SPACE RESOURCE REQUIREMENTS FOR FUTURE IN-SPACE PROPELLANT PRODUCTION DEPOTS

David Smitherman, NASA Marshall Space Flight Center
John Fikes, NASA Marshall Space Flight Center
Stephanie Roy, Futron Corporation
Mark W. Henley, The Boeing Company
Seth D. Potter, The Boeing Company

Space Resources Utilization Roundtable III
October 24–26, 2001
Colorado School of Mines, Golden Colorado

SPACE RESOURCE REQUIREMENTS FOR FUTURE IN-SPACE PROPELLANT PRODUCTION DEPOTS

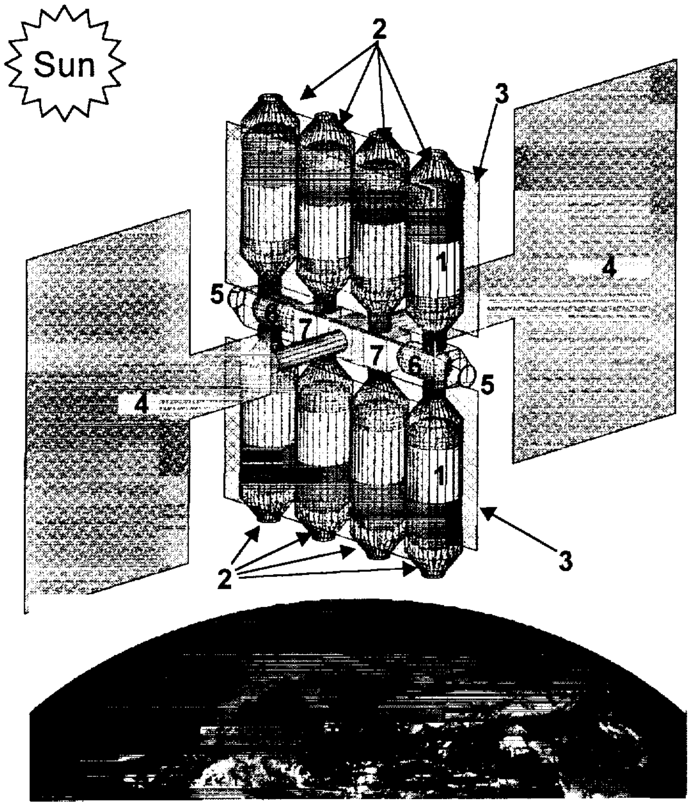
David Smitherman, NASA Marashall Space Flight Center
John Fikes, NASA Marshall Space Flight Center
Stephanie Roy, Futron Corporation
Seth D. Potter, The Boeing Company
Mark W. Henley, The Boeing Company

Abstract

In 2000 and 2001 studies were conducted at the NASA Marshall Space Flight Center on the technical requirements and commercial potential for propellant production depots in low-Earth-orbit (LEO) to support future commercial, NASA, and other Agency missions. Results indicate that propellant production depots appear to be technically feasible given continued technology development, and there is a substantial growing market that depots could support. Systems studies showed that the most expensive part of transferring payloads to geo-synchronous-orbit (GEO) is the fuel. A cryogenic propellant production and storage depot stationed in LEO could lower the cost of missions to GEO and beyond. Propellant production separates water into hydrogen and oxygen through electrolysis. This process utilizes large amounts of power, therefore a depot derived from advanced space solar power technology was defined. Results indicate that in the coming decades there could be a significant demand for water-based propellants from Earth, moon, or asteroid resources if in-space transfer vehicles (upper stages) transitioned to reusable systems using water based propellants. This type of strategic planning move could create a substantial commercial market for space resources development, and ultimately lead toward significant commercial infrastructure development within the Earth-Moon system.

