SCENARIOS FOR IN-SPACE PROPELLANT DEPOTS IN AN AGE OF EXPLORATION AND DEVELOPMENT

UNDER CONTRACT TO
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHALL SPACE FLIGHT CENTER
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INTRODUCTION

Recent work on the technical parameters[1] and market potential[2] of in-space propellant depots has raised the question of the role such depots may play in future space exploration and development scenarios. There is a general understanding that a wide range of commercial and government missions could benefit from the existence of some type of propellant depots in Earth orbit or elsewhere, but exactly which missions would benefit, and in what ways, has not been studied in detail to date. The missions that could best utilize a propellant depot will determine what kind of depot should be developed and when it should be deployed.

This study's objectives were to identify and qualitatively explore the applicability of a propellant depot to as wide a choice of projected space activities as possible. The study focuses on two scenarios: a near-term scenario for missions likely to take place from the present through 2020, and a long-term scenario for missions likely to occur from 2021 through 2040. All commercial and government missions, such as commercial activities in Earth orbit, public space travel, military missions, and exploration of the Moon and other solar system bodies, are examined here. This study is not predicated on any particular depot design, orbital location, or fuel type; all missions that could use any kind of depot, regardless of location and choice of propellants, are included here.

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METHODOLOGY

The first stage of this study involved compiling a list of all government and commercial missions likely to fly in the timeframes of the two scenarios. For government missions, Futron used missions planned and proposed by NASA and the Department of Defense (DOD), as well as logical extensions of those missions deemed likely to occur during the two scenarios. For commercial missions, Futron used the Analysis of Space Concepts Enabled by New Transportation (ASCENT) study, an ongoing Futron market study of existing and emerging commercial space markets for NASA's Space Launch Initiative. During this research phase there was no attempt to include or exclude missions based on their perceived ability to utilize any type of in-space propellant depot. At the end of this research phase Futron had identified 66 mission architectures – 34 government and 32 commercial – for which to study the applicability of a depot. The complete list of mission types and associated architectures is provided in the Appendix.

[1] The Boeing Company, *Space Solar Power Platform Technologies for In-Space Propellant Depots, Final Report* (under contract to NASA, Contract # NAS8-99140, Mod 2, Task 3), November 14, 2000.
[2] Futron Corporation, *An Analysis of Potential Markets and their Fuel Requirements for an In-Space Propellant Depot* (under contract to NASA, Contract # NAS8-99134), September 10, 2001.

In order to judge how well each mission could use a propellant depot, Futron and NASA developed a scoring system. Each mission was rated from 0 to 10 based upon its need for a depot and its ability to use one. If a mission had requirements potentially addressable by a depot, it received one point. If the mission would be enhanced in some manner by a depot – by moving up the earliest possible date the mission could begin, by expanding the mission's capabilities, or by extending the lifetime of the mission – the mission received two additional points. If a depot was deemed critical to carrying out the mission, such that it would be unlikely the mission could be performed without the existence of a depot, then the mission received three additional points, for a grand total of six. In addition, each mission was assigned additional points based on how effectively it could use a depot. A mission received one point for each of the following that applied:

- A depot could provide more than one service, such as life support consumables, cryogens, etc.
- A depot could provide more than two services.
- If the depot could provide more than one service, those services require the same propellant.
- The mission could use a recurring depot role.

The scoring system was designed to split missions into three categories, as defined in Table 1. At one extreme, a mission with a score of zero would have no use for an in-space propellant depot, while, at the other extreme, a mission with a score of ten could not be performed without a depot. Scores intermediate of those endpoints are for missions that could make some use of a depot. A score of four, for example, indicates that a mission does not require a depot to perform its mission, but could use a depot to some degree if available; a mission with a score of seven would be difficult or impractical to carry out without a depot.

TABLE 1: MISSION SCORING CATEGORIES

Score	**Category**	**Description**
0-3	Depot not required	Mission does not require a depot nor could it effectively use one if available.
4-6	Depot enhances mission	Mission does not require a depot but its capabilities could be enhanced if one was available.
7-10	Depot enables mission	Mission either would be very difficult or impossible to carry out without a depot.

OVERVIEW OF RESULTS

A graphical summary of how the missions scored is provided in Figure 1, while the number of missions that fit into each of the three categories described in the previous section is listed in Table 2. The complete list of all 66 missions analyzed in this study and their scores is provided in the Appendix. Median scores of government and commercial mission types are shown in Figures 2 and 3, respectively.

