from the Earth. This is an important aspect of the baseline HPM implementation, which utilizes on-orbit refueling to minimize the launch costs associated with repeatedly deploying mission hardware that is not reusable. The anticipated benefits are reduced future mission costs and increased mission robustness and flexibility for future space exploration and commercialization initiatives.

The initial HPM "Baseline" resulted from a focused Earth-Sun Lagrange Point mission concept analyzed in the summer of 2000. The application of the HPM concept towards additional exploration missions (i.e., human Lunar mission) and future commercialization scenarios is the focus of current efforts. Determining whether the HPM concept (or some derivative of the concept) is viable for more far reaching orbital transfers, such as Mars missions and near Earth asteroid rendezvous, will be the focus of future studies.

Each HPM is envisioned to have an operational lifetime of at least ten years and will be maintainable on-orbit, as well as refillable. The HPM concept has the potential to support NASA, commercial, and DOD missions. A key aspect of the HPM is its ability to sustain itself for long periods of time without the support of any other spacecraft or infrastructure. This allows the propellants resident on the HPM to be stored indefinitely, utilizing advanced Zero-Boil-Off (ZBO) technology, at any given location in support of a particular mission or architecture.

HPM ARCHITECTURE CONCEPT

The fundamental concept for an HPM based in-space transportation architecture requires two HPMs and two propulsive transfer stages, one chemical based and one electric based. The basic philosophy is to utilize the chemical propellant stored on-board the HPM in conjunction with a chemical transfer/engine stage to provide high thrust during the time critical segments of a mission (i.e., crew transfers), and utilize the electric propellant with a solar electric transfer/engine stage during non-time critical segments of the mission (i.e., pre-positioning of one HPM for the return crew segment of the mission and returning the second HPM back to the departure location). This architecture can save a significant amount of propellant when compared to an all chemical mission assuming that the efficiency of the electric propulsion system is sufficiently greater than the chemical propulsion. For the currently baselined propellants, liquid oxygen (LOX) and liquid hydrogen (LH2) is assumed to have an Isp = 466 s and electric propellant (Xenon) has an Isp = 3000 s or greater. Although chemical propellant is still required for each segment of the mission where a crew is being transferred, the mass penalty for carrying the return trip chemical propellant is substantially reduced due the more efficient specific impulse of the electric propulsion system. The larger the difference between the chemical and electric Isp values, the greater the benefit of employing an HPM based architecture. Figure 1 shows a layout of the major external and internal components of the HPM. The HPM propellants (LOX/LH2 and Xenon) are cryogenically stored to maximize the propellant densities. Figure 2 shows a system component mass breakdown assuming advanced technology efforts to minimize sub-system masses.

HPM Specifications

Although the HPM is currently at the conceptual design stage, and the characteristics are rapidly being refined, the following data provide an estimate of the expected specifications and performance characteristics of the HPM that has been sized to accommodate a LEO to Earth-Moon Lagrange Point mission architecture. The HPM dry mass assumes advanced technology developments which result in significant mass savings over current engineering implementations. Those technologies are identified later in a later section.

- HPM Dry Mass = 3,940 kg
- Maximum LOX Storage Mass = 26690 kg
- Maximum LH2 Storage Mass = 4,450 kg
- Maximum Xenon Storage Mass = 15,070 kg
- Average Operating Power Required = 3.1 kW

HPM Supporting Elements

The HPM by itself is simply a self-sufficient, long-term cryogenic propellant storage depot. An HPM based architecture concept requires the support of various mission elements in order to provide a completely reusable transportation system. The basic architecture is supported by the following space-based elements: a Chemical Transfer Module (CTM), a Crew Transfer Vehicle (CTV), and a Solar Electric Propulsion (SEP) module. Conceptual depictions of these elements are shown in Figures 3, 4, and 5, respectively. Additionally, the HPM architecture requires the support of inexpensive logistic resupply flights (fuels and replaceable on-board components), either via mass-produced Expendable Launch Vehicles (ELVs) or a Reusable Launch Vehicle (RLV).

The CTM serves as a high energy injection stage when attached to an HPM, and as an autonomous orbital maneuvering vehicle for proximity operations such as ferrying payloads, refueling (HPMs and other spacecraft), and servicing satellites. The CTM has high thrust cryogenic LOX/LH2 engines for orbit transfers and high-pressure LOX/LH2 thrusters for proximity operations and small delta-V maneuvers. It is also capable of and storing approximately 4000 kg of LOX/LH2 and a small amount of Xenon (Xe). The CTM main engines can use the internally stored propellant or burn propellant directly transferred from the HPM. The CTM does not utilize ZBO technology. The CTV is used to transfer the crew in a shirt sleeve environment and is being designed based on the requirements for crew transport from LEO to the Earth-Moon Lagrange Point and back. The CTV will be able to dock to the International Space Station (ISS) as well as any other crewed orbiting infrastructure that exists. One end of the CTV is a docking interface for the HPM or CTM, and the other end is the pressurized docking port for connecting to a pressurized vehicle or a CTM. The SEP module serves as a low-thrust transfer/engine stage when attached to an HPM for pre-positioning large elements or for slow return of elements for refurbishing and refueling.

It is worthwhile to note that the CTM and CTV are two independent vehicles that must interface with the HPM. For the purpose of transferring crew, the possibility exists to combine these two elements into a single vehicle, similar in functionality to the combined Apollo Command and Service Modules. Combining the CTM and CTV would reduce the number of elements in the architecture and simply the operational complexities of the system. However, this combined vehicle would have a significant mass overhead resulting from the CTV functions being permanently combined with CTM, if the vehicle is used for unmanned functions such as HPM refueling or satellite servicing. Having the functions separated into the CTM and CTV, provides significant flexibility to accommodate a wide range of missions and reduces the total number of vehicle development programs required for the overall HPM based architecture. The trade-offs of designing and developing a dedicated crew vehicle/propulsive transfer stage will be examined in the future.

Typical Mission Description – Earth-Moon L1

This section, and the accompanying figures, illustrates the application of the HPM for a typical crewed mission concept. In this case the departure point is LEO (ISS used as the crew's departure point) and the destination is the Earth-Moon Lagrange Point located at the L1 position (between the Earth and Moon).