The reference propellant production depot is deployed in a 400 km circular equatorial orbit. It receives tanks of water launched into a lower orbit from Earth (by a future gun launch or reusable launch vehicle), converts the water to liquid hydrogen and oxygen, and stores up to 500 metric tons of cryogenic propellants. For the purposes of space resource utilization, the water could possibly come from the moon or asteroids. Orbital maneuvering vehicles transfer the Earth-launched tanks from the lower orbit to the depot orbit. The propellant stored in the depot can support transportation from low Earth orbit to geostationary Earth orbit, the Moon, LaGrange points, Mars, etc. The propellant tanks on the depot are modified versions of those used in the Delta IV-Heavy launch vehicle. The tanks are configured in an in-line, gravity-gradient configuration to minimize drag and settle the propellant.

Figures 1 and 2 depict the referenced depot based on an Abacus configuration with large rotating arrays that track the sun and body mounted radiators covering large propellant tanks in a gravity gradient stabilized configuration. The tanks are sized to hold 500 metric tons of Liquid Oxygen (LOX) and Liquid Hydrogen (LH_2). In the scenario under study, water was delivered from Earth to docking ports forward and aft by projectiles or transfer vehicles. Electrolysis units in the center convert the water to LOX and LH2 for storage in eight large tank sets. Docking ports at the ends of these tank sets feed transfer vehicles for refueling or propellant transfer to other spacecraft.



1. LOX/LH2 Storage Tanks

2. Transfer Vehicle Docking Ports

3. Radiators

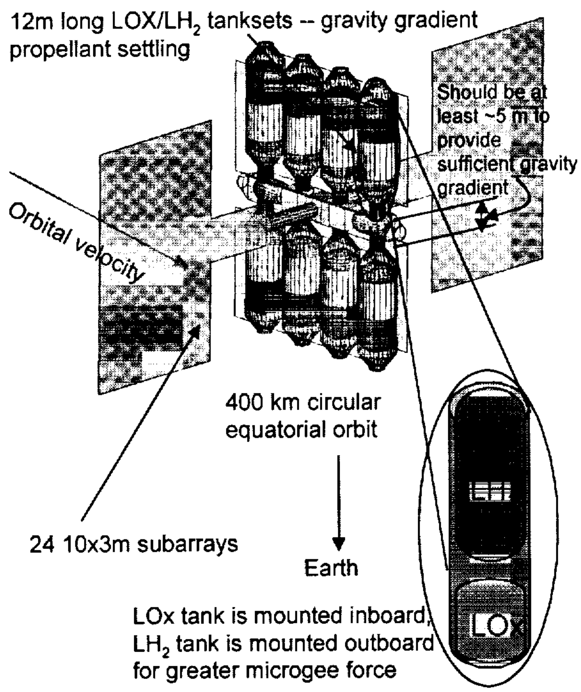
4. Solar Arrays

5. Water Docking Port

6. Water Storage Tanks

7. Electrolysis System

Figure 1. The Propellant Production Depot design includes seven key subsystems.



•ENTECH Stretched Lens Array (SLA's)
- Sized for 706kWe (635kWe delivered to bus)
- Inflatable abacus structure

•Power Management & Distribution (PMAD)
- 150V
- No converters at the arrays
- Two power conducting slip rings

•8 Delta IV Heavy-class tanksets
- 500 MT LOX & LH_2 per year
- Stoichiometric 8:1 mixture ratio

•Composite truss structure

•Robotics including infrastructure

•Stationkeeping & attitude control
- SEP 0.5N thrusters
- 50kWe Hall thrusters
- CMGs
- Attitude sensors
- Krypton stationkeeping propellant for 10 years

Figure 2. System Design Features of the Propellant Production Depot

The propellant production depot is complex, requiring significant advances in technology, but it avoids the large volume and safety issues related to containment of cryogenic propellants during launch. Water, in the form of liquid or ice, takes up one third of the volume that would be needed to contain the same mass of liquid hydrogen and oxygen. Cryogenic propellants are hazardous; hydrogen is extremely volatile and flammable, and liquid oxygen is a very powerful chemical oxidizer. Water, in contrast, is chemically inert. As an incompressible liquid, or as solid ice, water can also sustain high payload accelerations during launch. Future, high velocity projectile launch systems could potentially accelerate capsules of water, at several hundred g, to reach orbital velocity. Repeated launches of such a system could potentially transport large masses of water into orbit at a much lower cost than conventional space transportation systems.

