IAC-02-IAA.13.2.06

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53rd International Astronautical Congress
The World Space Congress - 2002
10-19 Oct 2002/Houston, Texas

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ABSTRACT

This paper summarizes the results of a NASA-led study performed to identify synergistic opportunities and concepts between human exploration initiatives and commercialization of space. The goal of this study, called Orbital Aggregation & Space Infrastructure Systems (OASIS), was to develop an in-space architecture and associated concepts that provide common infrastructure for enabling a large class of space missions. The concepts include communications, navigation and power systems, propellant modules, tank farms, habitats, and in-space transportation systems using several propulsion technologies. OASIS features in-space aggregation of systems and resources in support of mission objectives. The concepts feature a high level of reusability and are supported by launch of propellant and logistics payloads from the Earth-moon system. Industry, NASA and other users could share infrastructure development. The anticipated benefits of synergistic utilization of space infrastructure are reduced mission costs and increased mission flexibility for future space exploration and commercialization initiatives.

INTRODUCTION

The study was performed under the Revolutionary Aerospace Systems Concepts (RASC) activity led by the NASA Langley Research Center (LaRC). LaRC was chartered by the NASA Administrator to be the lead center for evaluating revolutionary aerospace systems concepts and architectures. The overarching goal of RASC is to identify revolutionary mission approaches and the associated technologies that address NASA strategic objectives. The RASC team seeks to maximize the cross-Enterprise benefits of these revolutionary capabilities as they define the enabling technology areas and performance levels.

An architecture is presented which is composed of common in-space transportation elements derived to support both human exploration and commercial applications in the Earth-moon vicinity. Mission concepts utilizing this architecture are included. These concepts are predicated on the availability of a low-cost launch vehicle for delivery of propellant and re-supply logistics.

OASIS ARCHITECTURE

The OASIS architecture minimizes point designs of elements in support of focused space mission objectives and maximizes modularity, reusability and commonality of elements across many missions, enterprises and organizations. A reusable Hybrid Propellant Module (HPM) that combines both chemical and electrical propellant in conjunction with modular orbital transfer/engine stages was targeted as the core OASIS element. The HPM provides chemical propellant for time critical transfers and provides electrical propellant for pre-positioning or return of the HPM for refueling and reuse. The HPM incorporates zero-boil off technology to maintain its cryogenic propellant load for long periods of time. The Chemical Transfer Module (CTM) is an OASIS element that serves as a high-energy injection stage when attached to an HPM. The CTM also functions independently of the HPM as an autonomous orbital maneuvering vehicle for proximity operations such as payload ferrying, refueling and servicing. The Solar Electric Propulsion (SEP) Stage serves as a low thrust transfer stage when attached to an HPM for pre-positioning large/massive elements or for the slow return of elements for refurbishing and refueling. The Crew Transfer Vehicle (CTV) is used to transfer crew in a shirt sleeve environment from low-Earth Orbit (LEO) to the L_1 Earth–Moon Lagrange point and back as well as to the International Space Station (ISS) and any other crewed infrastructure elements.

Figure 1. Vehicles Supporting OASIS Architecture.

FUTURE SCENARIO

Successful development of low-Earth orbit and beyond will require a coalescence of events and technologies anticipated to span decades. Event occurrence and technology development are a function of budgetary, scientific and political variables. The time frame and order in which these events develop will be gradual and evolutionary in nature unless paradigm shifting technology breakthroughs are introduced. Two developments that are major drivers in the future scenario are cost effective Earth-to-orbit transportation and discovery of commercially viable LEO business opportunities. For example, one school of thought is that space tourism will drive the initial development of inexpensive launch capability and space infrastructure. The future scenario that leads to the OASIS architecture is driven by the concurrent needs of NASA, military and commercial (including space tourism) sectors.