The Earth-Moon (E-M) L1 mission is predicated on the assumption that humans will return regularly to the Moon for on-orbit and surface operations and scientific studies. These missions will be facilitated by a small habitation facility called a "Gateway" at the E-M L1 point. Potentially, the Gateway will also serve as a facility for missions beyond the Moon. The Gateway concept, shown in Figure 6, provides a deployable pressurized volume, multiple vehicle docking capability, and all necessary subsystems, including power from the large photovoltaic (PV) arrays deployed on the attached SEP. A lunar lander (not depicted in the figure) provides crew transportation to and from the lunar surface.

The initial mission operation is for the first HPM (designated HPM-1 for this discussion of the E-M L1 mission scenario), to be launched to LEO. This launch could be supplied by any sufficiently capable launch vehicle. The current design of the HPM is being sized to fit within the shuttle cargo bay volume to maximize the compatibility of the HPM with potential launch vehicles. Figure 7 depicts the HPM being deployed from the cargo bay of a future shuttle class vehicle. The HPM PV arrays are deployed and tested in LEO, as shown in Figure 8, and HPM-1 will orbit autonomously until a SEP module docks with it for the transfer to the Gateway at L1. If the launch vehicle payload mass capability does not allow the HPM to be completely fueled, it's tanks will be "topped off" with LOX, LH2, and/or Xe by the second stage of a mass-produced ELV or a next generation RLV. The maximum wet-mass estimate for the HPM is approximately 50,150 kg. Being able to launch the HPM fully loaded simplifies operations, but since the HPM will be designed to be refueled many times this additional function is already accommodated by the HPM.

Once HPM-1 has sufficient propellants loaded, a SEP is launched to LEO on a future shuttle or ELV, as depicted in Figure 9. After the SEP PV arrays have been deployed and its systems activated, the SEP will autonomously rendezvous with HPM-1 (Figure 10). The SEP and the CTM will both be required to provide some amount of propulsive capability, since the HPM is not anticipated to have any reaction control system (RCS). The HPM will be required to provide some level of attitude control, to facilitate the rendezvous and docking, but this will accomplished using the fly wheel system. The combined SEP/HPM-1 “stack” then begins a slow, low-thrust trajectory to the Gateway at Earth-Moon L1, as depicted in Figure 11. This mission segment is anticipated to take up to 270 days. During the journey, HPM-1 supplies xenon propellant to the SEP while using ZBO systems to maintain and store the cryogenic hydrogen and oxygen. This chemical propellant will later be used to propel the crew from the L1 Gateway back to LEO.

The SEP/HPM-1 stack arrives at the L1 Gateway with almost the entire load of Xe propellant utilized (Figure 12). The vehicle stack can either dock or station-keep near the Gateway. The SEP utilizes its RCS system for final approach and docking, as shown in Figure 13. At the Gateway, the proper functioning of the HPM is verified to assure its ability to provide the propellant for the crew return mission. At this point in the mission, the Gateway has all the elements necessary to support the crew during their expedition and return them to LEO.

The HPM will be designed to provide the necessary redundancy for crewed missions. However, the HPM architecture concept also has another level of redundancy built in. In order to provide a continuous transportation system, multiple HPMs will be dispatched at the required interval (e.g., every 60 days). The outbound crew transfer will not occur until the designated return HPM has arrived and is confirmed to be functioning properly. In the event that an HPM cannot be used for the crew’s return, another HPM will nominally arrive at the L1 Gateway 60 days later. This HPM would provide a redundant capability in a failure scenario and subsequent crew missions would be pushed back to accommodate the interruption to the traffic flow. Additionally, the SEP at the E-M L1 Gateway should have enough capability to return the inoperable HPM for possible repairs in LEO as a payload on its regularly planned return trip.

The second segment of the mission utilizes a second HPM attached to a CTM to transport the crew, on-board the CTV, to the L1 Gateway. Figures 14 and 15 depict the arrival and attachment of the CTM and CTV to the ISS using the shuttle and station robotic arms to berth the CTM/CTV stack to the station via an International Berthing and Docking Mechanism (IBDM) located on a nadir port of the ISS. The CTV (shown as inflatable concept in Figure 16) is then configured and outfitted for the journey to the L1 Gateway.

A second HPM, designated HPM-2, is also launched to LEO during this same period of time. The second HPM will supply the LOX/LH2 propellant for the crew’s out-bound trip to the L1 Gateway. The CTM undocks from the ISS (Figure 17) to bring back the newly launched HPM. After HPM-2 has also been completely fueled, the CTM will rendezvous and dock with the second HPM. This HPM contains enough LOX/LH2 to deliver the crew from LEO to the L1 Gateway in less than four days, and carries sufficient Xe propellant so it can be returned from L1 to LEO using the SEP module during the final mission segment. The CTM returns HPM-2 to the ISS and docks with the CTV, as depicted in Figure 19. The crew boards the CTV from the ISS and is now ready to begin the journey to the L1 Gateway. The combined CTM/HPM-2/CTV stack utilizes its RCS to separate the vehicle to a sufficient distance and fires its main engines for transfer to the L1 Gateway (Figure 20).

The CTM/HPM-2/CTV stack arrives and docks to the E-M L1 Gateway, as shown in Figure 21. To facilitate the return segments of the mission, the CTM, SEP and HPMs must be repositioned such that the HPM with the full load of LOX/LH2 (HPM-1) is docked to the CTV and CTM and the HPM with the full load of Xenon propellant (HPM-2) is attached to the SEP module. These operations would likely be performed before the crew performs their mission at the Gateway and on the lunar surface to allow time for correcting any problems that might arise. It is envisioned that this repositioning will be performed in a nearly autonomous manner, such that the impact on the crew is minimized. Figure 22 shows the Gateway and the two vehicle stacks prior to the repositioning portion of the mission.

The repositioning begins with the CTM undocking HPM-2 and its full supply of xenon off the CTV and loitering at a safe distance from the Gateway (Figure 23). Next, the SEP utilizes its RCS to transfer HPM-1, which is full of LOX/LH2, to the

Gateway port where the CTV is docked, as shown in Figures 24 and 25. Similarly, the CTM moves HPM-2 to the now vacant port, as illustrated in Figure 26. Once this phase is complete, the HPM full of LOX/LH2 is attached to the CTV and the HPM with a sufficient supply of Xe propellant is attached to the SEP. Finally, the CTM and SEP separate from the HPMs and exchange places so that CTM is attached to the HPM-1 (full LOX/LH2 load) and the SEP is attached to the HPM-2 (full Xe load), as shown in Figures 27 and 28. Now, the newly configured CTM/HPM-1/CTV stack is ready for the crew return voyage to LEO and the SEP/HPM-2 stack can return the second HPM to LEO as well. With the successful exchange of the HPMs, the crew can perform their lunar excursion, and other mission operations, with the two vehicle stacks prepared for the return mission segments.