Propellant quantity requirements were determined by propellant depot mission requirements. Prospective depot-supported missions are illustrated below in Figure 3. The depot refuels Orbital Maneuvering Vehicles (OMVs) for maneuvers in LEO, such as satellite and payload transfers, satellite servicing and orbital debris removal. The Depot also refuels Orbital Transfer Vehicles (OTVs) for transfer of payloads between LEO and more distant orbits, such as commercial and Government missions to GEO, science and exploration missions to the moon, and large telescope delivery to the Earth/Sun L2 LaGrange point.

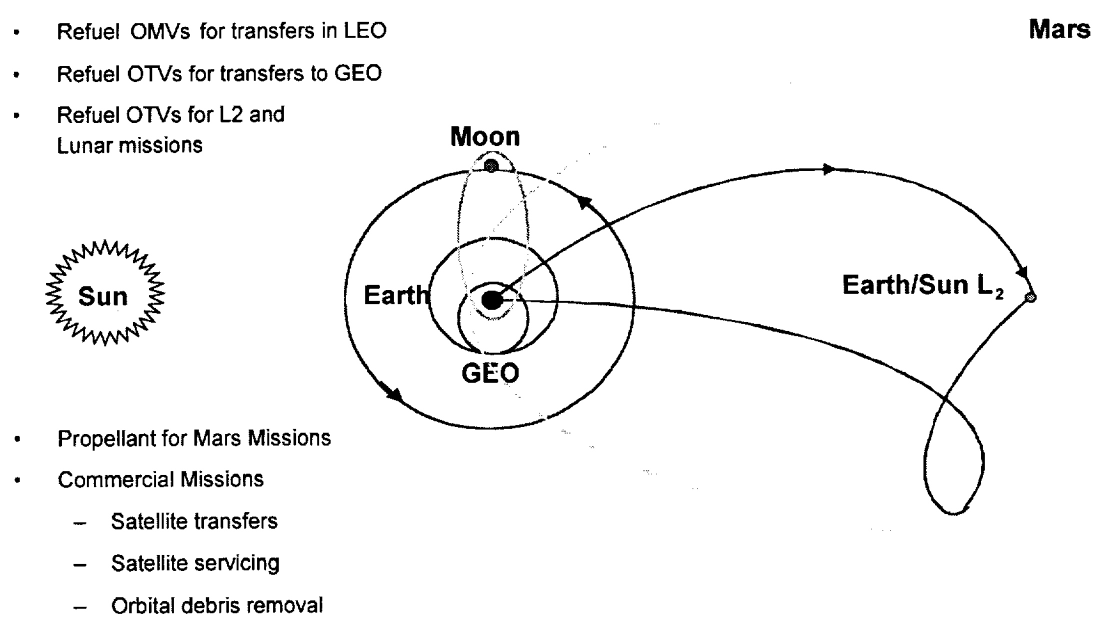


Figure 3. Potential mission scenarios that could be supported by propellant production depots

Depot propellant will also be required to support Mars missions, the most demanding of which is an all-propulsive (Abundant Chemical Propulsion Stage) mission, expected to require roughly 1,000,000 kg of propellant. While this enormous quantity may be reduced in alternate Mars mission scenarios, this requirement was considered in the sizing of this propellant production depot. As the Mars Hohmann Transfer departure window occurs every 2.2 years, approximately 450,000 kg of cryogenic propellant would need to be produced each year to support this mission. For our purposes, the round number of 500,000 kg was established as a requirement for propellant production per year. Interestingly, it was later found that Orbital Transfer Vehicles (OTV) utilized in a LEO to GEO satellite transfer market would require a depot of similar capacity. In addition, the propellant production depot could serve other future NASA and commercial needs:

- The production concept follows Science exploration goals for "following the water". Finding water in the solar system means there is a chance at finding life and sustaining human life. Development of such depot technology will enable sustainable human missions at any location where water can be found, (i.e., Moon, Mars, Asteroids, Europa, etc.).
- This baseline concept is for a cryogen production facility in low-Earth-orbit designed to supply human, robotic, and commercial missions with liquid hydrogen (LH2), and liquid oxygen (LOX) for high thrust chemical engines, LH2 for solar thermal propulsion, and excess LOX for human habitation at other stations.
- Production capabilities would enable new commercial markets for reusable high-energy upper stages, satellite services, and water and oxygen for ongoing human operations.
- Using water as the propellant of choice would create a demand for water on orbit that could eventually stimulate a space resource market at the moon and near earth asteroids.

Propellant launch system analyses included options to send a payload from Earth into a low altitude orbit, and an Orbital Maneuvering Vehicle (OMV) to carry the launch system's payload from an initial orbit to the Depot. A variety of water delivery methods are possible depending on the time frame and technology development level for the various systems. For the Propellant Production Depot, water delivery systems could include expendable launch vehicles, reusable launch vehicles (RLV), and gun launch methods. For the purposes of space resources development, very advanced systems could draw on potential water resources identified at the moon and asteroids. The following sections describe the market potential for water on orbit that could be utilized in the propellant production depot.

Market Study Parameters

This study consisted of an initial canvassing of potential markets for a propellant depot, a systematic evaluation of candidate markets for technical feasibility, and a quantitative fuel requirements analysis for surviving markets. Markets surviving the vetting process and meriting quantitative assessment for the propellant depot include:

- LEO to GEO transfer for both government and commercial markets
- Reboost for emerging markets

Large fuel requirements for satellite transfer from LEO to GEO make this market perhaps the most likely commercial user of a propellant depot. This market is characterized by the delivery of a satellite to the Depot orbit and the ferrying of the satellite to GEO by an orbital transfer vehicle (OTV). Moreover, the multi-module nature of emerging market platforms, along with their likely low dependence upon precision orbit maintenance (unlike commercial communications satellites) make periodic reboost by a visiting orbital maneuvering vehicle (OMV) a viable technical option for these assets. In order to determine the propellant required for each of these markets, a 20-year demand forecast was made of the orbital assets, ΔV required to carry out the indicated maneuvers was calculated, and then total propellant required given reference technical specifications of the propellant, OTV, and OMV was determined.

Commercial Geo Telecommunications Forecast Methodology

A demand-based forecast of commercial GEO telecommunications satellites was prepared which included a country-by-country analysis of the underlying demand for telecommunications satellites, the ability of the country to afford such services, and the competitive position of the satellite industry to provide such services. This analysis relies on Futron's 2000 Annual Commercial GEO Forecast, extended through 2020, (see Bibliography).