Through all but the last phases of this scenario, crew transportation to LEO is assumed to be provided by the current or upgraded U.S. Space Shuttle along with Russian Soyuz vehicles and other future international systems. Nearly all mass sent into space is in the form of hardware and propellant that does not require a human-rated launch vehicle. Expendable launch vehicles (ELVs) such as the Delta IV-Heavy can be used in the near future to launch valuable hardware while a new generation of mass-produced, inexpensive ELVs may be developed to launch propellant and raw materials that are aggregated in LEO. The reliability of this new generation of ELVs would not have to be as high as conventional launchers since a lost payload would typically be just a tank of liquid hydrogen or oxygen. A non-human rated reusable launch system for aggregation of propellant in LEO could replace the mass-produced ELVs later in the scenario. Systems for facilitating the aggregation of resources in LEO are already under development through the Department of Defense (DoD) Orbital Express program. Orbital Express is a system for maintaining and refueling satellites in support of military objectives. The technologies (e.g., automated rendezvous and docking, on-orbit refueling) and standards developed for the military are assumed to migrate to the commercial sector. Once automated on-orbit servicing of both military and commercial satellites is the norm, the next natural extension is the ability to deliver and transport satellites utilizing a space-based infrastructure. This is a leap in scale beyond Orbital Express requiring a large, reusable Orbital Transfer Vehicle (OTV) with cryogenic propellants. The OASIS HPM and CTM could serve as steps in the evolution of capabilities beyond a military/commercial OTV.

The International Space Station (ISS) offers the potential for reinvigorating the development of space. The key factor in unlocking its potential is the discovery of processes or products unique to the LEO environment that can form the basis of commercially viable enterprises. Whether these are new wonder drugs or valuable materials difficult to produce on Earth, a commercial demand for ISS resources will quickly follow. It is assumed that when ISS resources can no longer be expanded to accommodate the demand, unpressurized, crew-tended commercial platforms or pressurized, crewed platforms will be deployed in LEO. A reusable on-orbit infrastructure will be required to economically maintain a large number of LEO processing platforms. Economical transportation of materials to and from LEO will also be required if large-scale production occurs. Commercial crewed processing platforms could have much in common with crewed NASA platforms and could yield a core design that may eventually be utilized as a commercial space hotel in support of space tourism.

Satellite communications over more frequencies with higher bandwidth along with increased military and civilian remote sensing applications will require larger satellites with more power and on-orbit upgrade capability or increased constellations of smaller, more disposable systems. Reality will likely be a combination of the two. Both system concepts will benefit from an on-orbit infrastructure and reduced launch costs.

OASIS ELEMENTS

Hybrid Propellant Module A reusable Hybrid Propellant Module (HPM) that combines both chemical and electrical propellant in conjunction with modular orbital transfer/engine stages was targeted as the core OASIS element. The HPM incorporates zero boil-off technology to maintain its cryogenic propellant load for long periods of time. 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 onboard the HPM in conjunction with a chemical transfer/engine stage to provide high thrust during the time critical segments of a mission (e.g., crew transfers). The electric propellant is utilized with a solar electric transfer/engine stage during non-time critical segments of the mission (e.g., pre-positioning an HPM for the crew return segment of the mission, and return of an HPM to its parking orbit). 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 system. Chemical engines that use liquid oxygen (LOX) and liquid hydrogen (LH_2) are assumed to have a specific impulse (Isp) of 466 seconds. Electrical propulsion engines using xenon propellant are assumed to have an Isp of 3,000 seconds or greater. Although chemical propellant is still required for each crew transfer segment of the mission, the mass penalty for carrying the return trip chemical propellant is substantially reduced due to the substantially higher specific impulse of the electric propulsion system.

Figure 2. Hybrid Propellant Module (HPM).

The principal driver for the HPM configuration is the requirement for launch by a Shuttle-class vehicle. For Shuttle compatibility the HPM is restricted to a length of 14.2 m, a diameter of 4.5 m, and a maximum mass of 14.5 MT.

The HPM configuration is divided into an upper section with a maximum diameter of 4.5 m and a lower section with a maximum diameter of 4.0 m. The smaller diameter of the lower section allows the PV arrays, body mounted radiators and ORUs to be stowed along the HPM within the diameter constraints of the Shuttle payload bay. The HPM upper and lower sections are tapered to better transfer loads.