Although the choreography of this HPM repositioning portion of the mission is fairly complex, the ability of the SEP and CTM to perform routine autonomous rendezvous and docking is critical to minimize the risk associated with this exchange sequence. The combination of the CTM and CTV into a single vehicle, as discussed before, would greatly simplify this operation, but potentially at the expense of reduced architecture flexibility. In this case, only a simple exchange of the HPMs between the SEP and the combined CTM/CTV elements.

After the lunar mission is complete, the crew boards the CTV from the Gateway and the CTM/HPM-1/CTV stack departs from the Gateway (Figure 29). The CTM then propels HPM-1 and the CTV back to LEO (Figure 30) where the vehicle stack docks to the ISS. The CTV is refurbished at the ISS and the crew returns to Earth via the shuttle or other return vehicle.

After the crew's departure from the Gateway, the SEP/HPM-2 stack leaves the Gateway on a low-thrust trajectory back to LEO, as shown in Figures 31 and 32. With the return of all mission elements to their origination location in LEO, the HPM based architecture provides a closed, reusable concept that can be used repeatedly without additional mission elements being launched.
The final phase of architecture involves the resupply of propellants to the nearly empty HPMs, and the periodic replacement of various element components such as avionics, PV arrays, etc. Figure 33 depicts the CTM ferrying a propellant logistics carrier to an HPM in LEO, after which the HPM is ready to be used as the propellant module for another mission to the Moon or other application. It is expected that LEO will provide the resupply location for the HPM during its initial implementation. Any location could be used for the departure and return point for an HPM based architecture as long as propellants and other serviceable components can be provided. For more distant destinations, the E-M L1 point or even the lunar surface could be utilized as a staging point for a mission utilizing the HPM.

Although the duration of the SEP/HPM mission segment is relatively long (almost a year), more frequent crewed missions to the Moon simply would need to be supported by multiple SEPs and HPMs deployed at the proper time intervals. As mentioned previous, a properly developed traffic model will also allow for redundancy in an HPM based architecture by providing a continuos supply of propellant for the crew return in case of an element failure.

POTENTIAL HPM ARCHITECTURE AUGMENTATIONS

The dry mass of the HPM and other elements are the main drivers of an HPM based in-space transportation architecture. Each kilogram saved in systems mass reduced the overall propellant loads required to provide the necessary delta-Vs for the mission. In particular, there are significant mass penalties (structural and propellant requirements) associated with the SEP module, primarily due to the power storage and mechanical systems required for the power levels needed to provide the electric propulsion (several hundred kW). A highly beneficial augmentation to an HPM based architecture would be the incorporation of space-based power beaming to provide the required power to an electric propulsion transfer stage, and potentially the power for the HPM to maintain the propellant management and other on-board systems. The use of Space Solar Power (SSP) systems in Geostationary Earth Orbit (GEO), or Lunar based power sources, could provide an abundant supply of power to a flotilla of HPMs that would provide regular transportation from LEO to the Moon (or even more distance locations).

One possible extension of the HPM is the incorporation of a Hybrid Transfer Vehicle (HTV), which could use both chemical and electric propellants to provide the propulsive delta-V maneuvers required for a space mission. Many deep space missions could benefit from a possessing high thrust capability near the Earth and more efficient low-thrust electric propulsion once the vehicle is far enough from the Earth that the gravitational attraction is negligible. It is likely that many of these missions would not return to LEO. These missions could either make disposable use of the HPM and HTV, or could use an HPM that has already exhausted part of it operational lifetime performing other missions.

The HPM has the potential for significant utility when used outside of dedicated transportation architectures. As mentioned earlier, one of the drivers behind keeping the CTM and CTV functions separate is to allow the CTM to perform unmanned missions such as satellite servicing. HPMs can be strategically positioned to provide the indefinite storage of propellants in Earth orbit and beyond. This allows the HPM to function as a fuel depot to support the CTM missions including orbital transfer maneuvers for other spacecraft, as well as providing orbital replacement units (ORUs) and satellite refueling.

POSSIBLE FUTURE MISSIONS

The main focus of the analyses performed to date have been to define an HPM with a reasonable capacity to perform exploration missions in the near-Earth neighborhood, but there are no fundamental reasons why the HPM concept could not be applied to missions with the need for more propellant capacity. Either a larger version of the HPM could be developed or several HPMs could be "strapped" together to provide the propellants needed for the mission. Assuming that the goal is to provide a reusable architecture, the parasitic mass associated with multiple HPMs may become problematic. This prospect makes minimizing the HPM system masses a fundamental goal. Mass reductions can only be realized through the development of advanced technologies that reduce mass, size, power, etc.

There may be applications for the HPM for Mars missions, if not for human transfer due to the long transits time using chemical propulsion for the fairly rapid transfer of logistics. If the Earth-Moon L1 location eventually is used a staging point for interplanetary exploration, the HPM (or a derived version) may provide propulsive transfers for these mission utilizing propellants extracted from in-situ propellant production (ISPP) on the Lunar surface.

The use of an HPM based architecture for rendezvous and return with a near-Earth asteroid is another mission that will be investigated in the future. Again, if these types of missions were staged from the Earth-Moon L1 location, the required delta-Vs for this class of missions could be significantly smaller than the LEO to L1 mission outlined in this paper.

A final, novel approach to more distant mission destinations is to preposition multiple HPMs in orbits where a vehicle could make multiple rendezvous in a "stepping stone" approach to completing the mission. A fuel load of chemical propellant could be provided to the crew at each "way-point" along the way in a manner analogous to how long distance military sorties are performed with airborne refueling tankers. Undoubtedly, the trajectory analysis of such an application may prove unfeasible or impractical, but it highlights the wide range of possible applications of the HPM concept.

With the ability to provide long term cryogenic propellant storage in remote locations, the HPM could be the basis for many innovative applications. The scenarios described in this paper are only a few of the possible missions that could be developed from a HPM based architecture.