Government GEO Forecast Methodology

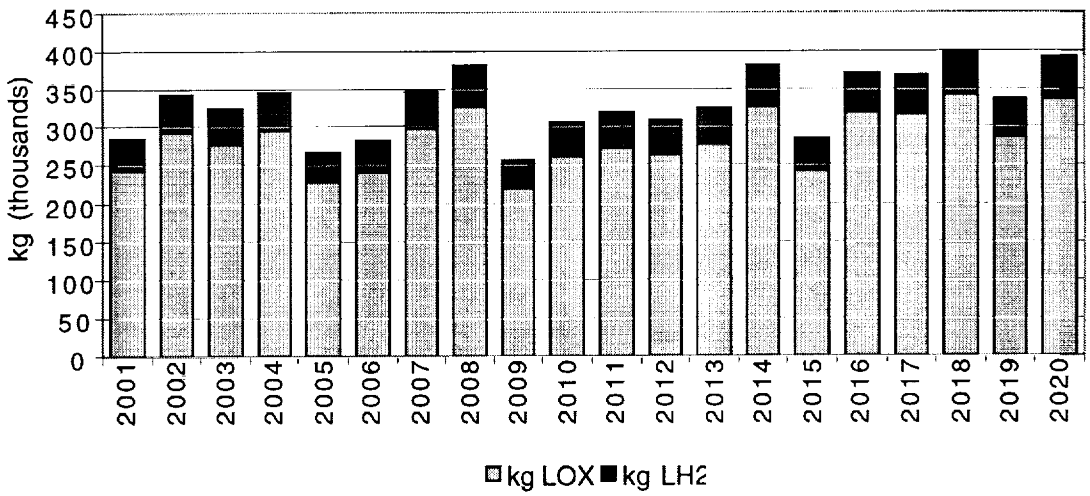
In addition to a commercial satellite forecast, Futron also uses a proprietary methodology for forecasting government satellites. Unlike commercial satellites, government missions are not market driven; in order to develop an accurate forecast, Futron researches and analyzes past trends and future plans of government space programs worldwide. The basis of the U.S. government forecast is the National Launch Forecast from the United States Air Force. This document is regularly updated and contains every launch and payload expected by the United States for the next 10 years. Futron projected these trends through 2020 for the purposes of this analysis.

Emerging Markets Forecast Methodology

Futron has developed an emerging markets forecast based on data from the Commercial Space Transportation Study (CSTS). While the CSTS data are limited in many respects, the study is the most comprehensive and quantitative to date. Futron updated and revised the CSTS data in late 2000 with information and market insight garnered since the 1994 CSTS study, and this analysis uses those revised projections. Futron also added enhanced price elasticity curves to allow analysis of emerging markets at different price points. At the current price per pound to LEO ($4000), it is not economically feasible for these markets to surface; therefore this analysis studies both crewed and uncrewed platforms at two lower price points: $1000/pound and $500/pound. The $1000/pound to orbit figure represents the 20-year goal of NASA's 2nd Generation Space Transportation Program. The order of magnitude reduction from current prices to $500/pound represents envisioned performance of a 3rd generation space transportation system.

Propellant Forecast

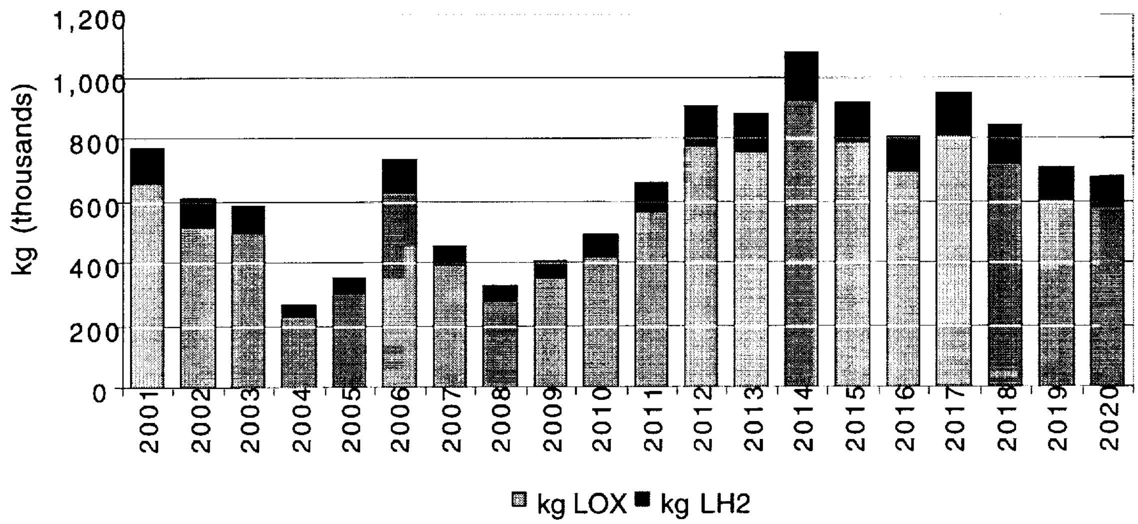
Using available government and industry launch forecasts for the next 10 to 20 years, estimates were prepared for the amount of propellant that would be required if a reusable transfer vehicle replaced the expendable upper stages. This was calculated for the government forecast, Figure 4; the commercial market forecast, Figure 5; and the emerging markets, Figure 6. It is interesting to note that the government market alone is relatively stable at around 350 metric tons per year and the commercial market can have large variances from 250 to 800 metric tons or more per year. These two existing markets alone, excluding the emerging markets that do not begin until 2008, appear to be sufficient to support a substantial propellant production depot in the 500 metric ton range as previously described.