Since the HPM will at times be flown and maintained in LEO, micrometeoroid and orbital debris (MMOD) shielding is required. The HPM upper section design incorporates an expandable (10 cm compacted, 30 cm expanded) multi-shock shield that is expanded at HPM deployment. Use of an expandable MMOD design for the HPM upper section allows for maximum diameter of the HPM primary structure within the Shuttle payload bay constraints. Due to packaging constraints and complications involved with deploying an expandable MMOD shield around the PV array arms, radiators and orbital replaceable units (ORUs), a non-expandable syntactic aluminum foam is used for MMOD shielding on the HPM lower section. A combined standoff distance of 30 cm was determined to be adequate between the primary structure and MMOD shielding.

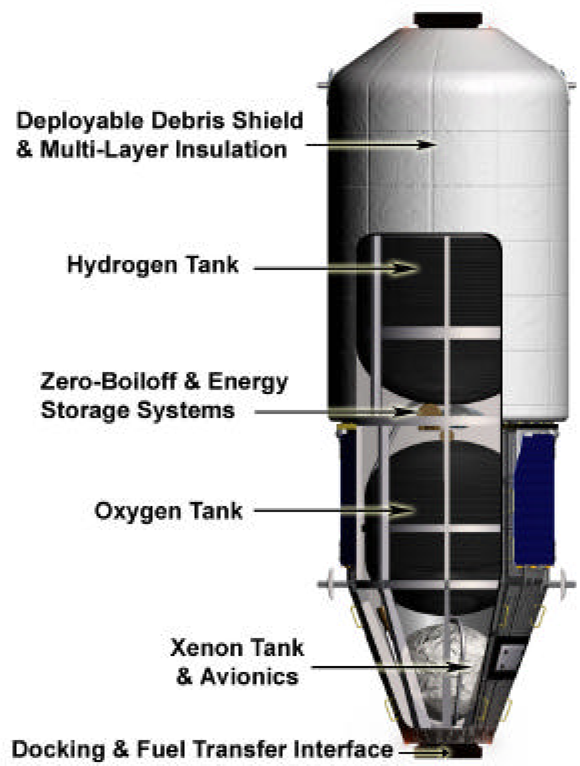

Figure 3. HPM Configuration Layout.

The maximum requirements for LH_2 and LOX were determined to be 4,450 kg and 26,750 kg, respectively. This gives a total chemical propellant mass of 31,200 kg. The internal volume required for the LH_2 and LOX tanks was thus found to be 66 m^3 and 24 m^3, respectively. The maximum requirement for LXe was found to be 13,600 kg, requiring an internal tank volume of 4 m^3.

Since the density of LOX and LXe is considerably greater than that of LH_2, these tanks are located as close to the propulsion module interface as possible in order to maintain the HPM center of gravity (CG) as far aft as possible. The HPM aft CG is necessary for controllability during HPM operations and to potentially meet CG constraints of the Shuttle-class launch vehicle.

The larger upper section of the HPM is used to accommodate the larger volume of LH_2. The LOX tank is placed directly adjacent to the LH_2 tank to utilize the same cryogenic cooling system. A single LXe tank utilizes a tapered, conical shape to maximize available tank volume.

<u>Chemical Transfer Module</u> The Chemical Transfer Module (CTM) serves as a high energy injection stage when attached to an HPM and an autonomous orbital maneuvering vehicle for proximity operations such as ferrying payloads a short distance, refueling and servicing. It has high thrust H_2O_2 engines for orbit transfers and high-pressure H_2O_2 thrusters for proximity operations and small delta-V translational or rotational maneuvers. It is capable of transferring and storing approximately 3,000 kg of cryogenic hydrogen and oxygen. The main engines can use the stored cryogens or utilize propellant directly transferred from the HPM. Unlike the HPM, the CTM does not incorporate zero boil-off technology.

The CTM deployed length is approximately 9.4 meters. The CTM width, with solar arrays deployed, is approximately 12.6 meters.