FIGURE 1: DISTRIBUTION OF MISSION SCORES

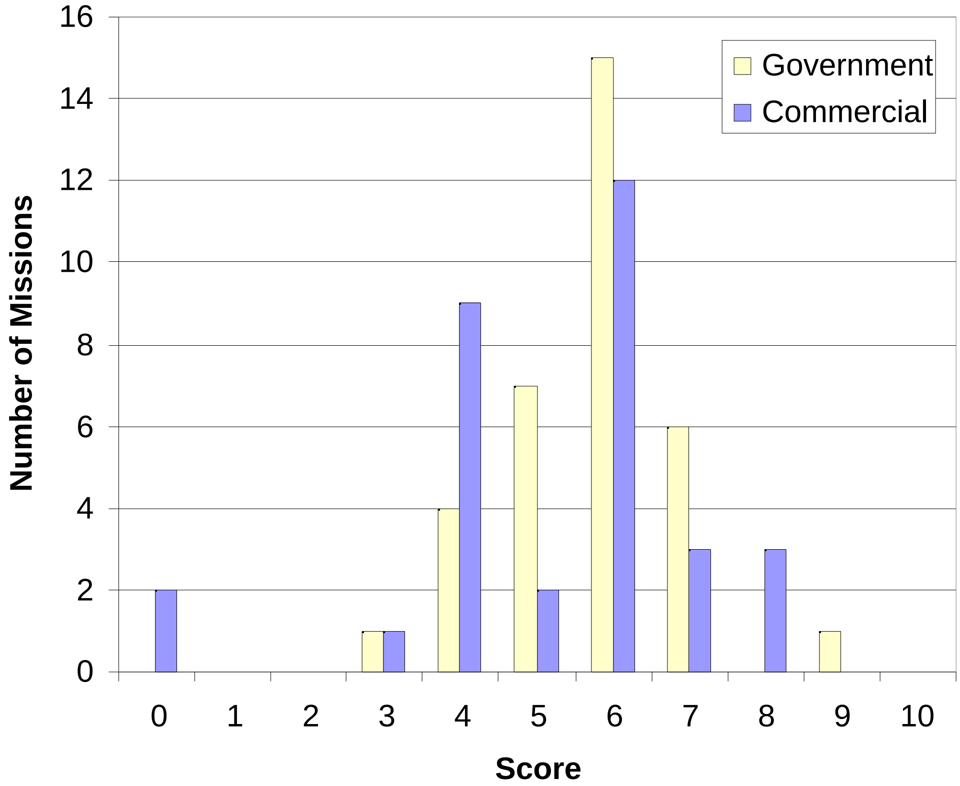


TABLE 2: MISSION SCORES BY CATEGORY

Score	Government	Commercial	Total
0-3	1	3	4
4-6	26	23	49
7-10	7	6	13

As shown in Figure 1, all but two of the missions studied – suborbital and short-duration public space travel – could make at least some use of an in-space propellant depot. In most cases the missions could make significant use of a depot. Note that there is a significant spike in the number of missions with a score of six: a total of 27, or 40 percent of all the missions studied. This score means that the mission could be significantly enhanced by making use of a depot, but does not require a depot to be successful. While these missions are not likely to drive the development and deployment of propellant depots, these results suggest that once such depots are available, there may be many additional missions that could take advantage of them.

FIGURE 2: MEDIAN SCORES FOR GOVERNMENT MISSION TYPES

Note: Most mission types considered several architectures. An individual architecture may have scored higher or lower than the median score for its group.