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	244,236	293,303	277,332	295,498	228,356	241,623	298,110	326,399	220,845	262,402
kg LH2	40,706	48,884	46,222	49,250	38,059	40,271	49,685	54,400	36,808	43,734

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
kg LOX	272,525	265,014	277,332	326,399	244,236	318,888	316,694	342,279	288,405	337,472
kg LH2	45,421	44,169	46,222	54,400	40,706	53,148	52,782	57,047	48,067	56,245

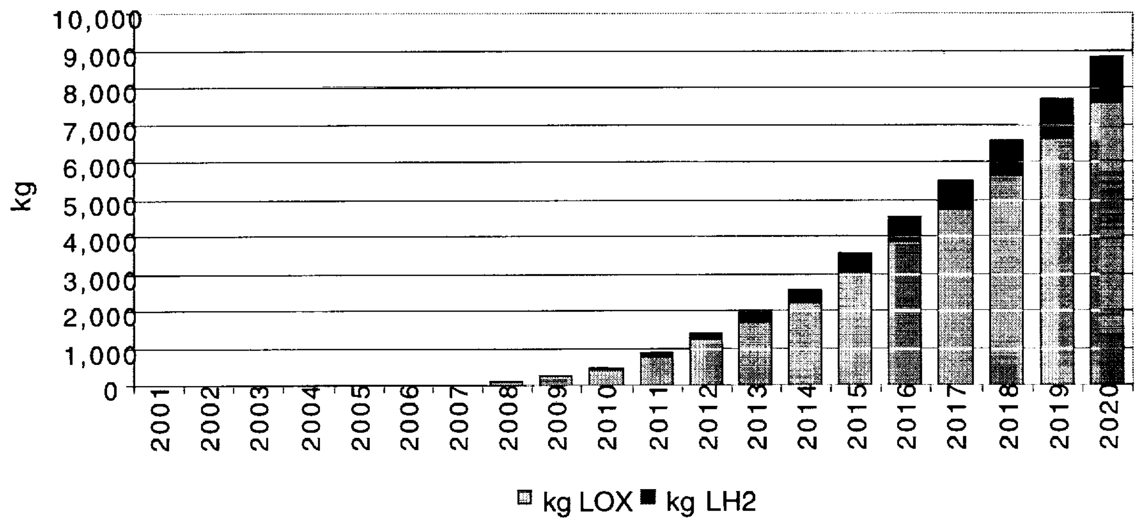
Figure 4. Government GEO Transfer Propellant Forecast.



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	657,432	519,700	501,534	228,683	298,855	628,612	392,418	278,077	348,249	421,034
kg LH2	109,572	86,617	83,589	38,114	49,809	104,769	65,403	46,346	58,042	70,172

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
kg LOX	566,277	774,181	755,689	924,323	786,591	693,028	812,268	721,317	604,363	580,972
kg LH2	94,380	129,030	125,948	154,054	131,098	115,505	135,378	120,220	100,727	96,829

Figure 5. Commercial GEO transfer propellant forecast.