The major components of the CTM are:

- Dual RL10 67 kN-class engines
- Liquid oxygen (LOX) tank
- Liquid hydrogen (LH_2) tank
- Gaseous oxygen (GOX) RCS tank
- Six gaseous hydrogen (GH_2) RCS tanks
- Two deployable solar arrays
- Avionics modules
- Two radiator panels
- Four sets of tri-pod RCS thrusters
- Four sets of tri-pod cold gas thrusters
- Docking adapter

The dual RL10 engines are mounted twenty degrees off the CTM centerline on a fixed thrust structure. Two engines are required to satisfy reliability requirements. Since only one engine is used at a time, the thrust structure and the two engines are rotated as a single unit such that the firing engine thrust vector is aligned with the vehicle center of gravity. A new development gimbal system is required to accomplish this operation.

Figure 4. Chemical Transfer Module (CTM).

Two sets of tri-pod RCS thrusters and two sets of tri-pod cold gas thrusters are mounted on the aft end of the CTM. The thruster pods are all canted forty-five degrees to avoid plume impingement on the CTM thrust structure MMOD shield. Two sets of tri-pod RCS thrusters and two sets of tri-pod cold gas thrusters are mounted on the forward end of the CTM. These thruster pods are mounted on fixed booms and canted forty-five degrees to prevent plume impingement on an attached HPM. MMOD shielding encloses the CTM tankage and plumbing to satisfy safety requirements. The avionics ORUs are packaged in the forward skirt to avoid the adverse thermal environment in the vicinity of the RL10 engines.

<u>Solar Electric Propulsion Stage</u> The Solar Electric Propulsion (SEP) Stage serves as a low-thrust stage when attached to an HPM for pre-positioning large and/or massive elements or for the slow return of elements to LEO for refurbishing and refueling.

The SEP Stage is comprised of three elements:

- Thruster Pallet
- Deployable Boom
- Base Pallet

The Thruster Pallet is a circular plate used to mount multiple electric thrusters on lightweight gimbals. The gimbals are incorporated to enable small pointing corrections to offset any beam aberrations in each thruster. A power processing unit (PPU), one per thruster, converts input power from the arrays into the required thruster power. A gas distribution unit (GDU), located on the thruster face of the pallet, serves as a manifold for propellant delivery to the thrusters. Each engine includes a propellant feed system that regulates input flow as required for engine operation. A loop heat pipe system is mounted on the Thruster Pallet to reject waste heat from the Power Processing Units (PPUs). The rejected heat is conducted to two radiator wings attached to the Thruster Pallet.

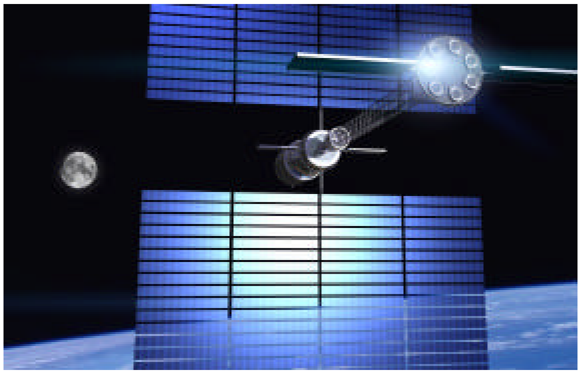

Figure 5. Solar Electric Propulsion (SEP) Stage.

The Thruster Pallet is attached to the Deployable Boom. This boom enables the Thruster Pallet to be articulated over large angles while the Base Pallet and the HPM are maintained in a solar inertial attitude for solar array pointing. The Thruster Pallet position is continually adjusted to maintain a relatively constant thrust vector through the spacecraft center of mass in order to maximize effective thrust. The Deployable Boom also provides sufficient distance between the thrusters and the solar arrays to prevent degradation due to exhaust plume impingement and erosion.

The Base Pallet houses the solar arrays and associated power management and distribution components, the docking mechanism and fluid transfer interfaces, and other systems. This pallet is a cylindrical structure with a rigid boom attached at the center of one face. On the opposite face is the docking mechanism and fluid transfer interface which mate with the HPM. Two large, rectangular-shaped solar arrays are attached to the Base Pallet sides. These arrays are on stand-off booms to provide the necessary clearance with the HPM structure.

The solar arrays consist of advanced, thin-film cells on a lightweight substrate supported on a collapsible, cell-structure wing architecture. This architecture has the advantage of packing very compactly and does not impose size limitations impacting launch vehicle manifesting. The arrays are required to accommodate a one-time deployment only.