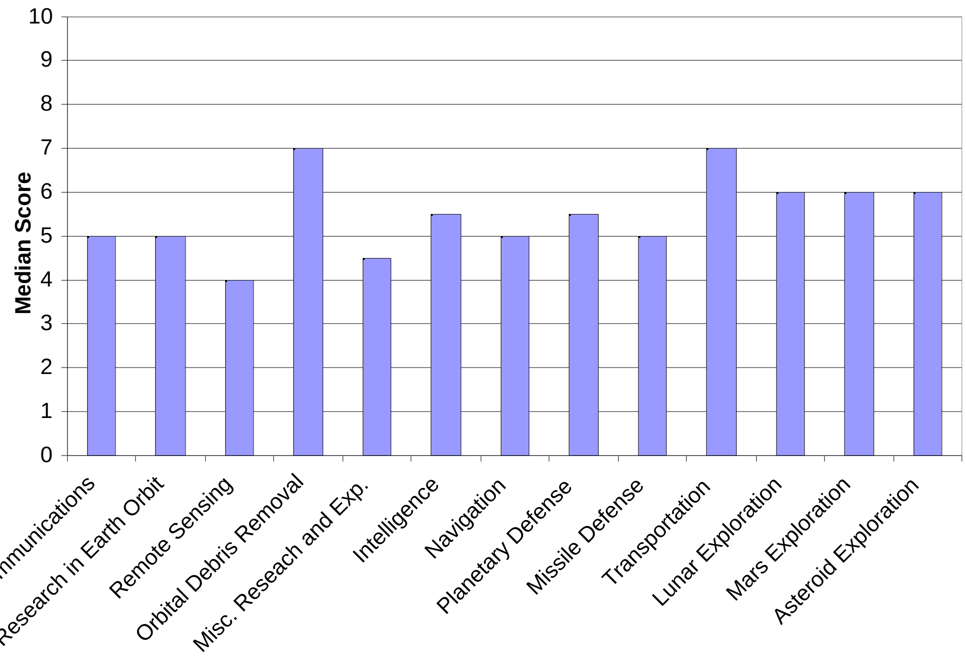
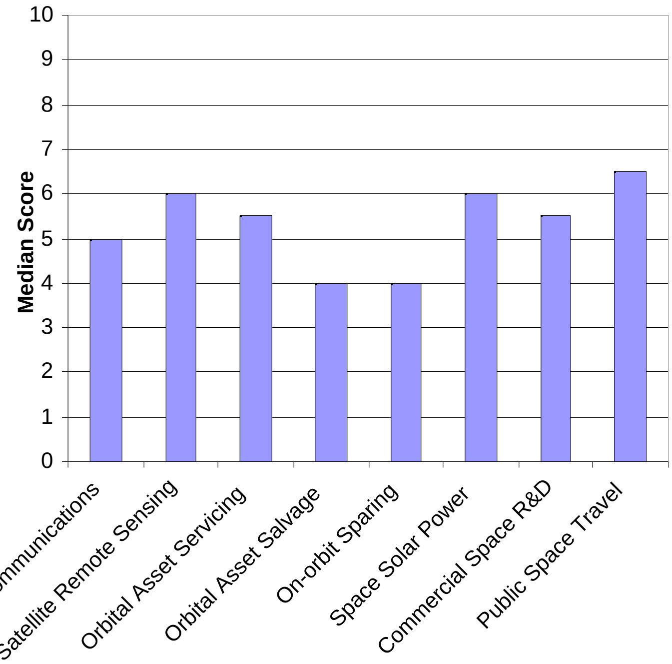


FIGURE 3: MEDIAN SCORES FOR COMMERCIAL MISSION TYPES

Note: Most mission types considered several architectures. An individual architecture may have scored higher or lower than the median score for its group.



This analysis found that those missions that scored the highest had at least one of two key characteristics responsible for their high scores. One characteristic is a mission design with high delta-V requirements. This can include missions beyond Earth, such as flights to the Moon, Mars, and asteroids, as well as missions within Earth orbit that require frequent orbit changes and/or reboosts to maintain orbit. In these cases, the availability of a depot to replenish propellants can reduce requirements for more expensive propellant resupply from Earth, extend mission lifetimes, and in some cases, even make a mission viable. The second characteristic responsible for high scores is the ability to find alternative uses for propellants. The most common alternative use is to use liquid oxygen (LOX) and liquid hydrogen (LH2) as life support consumables, providing oxygen and water for crewed missions. The ability of a propellant depot to provide additional services for a particular mission increases the importance of a depot to that mission and makes it more likely the mission would take advantage of a depot, if available.

The distribution of scores by scenario was also analyzed. The results, provided in Table 3, show only modest variation between the near-term scenario (2002 through 2020) and the long-term scenario (2021 through 2040). Government applications of a propellant depot are weighted more towards uses in the near-term scenario, while commercial uses are more common in the long-term scenario, particularly when considering the category of missions enhanced by, but not necessarily requiring, a depot. It should be noted that most missions assigned to the near-term scenario would also likely be used in the far-term scenario; for this analysis, the time frame during which a mission is first considered likely is used.

TABLE 3: MISSION SCORES BY SCENARIO

Score	2002-2020		2021-2040	
	Government	Commercial	Government	Commercial
0-3	1	3	0	0
4-6	20	9	6	14
7-10	4	2	3	4

SUMMARIES OF HIGHEST-RANKED MISSIONS

A total of 13 of the 66 missions studied in this report scored seven or higher, indicating that a propellant depot was essential to their success. The highest-ranking mission—a cislunar transport—scored a nine, while three public space travel missions – a space hotel, space entertainment platform, and transport to non-geosynchronous orbit (NGSO) space tourism destinations – each scored an eight. Because of similarities in some of the mission concepts, the 13 highest-ranking missions have been condensed into ten descriptions, provided below.

EARTH ORBIT RESEARCH AND OTHER APPLICATIONS

CREWED RESEARCH PLATFORM

A crewed research platform is a facility in low Earth orbit (LEO) or another non-geostationary orbit that supports crews performing research and related activities. A prime example of such a facility is the International Space Station (ISS). Government and commercial research platforms were considered separately in this study; both received the same score (seven) and are considered together here.