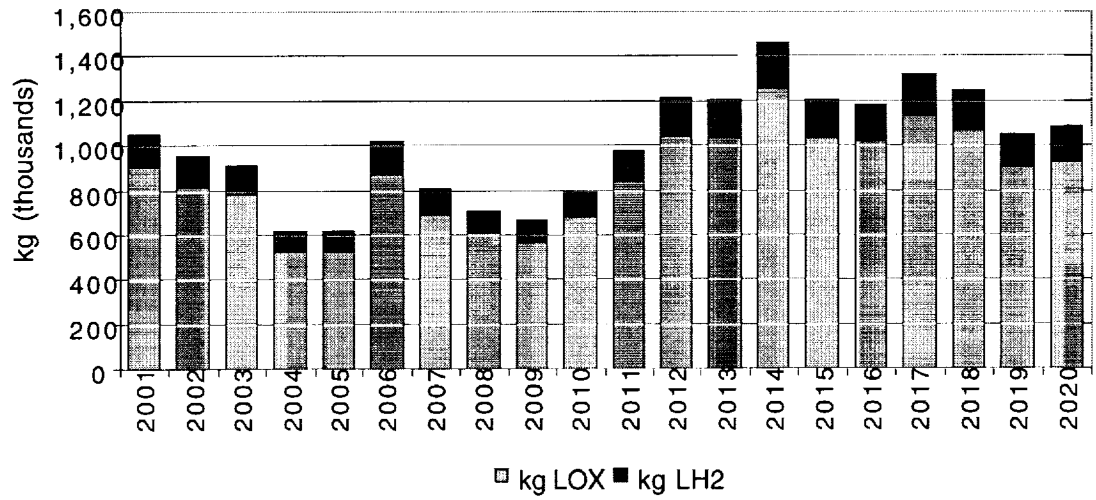
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	0	0	0	0	0	0	0	103	237	401
kg LH2	0	0	0	0	0	0	0	17	40	67

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
kg LOX	763	1,205	1,695	2,217	3,030	3,846	4,697	5,635	6,595	7,565
kg LH2	127	201	282	370	505	641	783	939	1,099	1,261

Figure 6. Emerging markets propellant forecast 2001 – 2020 at $1000 per pound

Figure 7 shows the aggregate propellant forecast through 2020; commercial, government and emerging markets (at $1000/lb) have been included. The depot faces an average annual propellant mass requirement of 1 million kg, with a standard deviation of 245,000 kg. Based on a 6:1 oxidizer to fuel mass ratio, 86% of this mass is LOX and 14% is LH2, which relates to 860,000 kg LOX and 140,000 kg of LH2.

This forecast represents the minimum propellant required to service these markets if these markets relied fully on the depot for the indicated maneuvers. Actual propellant required to fully meet market needs would be in excess of the amount indicated here to accommodate OTV "fetching" of GEO satellites from their initial LEO orbits, orbital plane changes, and the ferrying of the OMV to and from the as of yet undetermined orbits of the emerging market assets.