Other elements inside the Base Pallet include:

- A gas distribution unit to handle xenon flow through the pallet from the HPM to the thrusters
- A reaction wheel-based system for attitude control during electric thruster operation
- A Guidance Navigation & Control (GN&C) unit
- A Command & Data Handling (C&DH) unit
- A battery system to power deployment of the solar arrays
- A xenon tank loaded with 2,000 kg of xenon for free-flying operations during SEP Stage orbital parking
- A Reaction Control System (RCS) for docking maneuvers consisting of four thruster pods and two propellant tanks (containing gaseous hydrogen and gaseous oxygen)
- A Thermal Control System (TCS) comprised of two radiator wings attached to the outside of the base pallet and a loop heat pipe system mounted inside that conducts waste heat from the Power Processing Units (PPUs).

<u>Crew Transfer Vehicle</u> The OASIS Crew Transfer Vehicle (CTV) is used to transfer a crew of four in a shirt sleeve environment from LEO to the Lunar Gateway and back and to transfer crew between the ISS and any other crewed, orbiting infrastructure.

The CTV is composed of a 4.0 m diameter upper section and a 4.5 m diameter lower section that are derived form portions of the HPM structure. The crew pressure vessel is located in the wider lower section. The unpressurized upper section is used to house CTV subsystems including: Atmosphere Control and Supply; Atmosphere Revitalization; Temperature and Humidity Control; Fire Detection and Suppression; and Water Recovery and Management.

Figure 6. Crew Transfer Vehicle.

MISSION APPLICATIONS

Exploration New opportunities for scientific investigation in the Earth's neighborhood have led architecture designers to take revolutionary new approaches for accommodating these various missions in a sensible, integrated fashion. In the past, such destinations were considered on their own basis with little thought given to how they fit together. This new approach has led to a particular architecture for exploration within the Earth's neighborhood known as the Gateway Architecture. Central to this concept is the emplacement of a mission-staging platform near the moon - specifically at the Earth-Moon L_1 Lagrange point. This facility, the Lunar Gateway, will serve as a "gateway" to future exploration of space including the lunar surface, other Lagrange points, and Mars.

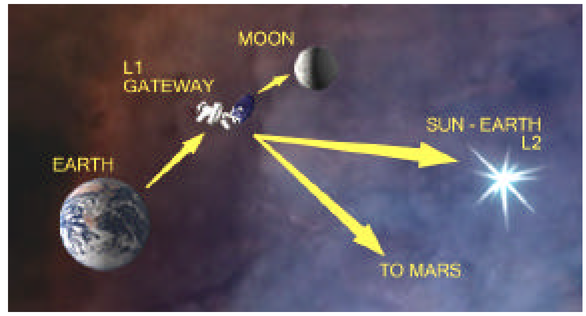

Figure 7. Gateway Architecture.

The primary goal of the Gateway Architecture is to enable both short-duration and extended-stay exploration of the entire lunar surface as well as to enable the on-orbit assembly of large astronomical observatories. Utilizing the collinear Earth-moon L_1 Lagrange point as a mission staging node allows access to all lunar latitudes for essentially the same transportation costs as a direct Earth-to-Moon mission while providing a continuous launch window to and from the lunar surface.

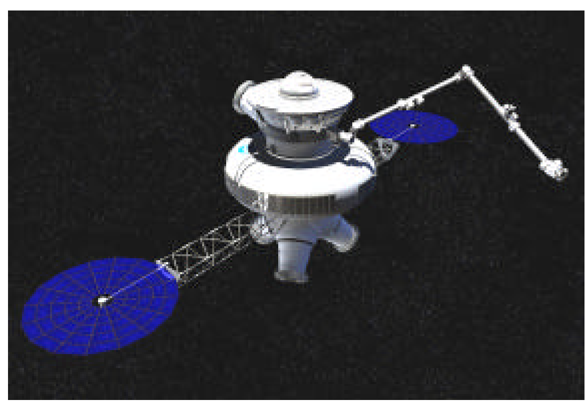

Figure 8. Lunar Gateway.