TECHNOLOGIES

There are many advanced technologies that need to be developed to make an HPM based architecture a reality, including many technologies specifically applicable to the CTM, CTV, and SEP. With the proper funding levels, many of the technologies needed to support an HPM based in-space transportation system architecture could be achievable within the next 15 years. Accelerated funding levels could make this timeline significantly shorter. The following is a brief description of some of the key technologies for the development of an HPM based architecture.

- Zero boil-off cryogenic propellant storage system with up to 10 years of storage without boil-off.
- Extremely lightweight integrated primary structure and meteoroid and orbital debris shield - non-metallic hybrids to maximize radiation protection.
- High efficiency power systems, such as advanced triple junction crystalline solar cells providing at least 250 W/kg (array level specific power) and 40% efficiency, along with improved radiation tolerance.
- Long term autonomous spacecraft operations including rendezvous and docking, propellant transfer, deep-space navigation and communications, and vehicle health monitoring (miniaturized monitoring systems).
- Reliable on-orbit cryogenic fluid transfer with minimal leakage using fluid transfer interfaces capable of multiple autonomous connections and disconnects.
- Lightweight composite cryogenic propellant storage tanks highly resistant to leakage of propellants.
- Advanced materials such as graphitic foams and syntactic metal foams.
- Long-life chemical and electric propulsion systems or systems with on-orbit replaceable and/or serviceable components.
- High thrust electric propulsion systems (greater than 10 N).
- Integrated flywheel energy storage system - combination energy storage and attitude control.
- Space solar power and power beaming infrastructure to reduce HPM architecture mass and increase robustness.

CONCLUSIONS

Although the preliminary assessment of the HPM indicates that the concept is feasible, rigorous engineering analyses and detail design work are required to determine if the HPM can be built and function as envisioned. The preliminary sizing of the HPM and the associated architecture elements appear reasonable for near-Earth neighborhood missions. There may also be many other innovative applications of the HPM concept to solving exploration related problems. The HPM approach appears to hold promise of opening a new family of capabilities for future space exploration and the development of near-Earth space and beyond.

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GLOSSARY OF ACRONYMS

CTM	Chemical Transfer Module
CTV	Crew Transfer Vehicle
DOD	Department of Defense
DRM	Design Reference Mission
ELV	Expendable Launch Vehicle
E-M	Earth-Moon
GEO	Geostationary Earth Orbit
HPM	Hybrid Propellant Module
HTV	Hybrid Transfer Vehicle
IBDM	an International Berthing and Docking Mechanism
Isp	Specific Impulse
ISPP	In Situ Propellant Production
ISS	International Space Station
kg	kilograms
kW	kilowatts
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen

m	meters
N	newtons
NASA	National Aeronautics and Space Administration
ORU	Orbital Replacement Units
PV	Photovoltaic
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
s	seconds
SEP(S)	Solar Electric Propulsion (Systems)
SSP	Space Solar Power
Xe	Xenon
ZBO	Zero-Boil-Off

FIGURES

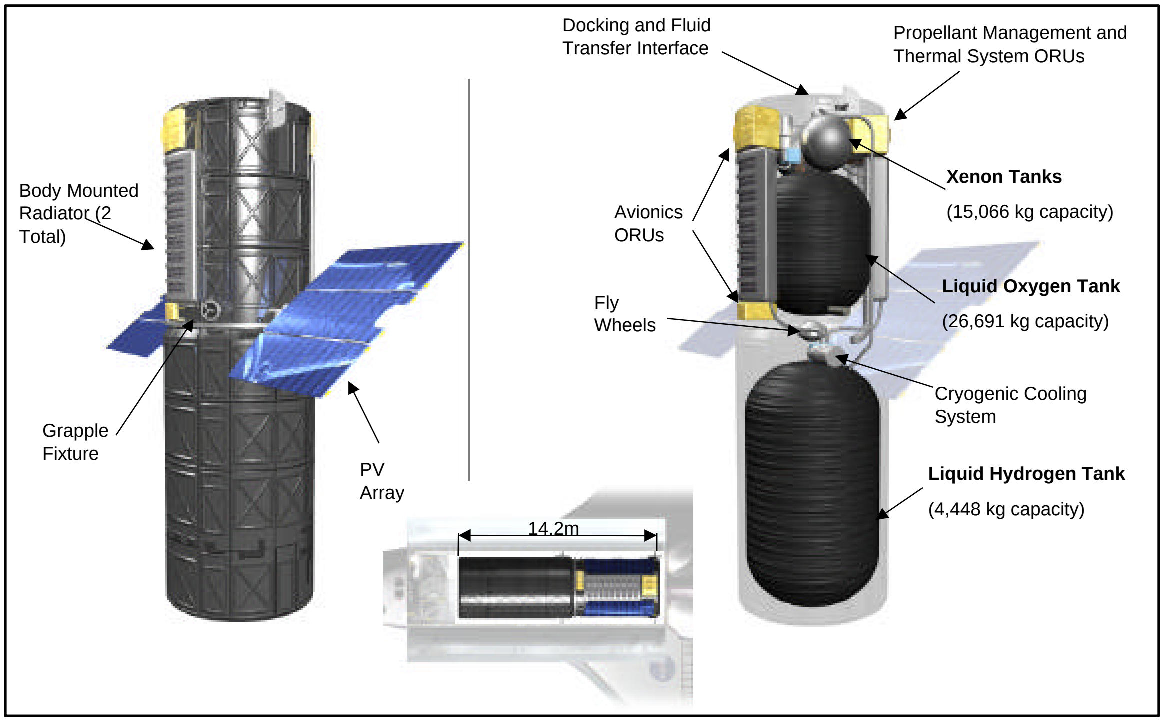

Fig. 1 – Basic HPM layout and major components.

Subsystem	Calculated Mass (kg)
Navigation/Attitude Control	12
Command/Control/Comm	42
Thermal	234
Power	305
Structures	1,314
Propellant Management	1,089
Shielding	943
Calculated Dry Mass	3,939
Chemical Propellant Capacity (LOX/LH2)	31,139
Electric Propellant Capacity (Xe)	15,066

Fig. 2 – HPM subsystem mass breakdown.