Although the ISS currently operates without using an in-space propellant depot, it does have significant propellant requirements in order to maintain its orbit and to occasionally maneuver to avoid orbital debris. Those requirements are currently met by Progress spacecraft and the Space Shuttle, but they could alternatively be served by a depot and associated orbital maneuvering vehicle (OMV). Other crewed research platforms would also likely have similar propellant requirements.

While the most likely propellant to be used for stationkeeping would be hydrazine or a similar monopropellant, the use of LH2 and LOX systems would provide additional advantages for a crewed facility. These propellants could provide water and oxygen for use in the station's life support systems, as well as for research and related needs. A depot could deliver the propellants to the station in the form of both water and LH2/LOX as required.

ORBITAL DEBRIS REMOVAL

An orbital debris removal mission would involve a robotic platform that would maneuver to identified debris objects and remove them from orbit. This could be accomplished by a number of methods, such as applying a change in velocity to the debris to cause it to deorbit, or stowing the debris on the platform for later processing.

To be effective, an orbital debris removal platform requires a high degree of maneuverability to allow it to move from orbit to orbit to rendezvous with debris objects. This requires, in turn, a great deal of propellant. Without the ability to refuel, the lifetime and overall effectiveness of such a platform would be severely limited. While additional propellant could be launched from the ground, the most efficient way to provide the debris removal platform with additional propellants would be through an in-space depot. That platform could use hydrazine or a similar monopropellant, although a high-specific-impulse propellant system, like LOX and LH2, could provide maneuverability advantages.

ORBITAL MANEUVERING VEHICLE / SPACE TUG

An OMV, or "space tug", is a robotic or crewed spacecraft that would ferry cargo, including other spacecraft, from one Earth orbit to another. An example of an OMV is a platform that latches onto a spacecraft in LEO or geosynchronous transfer orbit (GTO) and moves the spacecraft into its designed slot in geosynchronous Earth orbit (GEO), without any expenditure of propellant by the spacecraft itself. Commercial and government OMV missions were examined separately in this study; both scored identically (seven) and are considered here together.

As in the case of an orbital debris removal spacecraft, an OMV would require a high degree of maneuverability to transfer payloads from one orbit to another, making its ability to refuel critical to its ultimate success. The most efficient way to refuel an OMV would be through an in-space depot. In addition, the OMV itself could be used to transfer the depot to various orbits as needed, or serve as a tanker to transport propellants from the depot to various destinations. The OMV could use either low-I_{sp} (e.g., hydrazine) or high- I_{sp} (e.g., LOX-LH2) propellants as needed. Boeing and the US Air Force have studied a concept called the Solar Orbit Transfer Vehicle (SOTV)[3] that would use LH2 alone, heated to high temperatures by concentrated solar energy, as propellant. This system would provide even higher specific impulses (up to 800 seconds).

[3] Boeing Phantom Works. "Solar Orbit Transfer Vehicle," Available at: http://www.boeing.com/defense-space/space/propul/SOTV.html, accessed July 2002.

CREWED SERVICING OF NGSO ASSETS

This mission would feature a crewed spacecraft that travels to other spacecraft to perform routine servicing or emergency repairs. The vehicle would rendezvous with the spacecraft and either carry out the repairs at the site using the repair personnel and equipment on the vehicle, or bring the spacecraft to another platform for additional work and/or transport to Earth. This mission would be similar to the Hubble Space Telescope servicing missions that have been performed by the Space Shuttle, but in this case, performed by a dedicated vehicle based on a space station or other orbiting platform.

As with the orbital debris removal and OMV missions, servicing missions would require high maneuverability to change orbits and rendezvous with spacecraft. In addition, a crewed spacecraft would have life support requirements, including oxygen and water, which would need to be replenished. As with the other missions, the most efficient way to both refuel the spacecraft and replenish its other consumables would be through an in-space propellant depot. The use of high- I_{sp} propellants, like LOX and LH2, would be the most effective choice for this mission, as they would allow for the shortest transit times for the crews and also provide consumables for life support.

PUBLIC SPACE TRAVEL

SPACE HOTEL/ENTERTAINMENT PLATFORM

Space hotels and space entertainment platforms are two separate but related missions that could both take advantage of in-space propellant depots. A space hotel would be an orbiting crewed facility that would provide accommodations and activities for visiting non-professional space travelers. A space entertainment platform would be an enclosed volume, either permanently occupied or human-tended, that would provide space for orbital sports activities. A space entertainment platform could be part of a space hotel complex or it could be a separate facility. The two missions were treated separately in this study and both had identical scores (eight); they are grouped together here.

Both a space hotel and a space entertainment platform would have requirements similar to a crewed space research platform. Both would require propellant for stationkeeping and debris avoidance maneuvers. Depending on the choice of propellants, the depot could also supply water and oxygen for use in the facility’s life support systems.