OASIS Exploration Operations The Earth-Moon L_1 mission scenario for the OASIS architecture is based on the assumptions that humans will return to the lunar surface for scientific operations and that the Lunar Gateway with Lunar Lander have been deployed to their operational L_1 Lagrange point location. The Gateway will also provide a facility for in-space science missions and missions beyond the moon.

After the Gateway/Lunar Lander stack has completed its journey to the L_1 Lagrange point, an HPM is sent to the Gateway to be pre-positioned for the crew return-to-Earth flight. This first HPM is launched on a Shuttle-class launch vehicle. While the HPM is in LEO, it is fueled or topped off with liquid oxygen, liquid hydrogen and xenon delivered by a next generation, low-cost ELV or RLV. The SEP Stage is launched and autonomously rendezvous and docks with the HPM. The SEP Stage/HPM stack then begins a 270-day trip to the Lunar Gateway. During the journey the HPM supplies xenon to the SEP Stage while using zero-boil off systems to maintain and store the liquid hydrogen and liquid oxygen that will later be used to transfer the crew from the Lunar Gateway back to LEO. The SEP Stage/HPM stack arrives at the Lunar Gateway with almost all of the xenon propellant expended but a full load of hydrogen and oxygen in the HPM to be used for crew return propellant.

The lunar expedition crew is now transported to the Lunar Gateway utilizing a second HPM, CTM, and a CTV. A Shuttle-class launch vehicle performs a rendezvous with the ISS and berths the CTV to the station via an International Berthing & Docking Mechanism (IBDM) located on the nadir face of the ISS. The CTV is then configured and outfitted for the journey to the Lunar Gateway. The HPM for crew transport to the Lunar Gateway is launched to LEO and topped off with propellants. This HPM contains enough liquid oxygen and hydrogen to deliver the crew from LEO to the Lunar Gateway in less than four days. The HPM also carries enough xenon propellant so that the HPM can be returned from L_1 using a SEP Stage. The first CTM performs a rendezvous and docks with the HPM. The CTM then rendezvous and docks the CTM/HPM stack to the CTV on the ISS. The crew enters the CTV from the ISS and is now ready to begin the journey to the Lunar Gateway. Four days later, the CTM/HPM/CTV stack arrives and docks to the Lunar Gateway.

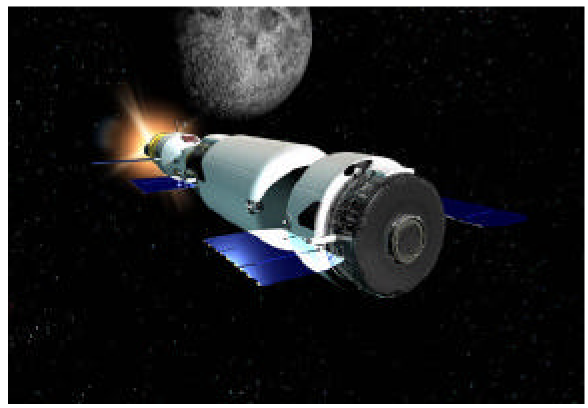

Figure 9. CTM/HPM/CTV Stack.

The crew and all elements required to perform a lunar excursion are now at the Gateway. Before the lunar excursion is performed, the CTM, SEP Stage and HPMs must be repositioned such that (1) the HPM with the full load of liquid hydrogen and liquid oxygen is connected to the CTV and CTM, and (2) the HPM with the full load of xenon propellant is attached to the SEP Stage. Once they have been checked out in this configuration, both stacks are ready for the return voyage to LEO. The lunar excursion can now be performed.

After the lunar excursion has been completed and the crew has returned to the Gateway, the return-to-Earth mission sequence can begin.

The crew enters the CTV from the Gateway and the CTM separates the CTM/HPM/CTV stack from the Gateway. The CTM then propels the HPM and crewed CTV back to LEO. The stack docks to the ISS where the crew will depart for Earth on a Shuttle flight. The CTV is refurbished on the ISS and the HPM and CTM are autonomously refueled in LEO for the next Gateway mission sortie.