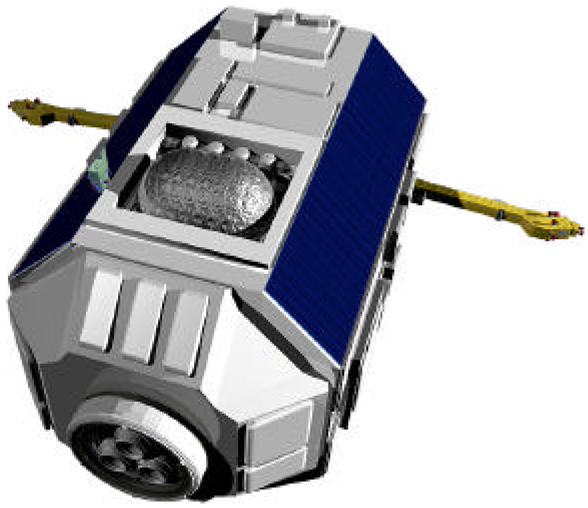

Fig. 3: Chemical Transfer Module (CTM) concept.

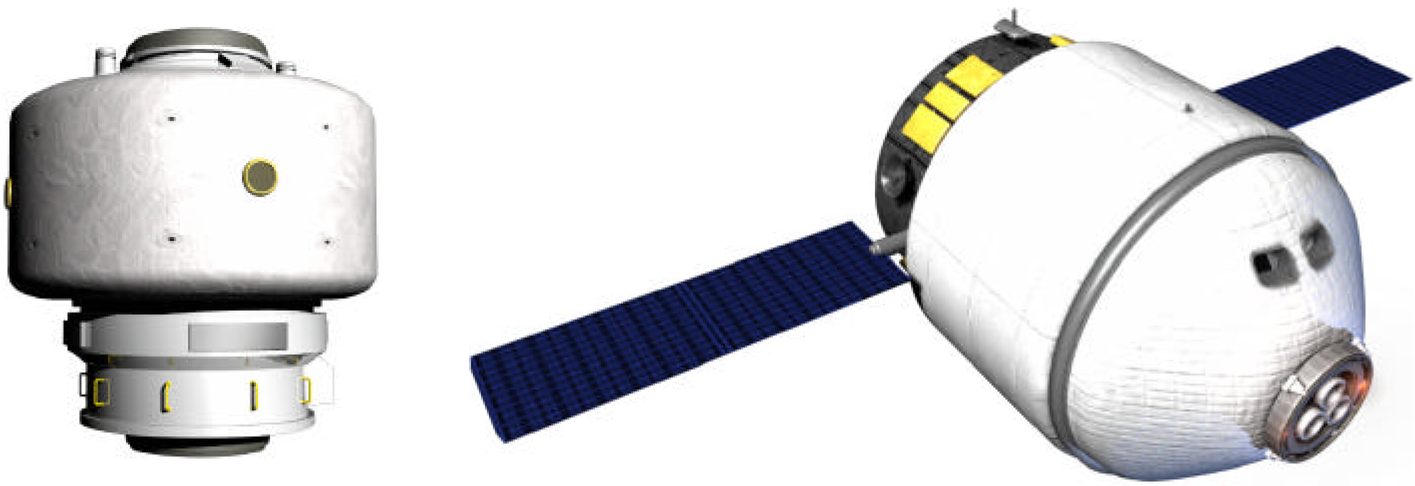

Fig. 4: Crew Transfer Vehicle (CTV) concepts - left-hand concept depicted in mission sequence – Figs. 6-33.

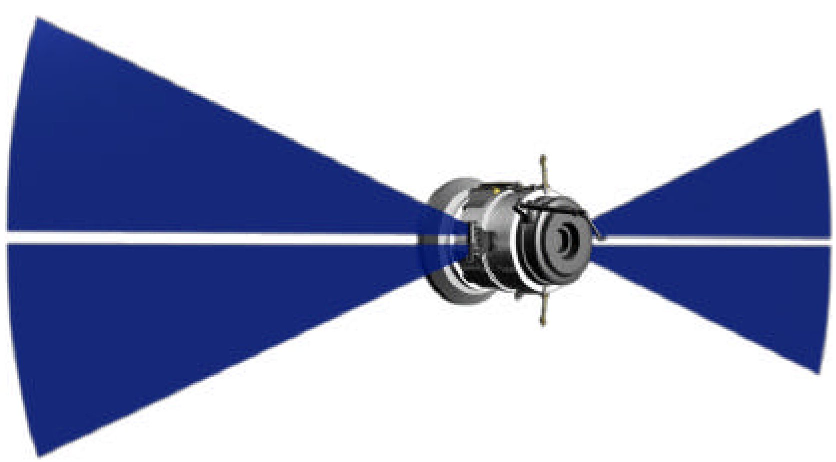

Fig. 5: Solar Electric Propulsion (SEP) concept - note: scaled reduced from Fig. 3 and 4.

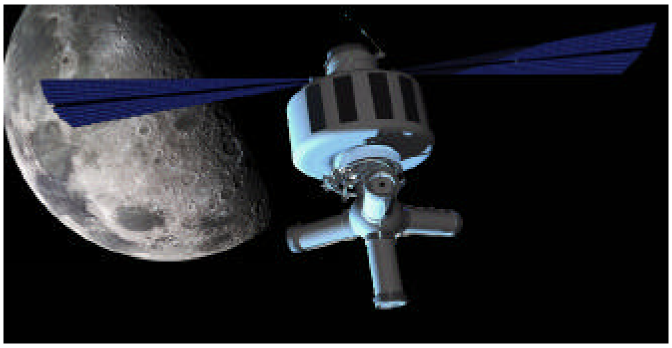

Fig. 6: Earth-Moon L1 Gateway concept with four docking ports and SEP module attached.

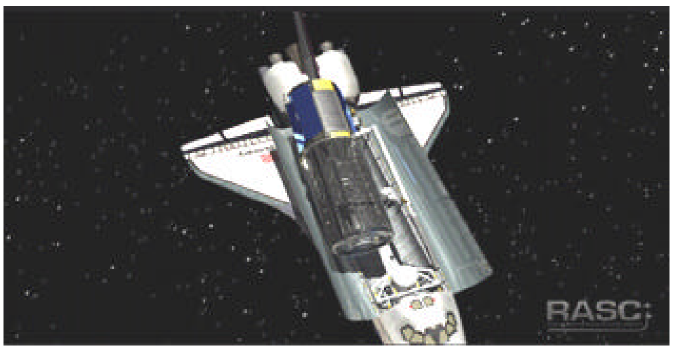

Fig. 7: HPM-1 being deployed from Shuttle cargo bay.