TRAVEL TO NGSO DESTINATIONS

This mission would involve the use of a spacecraft that would transport non-professional space travelers from one destination in Earth orbit to another. For example, this spacecraft could carry passengers between a space hotel and a space entertainment platform. This mission is similar to an OMV, but requires a vehicle capable of carrying passengers.

This vehicle would require some maneuverability, since space tourist destinations may be scattered in various orbits. As with the OMV, this requires an ability to refuel, which would be done most efficiently through an in-space depot. A choice of high- I_{sp} propellants may be preferred here, in order to reduce the travel time between orbital destinations. In this case, the depot could also supply water and oxygen for use in the spacecraft's life-support systems.

LUNAR EXPLORATION

CISLUNAR TRANSPORT

A cislunar transport is a spacecraft designed to carry cargo and/or passengers between low Earth orbit to the vicinity of the Moon, such as lunar orbit or the Earth-Moon L1 Lagrange point. A similar system could also be used to provide transport to other destinations in cislunar space, such as the Earth-Moon L4 and L5 points or even the Earth-Sun L1 and L2 points, although the primary use of such a transport in the timeline of the scenarios considered here is likely to be to the vicinity of the Moon.

One example of this mission design is the proposed Hybrid Propellant Module (HPM),[4] a module that would carry both chemical (LOX-LH2) and solar electric (xenon) propellants that would be used as part of a system to ferry cargo and passengers between LEO and the Earth-Moon L1 point. Chemical propulsion, with its high I_{sp}, would be used for time-critical transits, such as crewed flights, while the low- I_{sp} solar electric system would be used for transfers that are less time-critical, saving chemical propellant. Although the HPM design would require less chemical propellant than an all-chemical system, it would still require regular resupply of both chemical and solar electric propellants, and an in-space depot would be most efficient way to do this. In addition, the LOX-LH2 chemical propellants can also be used to provide life support consumables (water and oxygen) and radiation shielding during the crewed stages of the transport's flight.

LUNAR OBSERVATORY

A lunar observatory would be a facility on the surface of the moon, either crewed or robotic, designed to carry out astronomical observations at optical, radio, and other electromagnetic wavelengths. Unlike other missions, the observatory would be based on the surface of a celestial body – the Moon – and thus would not need propellant for stationkeeping or other maneuvers. However, such a facility would need propellant for landers that transport personnel, equipment, and other supplies to and from the facility. If the facility is crewed, it would also require life support consumables like water and oxygen that could also be supplied by a propellant depot. In addition, the facility may require cryogens to cool scientific instruments to operating temperatures; these could also be supplied by a propellant depot, depending on the choice of propellants.

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[4] Mankins, John C. and Manzanek, Daniel D. "The Hybrid Propellant Module (HPM): A New Concept for Space Transfer in the Earth's Neighborhood and Beyond." IAF Paper IAF-01-V.3.03, presented at the 52nd International Astronautical Federation Congress, Toulouse, France, 2001.

OTHER PLANETARY EXPLORATION

EARTH-MARS TRANSFER SPACECRAFT

An Earth-Mars transfer spacecraft would ferry crews and supplies between the Earth and Mars—specifically, from Earth orbit to Mars orbit and back again. One mission design would require the spacecraft to use its engines to exit Earth orbit on a trajectory towards Mars and again to enter Mars orbit; the process would be reversed for the return trip. Alternatively, a "cycler" spacecraft remain in a transfer orbit between the two planets; shuttles would then travel to the spacecraft when it is in the vicinity of each planet to exchange crews and cargos.

Under the first scenario, the spacecraft would have significant propellant requirements in order to achieve the delta-V needed to enter and leave the orbit of each planet. This would most likely require a propellant depot in orbit around each planet. The spacecraft may use high- I_{sp} chemical propellants (like LOX and LH2), or LH2 as a working fluid for a plasma propulsion system like VASIMR.[5] Under the second scenario, the spacecraft's propellant requirements would be significantly less, since the spacecraft would remain in a stable transfer orbit with few maneuvers required. However, in both cases the spacecraft would need consumables like water and oxygen for use in life support and radiation shielding that could be supplied from an orbiting depot, depending on the choice of propellants.

CREWED ASTEROID EXPLORATION

Future exploration of asteroids and other small solar system bodies may eventually involve sending crewed spacecraft to them. These spacecraft will be required to fly trajectories from Earth to the asteroid, go into orbit and/or land on the asteroid, and return to Earth. Depending on the destination of the mission and that asteroid's orbit relative to Earth, the spacecraft may require less propellant than a mission to the Moon (because of the reduced delta-V requirements for landing on and taking off from the asteroid), but may require extra life-support consumables for a long-duration mission.