Either prior to or shortly after the crew departs from the Gateway, the SEP Stage and xenon-loaded HPM leave the Gateway for the return to LEO. Once the SEP Stage/HPM stack is back in LEO, the HPM is refueled via the ELV-delivered propellant logistics carriers. The SEP Stage internal tank is also topped off with xenon. The SEP Stage arrays may need replacement at the ISS. At this point, all of the elements that were utilized for crew and supply transfer with the exception of the Lunar Lander have returned to LEO and are ready to support another mission.

OASIS Commercial Operations An on-orbit reusable propellant depot could perform a number of missions to support commercial and military orbital assets in the future. The HPM when combined with a propulsion module such as a CTM is envisioned to be used as an upper stage to augment the launch capability of a low cost RLV or ELV that would only provide access to LEO (altitude $\leq$ 400 km). One potential mission is the deployment of a satellite to its final orbital position. Figure 10 illustrates the deployment scenario. With HPMs paired with CTMs and pre-positioned in storage orbits, mission planners would select the HPM/CTM closest to the final orbit position of a payload for use on this mission. Prior to launching the satellite, one or more ELVs would launch LH_2 and LOX propellants into LEO. The HPM/CTM (or perhaps CTM only) would rendezvous and dock with the propellant delivery stage and transfer the propellants into the HPM. The satellite would then be launched on another ELV or RLV to LEO. The HPM/CTM would rendezvous and dock with the satellite and use CTM propulsion to move the combined stack to the final deployment orbit position and release the satellite. It may be possible to deliver more than one satellite per mission with the HPM/CTM maneuvering to release each satellite at the correct true anomaly. Following deployment, the HPM/CTM would perform the necessary engine burns to return to the parking orbit to await the next mission.

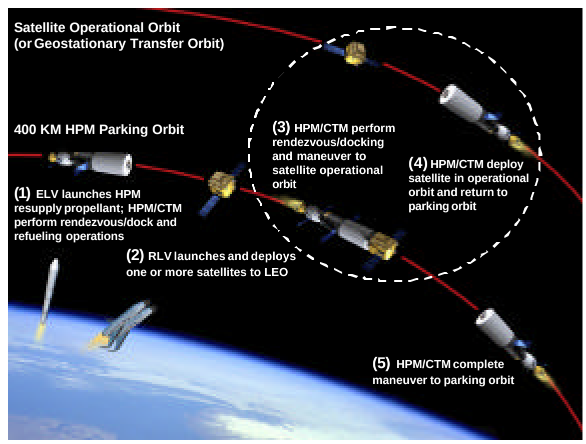

Figure 10. HPM Commercial Satellite Deploy Scenario.

Figure 10 illustrates a satellite delivery to a final orbit requiring no additional propellant usage for maneuvering by the satellite to complete the delivery. For satellites destined for orbits requiring velocity increments (ΔV's) greater than the velocity capability of the HPM/CTM, the system could be used to transfer the satellite(s) from LEO into a transfer orbit (e.g., geosynchronous transfer orbit (GTO)) as is commonly done by the present day launch systems. The scenario would be the same; however, the satellite would be required to carry a propulsion system such as an apogee kick motor with enough propellant to complete delivery to the final orbit position.

One advantage of a reusable propellant depot with autonomous operations capability is the opportunity to directly service satellites already in orbit. Servicing could extend their life beyond original design and delay the need to replace these expensive assets. Satellite lifetime is primarily governed by the depletion of station keeping propellant and, secondarily, by degradation of power-generating solar panel cells. The ability to refuel and refurbish satellites could significantly extend their useful lives. The capability of changing out components of healthy satellites with newer technology components could improve satellite performance without the cost of designing, manufacturing and launching entirely new spacecraft. While there are minor differences in the details of the refueling and refurbishing missions, they can generally be combined into a category of on-orbit servicing. Figure 11 illustrates a servicing mission scenario. Most of the steps in the mission sequence are the same as for the deployment scenario.

One form of on-orbit servicing for which the OASIS architecture is uniquely suited is refueling those satellites designed to use xenon propulsion systems for station keeping and maneuvering. Rather than using its supply of xenon to fuel a SEP Stage, an HPM/CTM stack could use the xenon supply to refuel one or more satellites nearing the end of their useful life due to propellant depletion. This mission would require that the HPM have the plumbing lines and valves to control the transfer of xenon to the satellite. For this to be a viable market, a good share of the satellite industry would need to adopt xenon propulsion systems and provide a common refueling port to accommodate the transfer of fuel.