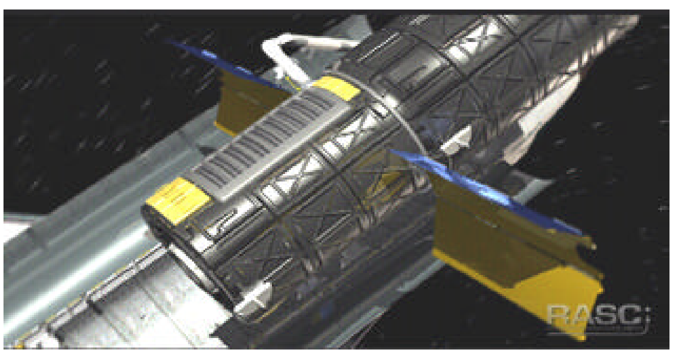

Fig. 8: HPM-1 PV array deployment.

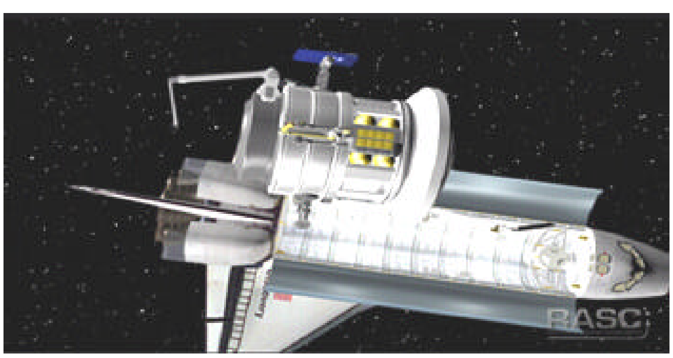

Fig. 9: Deployment of SEP from Shuttle cargo bay.

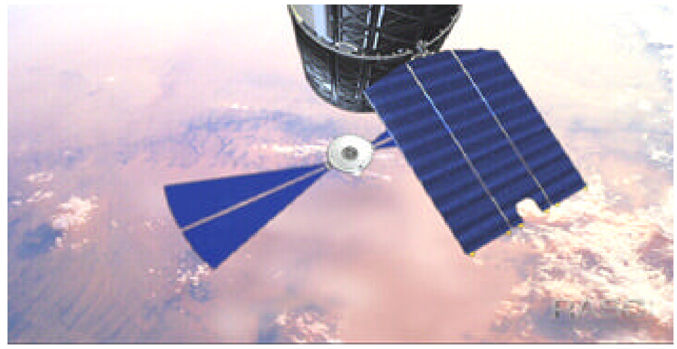

Fig. 10: SEP autonomous rendezvous and docking with HPM-1.

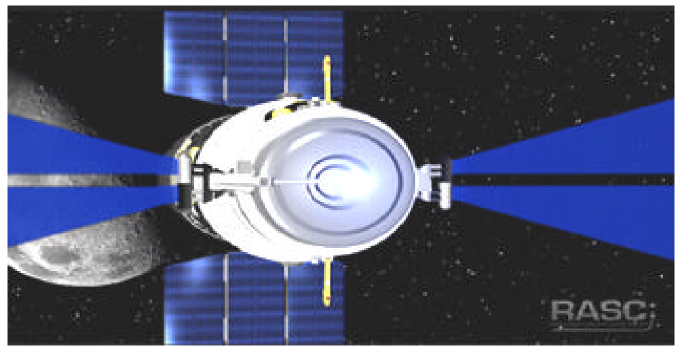

Fig. 11: SEP/HPM-1 stack performs low-thrust maneuver for transfer to Earth-Moon L1 Gateway.

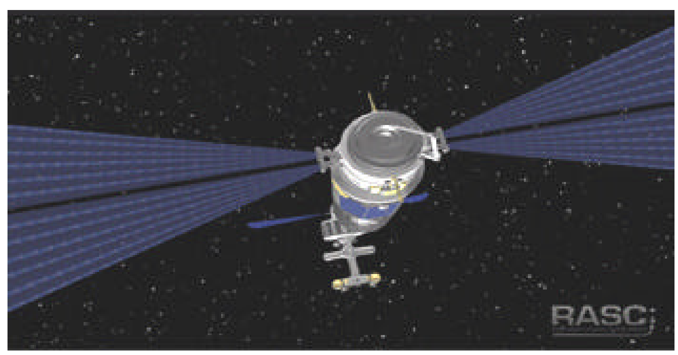

Fig. 12: SEP/HPM-1 stack arrives at Earth-Moon L1 Gateway.

Fig. 13: Autonomous rendezvous and docking of the SEP/HPM-1 stack with the Gateway.

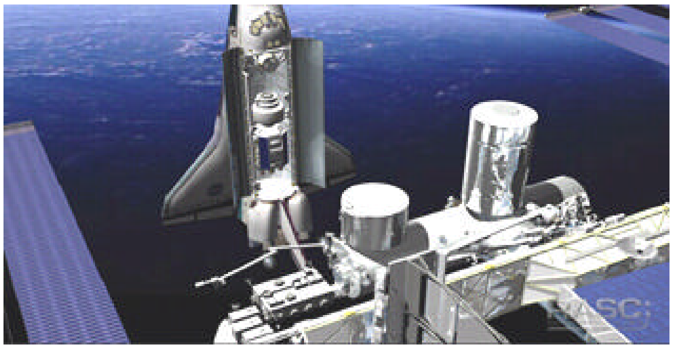

Fig. 14: CTM and CTV arrival at the ISS in the Shuttle cargo bay.

Fig. 15: CTM and CTV attachment to ISS nadir docking port using Station and Shuttle robotic arms.

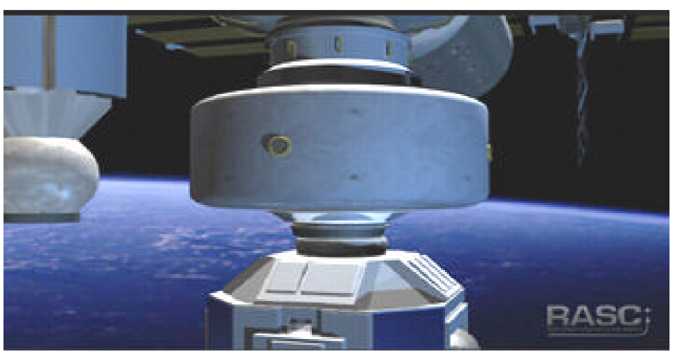

Fig. 16: CTM and CTV attached to the ISS for deployment and outfitting of the CTV.