Like crewed missions to the Moon and Mars, an asteroid exploration mission would have significant propellant requirements both for transportation and, depending on the choice of propellants, life support consumables and radiation shielding. A propellant depot in Earth orbit, or at another location in cislunar space, would be required to provide the spacecraft with the propellant it needs prior to departure. Since it is unlikely propellant depots will be established at each asteroid, the Earth orbit/cislunar space depot would be required to provide the spacecraft will all the propellant it would need for its mission. This requirement may be mitigated by the existence of water-ice deposits in near-Earth asteroids.

[5] Chang-Diaz, Franklin R. et al. "The Development of the VASIMR Engine." International Conference on Electromagnetics in Advanced Applications, Torino, Italy, 1999. Available at: http://spaceflight.nasa.gov/mars/reference/aspl/develop.pdf, accessed July 2002.

CONCLUSIONS

The great majority of commercial and government missions planned through 2040 would be able to use in-space propellant depots to enhance their missions. This study identified 13 missions that are enabled by the existence of an appropriate depot, meaning that these missions would be difficult, if not impossible, to carry out without the existence of a depot or some other kind of in-space refueling option. These missions are the ones most likely to drive the development of a depot, although the study shows that there are many more missions that do not rely on a depot, but could still benefit from one.

While this study did not put any restrictions on the type or location of a depot, the missions that would benefit most from a depot can help determine the most economical and practical depot configuration. Since all the missions examined here (except for a lunar observatory) would either be based in or staged from Earth orbit, the best location for the first depot would be in LEO. Space tugs – themselves major customers of such a depot – could either transport propellant to destinations in other Earth orbits, or move the entire depot to the desired orbit, as necessary. Most of the missions would be able to take advantage of a propellant mix of LOX and LH2, delivered to orbit in either in cryogenic form or as water to be cracked at the depot itself or provided as a straight consumable to crewed spacecraft. This propellant mix has the advantage of not only providing a high- I_{sp} thrust needed for maneuvers beyond station keeping and simple orbital plane changes, it has alternative uses such as oxygen and water for life support.

This study can serve as the basis for more detailed analyses of the requirements for in-space propellant depots. Future work should focus on creating quantitative requirements for such depots, including orbital location, size, and propellant mix. Cost information is also important for appropriate cost/benefit analyses. The completion of the ASCENT study in January 2003 will provide detailed quantitative data on commercial market requirements for the next 20 years; a ten-year extension of the ASCENT forecast would provide this data for a portion of the long-term scenario as well. Quantitative forecasts of the addressable depot market should be contrasted, side-by-side, with assessments of the costs and benefits of alternative depot scenarios.

APPENDIX: COMPLETE LISTING OF MISSIONS AND SCORES

GOVERNMENT MISSIONS

Mission	Architecture	Scenario (1=2002-2020, 2=2021-2040)	Mission Elements	Score
Communications	Earth orbit (GEO) communications	1,2	Robotic spacecraft in GEO designed to facilitate communications among other orbiting spacecraft, and between spacecraft and ground stations.	**4**
	Earth orbit (NGSO) communications	1,2	Robotic spacecraft in NGSO designed to facilitate communications among other orbiting spacecraft, and between spacecraft and ground stations.	**4**
	Lunar communications	1,2	Satellites orbiting in Lunar orbits to provide telecommunications relay services to surface facilities or orbiting spacecraft.	**6**
	Mars communications	1,2	Satellites orbiting in Martian orbits to provide telecommunications relay services to surface facilities or orbiting satellites.	**6**
Research in Earth Orbit	Crewed research platform	1	Multiple modules in LEO designed to support several people conducting research and other activities. The station would be inhabited throughout its lifetime (15+ years) with crew transfers taking place every 3-4 months.	**7**
	Extended duration orbiter missions (shuttle and follow-ons)	1	A crewed orbiter spacecraft that would remain in orbit for an extended mission (60-90 days) carrying several people performing scientific research and other activities to supplement or replace work planned for space stations.	**5**
	NGSO science spacecraft	1,2	Robotic spacecraft in NGSO designed to study astronomical, space science, and other phenomena.	**5**
Remote Sensing	Research spacecraft	1,2	Robotic spacecraft in GEO or NGSO designed to carry out observations of the Earth's land masses, oceans, and/or atmosphere for scientific research.	**4**
	Meteorological spacecraft	1,2	Robotic spacecraft in polar or GEO orbits designed to carry out observations of weather patterns and conditions.	**4**
Orbital Debris Removal	Debris removal spacecraft	1,2	Robotic spacecraft in LEO or other orbits tasked to identify and remove potentially harmful orbital debris by collecting, vaporizing, or deorbiting the debris.	**7**
Miscellaneous Reseach and Exploration	Space sciences spacecraft in L1/L2	1,2	Robotic spacecraft in the Earth-Sun L1 and L2 Lagrangian points engaged in observations of the Earth. Sun, and astronomical phenomena.	**6**
	Outer solar system missions	1,2	Robotic missions, including flybys, orbiters, and landers, to destinations in the solar system beyond the asteroid belt.	**3**