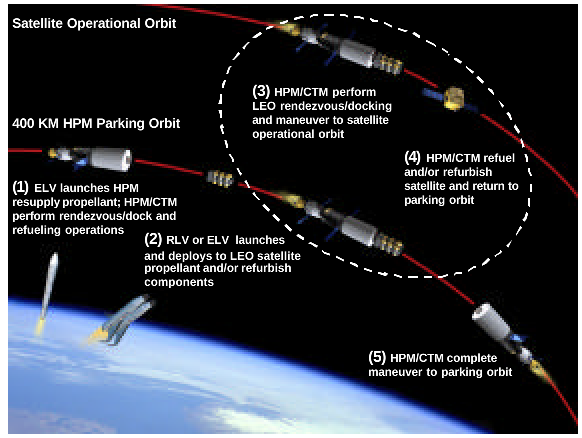

Figure 11. HPM Commercial Satellite Servicing Scenario.

The refurbishment mission would be conducted in the same manner; however, the HPM/CTM stack would require the capability of removing old components and installing the replacements. This may be accomplished by formation flying in close proximity to the satellite or by docking with the satellite. In either case, a tele-operated or autonomous robotic arm would be required to accomplish the mission. Hence, HPM subsystems in addition to those required for the exploration missions may need to be designed and developed to support the variety of potential commercial missions.

Additional commercial missions for which the HPM would be suited include rescue and subsequent retrieval or deployment in correct final or transfer orbits. Removal of older satellites into disposal orbits or possibly even self-destructive reentry orbits may be a possible commercial application for OASIS elements. Details of each of these scenarios would differ slightly from those discussed above. However, the major scenario steps would be similar in all of these missions.

TECHNOLOGY REQUIREMENTS

The advanced technologies necessary to make the OASIS architecture a reality, including technologies specifically applicable to the HPM, CTM, CTV, and SEP Stage, are described below:

- Zero boil-off cryogenic propellant storage system for the HPM providing up to 10 years of storage without boil-off.
- Extremely lightweight, integrated primary structure and micrometeoroid and orbital debris shield incorporating non-metallic hybrids to maximize radiation protection. This is required for all OASIS elements.
- 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. Required for the HPM, CTM, and CTV.
- Long-term autonomous spacecraft operations including rendezvous and docking, propellant transfer, deep-space navigation and communications, and vehicle health monitoring (miniaturized monitoring systems). Applicable for all OASIS elements.
- 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 propellant leakage
- Advanced materials such as graphitic foams and syntactic metal foams. Required for all OASIS elements.
- Long-life chemical and electric propulsion systems with high restart (greater then 50) capability, or systems with on-orbit replaceable and/or serviceable components.
- High thrust electric propulsion systems (greater than 10 N).
- Integrated flywheel energy storage system combining energy storage and attitude control functions.

These technologies needed to enable the OASIS elements require targeted research and development. With the proper funding levels, many of the technologies could be available within the next 15 years. Accelerated funding levels could make this timeline significantly shorter.

SUMMARY AND CONCLUSIONS

There are many challenges confronting humankind'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. Orbital Aggregation & Space Infrastructure Systems (referred to as OASIS) is a set of concepts that provide a common infrastructure for enabling NASA exploration and commercial space missions. The OASIS architecture maximizes modularity, reusability and commonality of elements across many missions and organizations. Mission concepts utilizing this architecture are predicated on the availability of a low-cost launch vehicle for delivery of propellant and re-supply logistics.

The technologies needed to enable the OASIS elements require targeted research and development. The key technology enablers are zero boil-off cryogenic propellant storage, cryogenic fluid transfer and high cycle reusable cryogenic engines. High efficiency solar cells and advances in electrical propulsion are also required. Lightweight multi-function structures and advanced composite propellant tanks also greatly contribute to the efficiency of the elements. Long-term autonomous spacecraft operations including rendezvous and docking and vehicle health monitoring are also necessary for OASIS elements to support both NASA and commercial missions.

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