Fig. 17: CTM undocking from the ISS.

Fig. 18: CTM autonomous rendezvous and docking with HPM-2.

Fig. 19: CTM returns HPM-2 to dock with CTV at ISS.

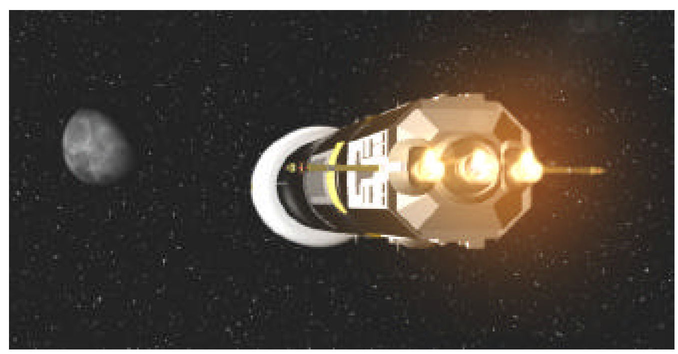

Fig. 20: CTM/HPM-2/CTV stack transit to Earth-Moon L1 Gateway.

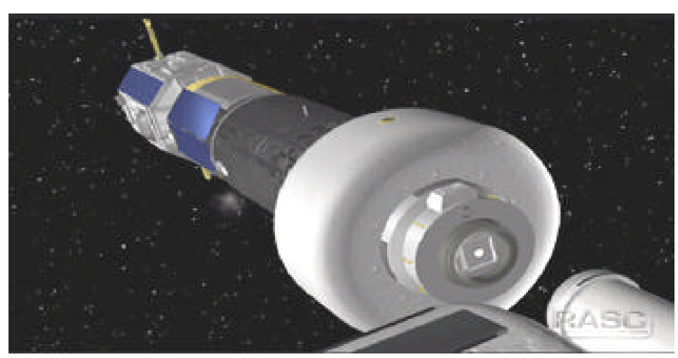

Fig.21: CTM/HPM-2/CTV stack arrival at Gateway.

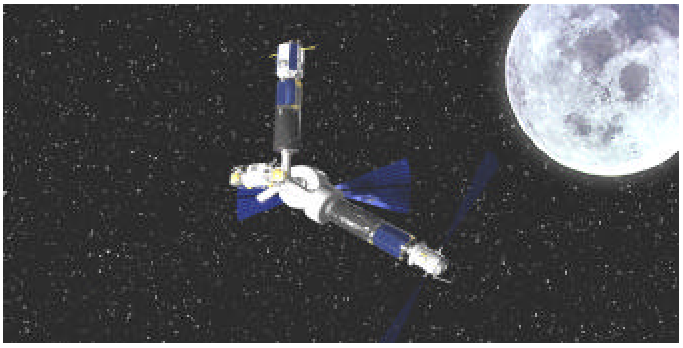

Fig. 22: Earth-Moon L1 Gateway with both vehicle stacks attached.

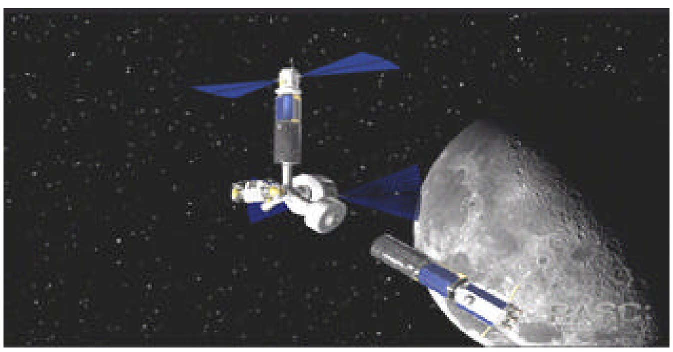

Fig.23: CTM and HPM-2 undock from CTV and loiter at safe distance from the Gateway.

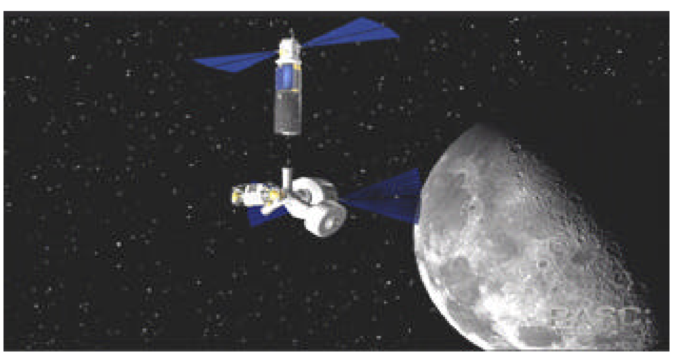

Fig. 24: SEP and HPM-1 undock from the Gateway.

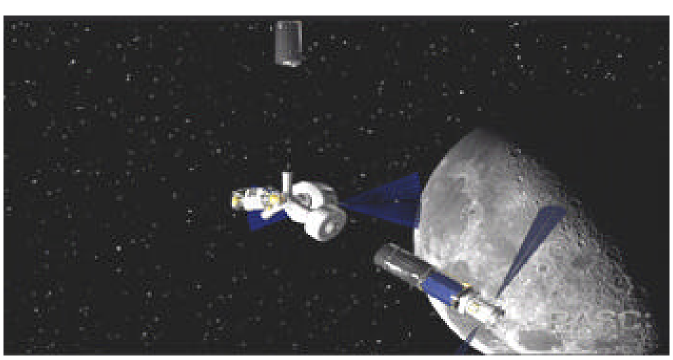

Fig. 25: SEP docks HPM-1 to the CTV.

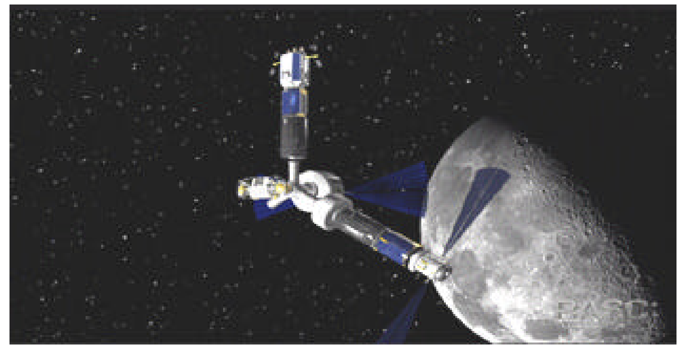

Fig. 26: CTM docks HPM-2 to the vacant Gateway port.