Intelligence	Reconnaissance spacecraft	1,2	Vehicle with operational range extending from Earth's surface to GEO capable of providing intelligence across the electromagnetic spectrum.	**6**
	Crewed LEO military installation	2	Pre-fabricated modular LEO space station or LEO space station built in space for purposes of servicing military vehicles and payloads, and conducting Earth observations.	**5**
Navigation	Planetary navigation and timing systems	1,2	Orbital spacecraft systems designed to provide extremely precise navigation and timing services to personnel and equipment on the Earth or in orbit.	**5**
Planetary Defense	NEO search system	1,2	Constellation of spacecraft in Earth orbit or near-Earth space that would search for and track near-Earth objects and assess any threats these objects may pose to the Earth.	**6**
	Earth orbital NEO defense system	2	Constellation of satellites and other platforms capable of detecting, identifying, tracking, and deflecting near-Earth objects (NEOs) that could pose a collision threat to the Earth.	**5**
Missile Defense	Earth orbital missile defense system	1,2	Constellation of satellites and other platforms capable of detecting, identifying, tracking, and destroying missiles.	**5**
Transportation	Orbital maneuvering vehicle (OMV)	1,2	Robotic vehicle used to transfer spacecraft from one Earth orbit to another (also known as a "space tug").	**7**
Lunar Exploration	Cislunar transport	1,2	Robotic and/or crewed spacecraft designed to ferry crews, equipment, supplies, etc. from Earth orbit to lunar orbit or the Earth-Moon L1/L2 Lagrangian points.	**9**
	Lunar orbiters	1,2	Robotic and/or crewed spacecraft in lunar orbit designed to carry out scientific and other research, as well as support for operations on the lunar surface.	**6**
	Lunar landers	1,2	Robotic and/or crewed spacecraft that travel between the lunar surface and lunar orbit and/or the Earth-Moon L1 point carrying crews, supplies, experimental/research payloads, etc. Such spacecraft may also be robotic spacecraft launched directly from the Earth to the lunar surface.	**6**
	Lunar bases	2	Crewed facilities on the lunar surface engaged in scientific study of the Moon and utilization of its resources.	**6**
	Lunar observatories	2	Robotic and/or crewed facilities on the lunar surface primarily engaged in astronomical observations at optical, radio, and other electromagnetic wavelengths.	**7**
	Lunar mining activities	2	Robotic and/or crewed facilities on the lunar surface designed to extract resources from the lunar surface and interior for use by other lunar stations or facilities beyond the Moon.	**6**
Mars Exploration	Mars orbiters	1,2	Robotic and/or crewed spacecraft in martian orbit designed to carry out scientific observations as well as support activities on the martian surface.	**6**

	Mars landers	1,2	Robotic and crewed spacecraft that are designed to ferry crews, supplies, etc. between the martian surface and orbit. Can also include robotic spacecraft traveling directly from Earth to the martian surface.	**6**
	Mars sample return missions	1,2	Robotic spacecraft launched from Earth to land on Mars, collect martian rock and soil samples, and launch them from the surface either directly to Earth, or into martian orbit to be collected by another spacecraft for return to Earth.	**5**
	Earth-Mars transport ("cycler") spacecraft	2	Crewed spacecraft that fly in a solar transfer orbit between Earth and Mars, allowing them to ferry crews, supplies, etc. between the two planets.	**7**
	Mars bases	2	Crewed facilities on the martian surface engaged in scientific research. An initial base would support 4-6 people, with expansion possible with future missions.	**6**
Asteroid Exploration	Asteroid/comet orbiters	1,2	One or more robotic spacecraft that would enter orbit around an asteroid(s) and study its composition and structure, with possible emphasis on the asteroid's suitability for future mining operations.	**6**
	Asteroid/comet landers	1,2	One or more robotic spacecraft designed to land on the surface of an asteroid to carry out scientific research and/or mining suitability studies.	**6**
	Crewed asteroid exploration	2	A crewed platform that serves as transport and base for asteroid explorers.	**7**
	Asteroid bases/mining operations	2	Robotic and/or crewed facilities on the surface of an asteroid(s) designed for scientific studies of the asteroid and/or extraction of resources for use elsewhere in the solar system.	**6**