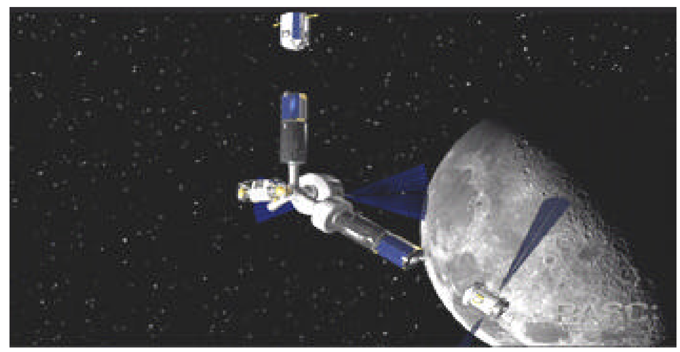

Fig. 27: CTM and SEP separate from the HPMs.

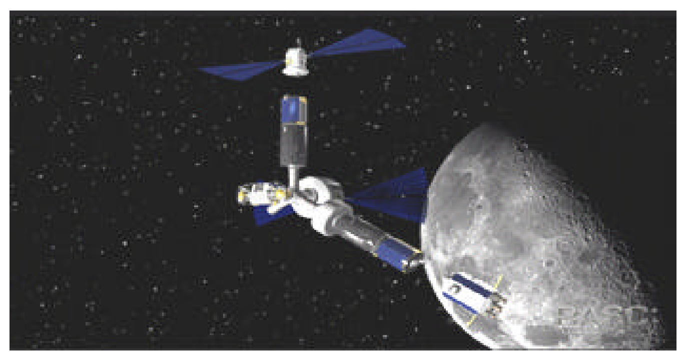

Fig. 28: CTM and SEP dock to the proper HPM for the return trips to LEO.

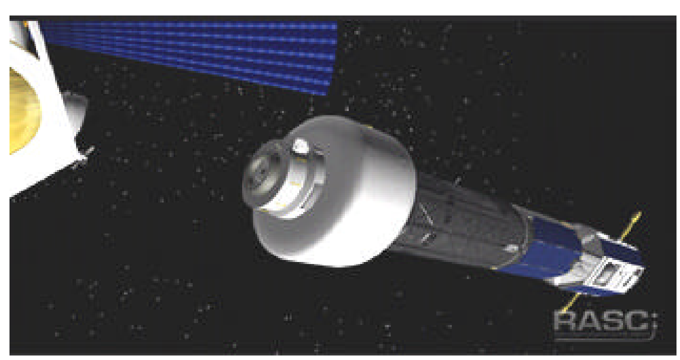

Fig. 29: CTM/HPM-1/CTV stack departs from the Gateway for return trip to LEO.

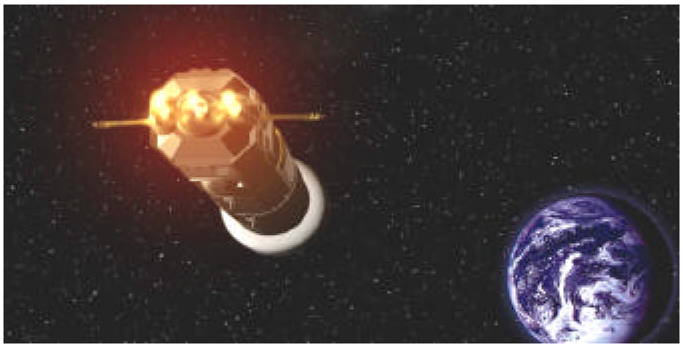

Fig. 30: CTM/HPM-1/CTV stack performs Earth transfer burns.

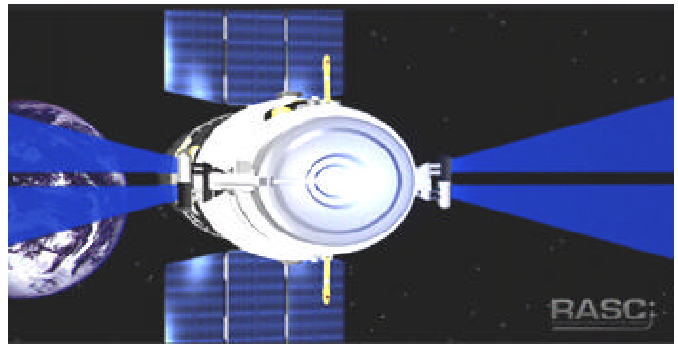

Fig. 32: SEP/HPM-2 stack performs low-thrust maneuver for transfer back to LEO.

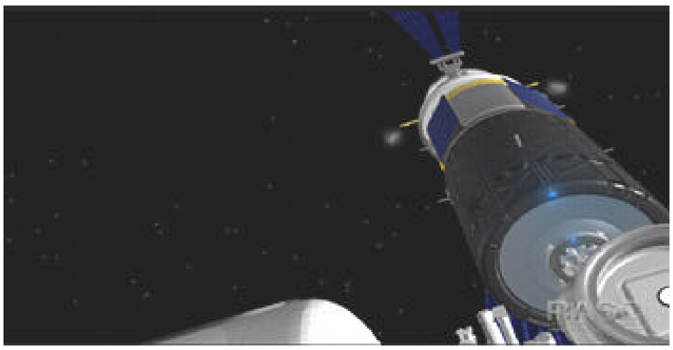

Fig. 31: SEP/HPM-2 stack departs from Gateway.

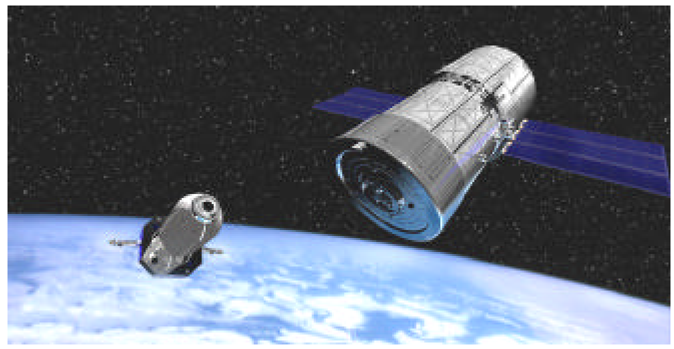

Fig. 33: CTM ferrying a propellant logistics carrier to an HPM in LEO for refueling.