COMMERCIAL MISSIONS

Architecture	Mission	Scenario (1=2002-2020, 2=2021-2040)	Mission Elements	Score
Communications	NGSO Earth communications	1,2	Satellites orbiting in NGSO orbits to provide telecommunication services to users on Earth. Life of 10 years.	**4**
	GEO Earth communications	1,2	Satellites orbiting in GEO orbits to provide telecommunication relay. Life of 15 years.	**6**
Satellite Remote Sensing	Earth Remote Sensing from NGSO orbit	1,2	Satellites orbiting in NGSO orbits to collect remote sensing data for Earth. Life of 10 years.	**6**
	Earth Remote Sensing from GEO orbit	1,2	Satellites orbiting in GEO orbits to collect remote sensing data for Earth. Life of 10 years.	**6**
	Mars Remote Sensing	2	Satellites orbiting around Mars to collect remote sensing data of Mars.	**6**

	Lunar Remote Sensing	1	Satellites orbiting around the Moon to collect remote sensing data of the Moon.	**6**
Orbital Asset Servicing	Uncrewed servicing of Earth-orbiting assets	1,2	Uncrewed platform or satellite that approaches and services GEO and NGSO satellites and platforms. Temporary installation.	**4**
	Uncrewed servicing of ExtraGEO assets	2	Uncrewed platform or satellite that approaches and services NGSO satellites and platforms outside of the Earth’s orbit.	**4**
	Crewed servicing of NGSO assets	2	Crewed platform or satellite that approaches and services NGSO satellites and platforms.	**7**
	Space tug	1,2	Robotic vehicle used to transfer spacecraft from one Earth orbit to another.	**7**
Orbital Asset Salvage	Return of GEO asset	2	Uncrewed platform that would rendezvous with a defunct spacecraft in GEO and either restore it or transfer it to another orbit or the Earth.	**4**
	Return of NGSO asset	2	Uncrewed platform that would rendezvous with a defunct spacecraft in NGSO and either restore it or transfer it to another orbit or the Earth.	**4**
	Return of ExtraGEO assets	2	Uncrewed platform that would rendezvous with a defunct spacecraft beyond the Earth and either restore it or transfer it to Earth orbit or the Earth.	**4**
On-orbit Sparing	Sparing of NGSO assets	1,2	A NGSO asset that is in orbit for the purpose of backing up other NGSO assets. Life of 10 years.	**4**
	Sparing of GEO assets	1,2	A GEO asset that is in orbit for the purpose of backing up other GEO assets. Life of 15 years.	**4**
	Sparing of Extra GEO assets	2	An asset that is in an orbit beyond Earth for the purpose of backing up similar assets. Life of 15 years.	**4**
Space Solar Power	Beaming to NGSO assets	2	A satellite in GEO orbit that collects solar power and beams that power to satellites and platforms in NGSO orbits.	**6**
	Beaming to GEO assets	2	A satellite in GEO orbit that collects solar power and beams that power to other satellites and platforms in GEO orbits.	**6**
	Beaming to Extra GEO assets	2	A satellite in GEO orbit that collects solar power and then beams that power in laser or microwave form to satellites and platforms beyond Earth orbit.	**6**
	Beaming to assets orbiting other planets.	2	A satellite in GEO orbit around a planet that collects solar power and then beams that power in laser or microwave form to satellites and platforms also orbiting that planet.	**6**
	Terrestrial power usage (Earth)	2	A satellite in GEO orbit that collects solar power and beams that power to a large antenna on the Earth’s surface.	**6**
	Terrestrial power usage (Moon)	2	A satellite in GSO orbit around the Moon which collects solar power and beams that power to a large antenna on the Lunar surface.	**6**
Commercial Space Research and Development	Uncrewed NGSO platform	1,2	An uncrewed platform in NGSO orbit used for a variety of research and development purposes.	**5**

	Crewed NGSO platform	1,2	A crewed platform in NGSO orbit used for a variety of research and development purposes.	**7**
	Uncrewed GEO platform	1,2	An uncrewed platform in GEO orbit used for a variety of research and development purposes.	**3**
	Uncrewed Extra GEO platform	2	An uncrewed platform beyond Earth orbit used for a variety of research and development purposes.	**6**
Public Space Travel	Suborbital tourist flights	1,2	A spacecraft carrying paying passengers flying a suborbital trajectory from the Earth's surface.	**0**
	Short-duration orbital flights	1,2	A spacecraft carrying paying passengers flying from the Earth's surface into low Earth orbit and remaining there for no more than one day.	**0**
	Medium-duration orbital flights	2	A spacecraft carrying paying passengers flying from the Earth's surface into low Earth orbit and remaining there for one to two weeks, similar to space shuttle missions.	**5**
	Crewed NGSO space entertainment platform	2	A crewed platform in NGSO orbit to support athletic events.	**8**
	Crewed NGSO space hotel	2	A crewed platform in NGSO orbit that serves as a hotel and resort facility for space travelers.	**8**
	Travel to NGSO destinations	2	A crewed platform that moves between NGSO destinations.	**8**