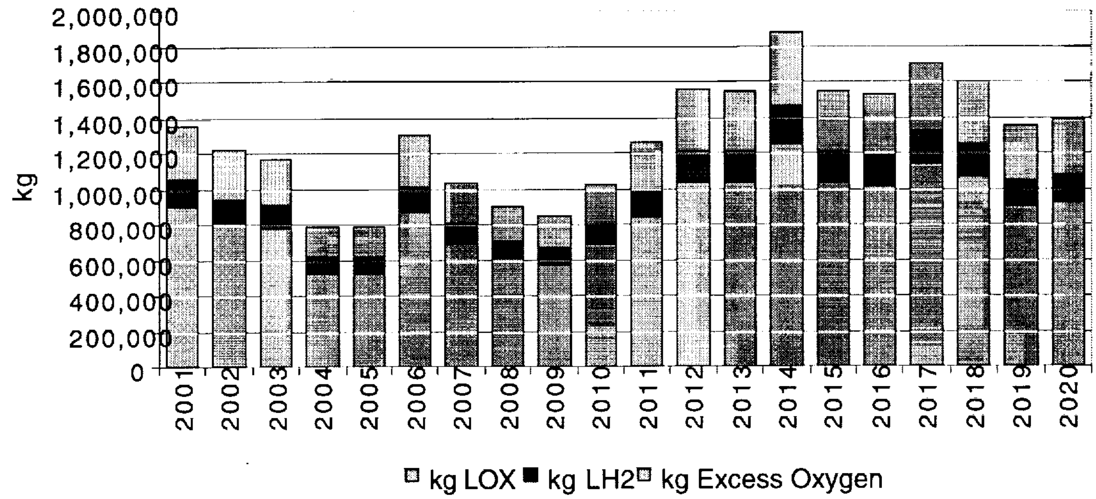
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
kg LOX	901,668	813,004	778,866	524,180	527,211	870,235	690,528	604,579	569,331	683,837
kg LH2	150,278	135,501	129,811	87,363	87,869	145,039	115,088	100,763	94,889	113,973

	2011	2012	2013	2014	2015	2016	2017	2018	2019	20
kg LOX	839,565	1,040,401	1,034,716	1,252,940	1,033,857	1,015,763	1,133,659	1,069,231	899,363	92
kg LH2	139,927	173,400	172,453	208,823	172,309	169,294	188,943	178,205	149,894	15

Figure 7. Propellant Forecast 2001 – 2020.

On-Orbit Electrolysis

The analysis discussed above is based on a propellant depot that receives, stores, and transfers cryogenic propellants; however in the case that on-orbit electrolysis becomes a viable alternative, the amount of water required for delivery to the depot to meet the above-calculated propellant requirements can be determined based on the stoichiometric relationship for water, which is 8:1 (Oxygen:Hydrogen). Figure 8 provides a break down of the amount of LOX, LH2, and excess oxygen that would be available from a propellant production depot utilizing a water resource. Water requirements from Earth or space resources (i.e., moon or asteroids) are on the order of 1 million kilograms per year.



	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
LOX	901,668	813,004	778,866	524,180	527,211	870,235	690,528	604,579	569,331	683,837
LH2	150,278	135,501	129,811	87,363	87,869	145,039	115,088	100,763	94,889	113,973
Excess Oxygen	300,556	271,001	259,622	174,727	175,737	290,078	230,176	201,526	189,777	227,946
Water	1,352,502	1,219,505	1,168,299	786,270	790,817	1,305,353	1,035,792	906,869	853,997	1,025,755

	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
LOX	839,565	1,040,401	1,034,716	1,252,940	1,033,857	1,015,763	1,133,659	1,069,231	899,363	926,010
LH2	139,927	173,400	172,453	208,823	172,309	169,294	188,943	178,205	149,894	154,335
Excess Oxygen	279,855	346,800	344,905	417,647	344,619	338,588	377,886	356,410	299,788	308,670
Water	1,259,347	1,560,601	1,552,074	1,879,409	1,550,785	1,523,644	1,700,488	1,603,846	1,349,045	1,389,014

Figure 8. Water (H_2O) forecast 2001 – 2020 for the GEO satellite transfer and platform orbital reboost at $1000/lb price point

Conclusions

Communications satellite transfers from LEO to GEO will present the single largest market opportunity for a propellant depot, generating a steady demand for approximately 700,000 kg of propellant annually. In addition, the government GEO market will continue at about $^1/_3$ of the commercial GEO market throughout the forecast period. The markets assessed here represent LOX/LH2 propellant demand more than twice the annual propellant requirements for the most propellant-intensive human Mars mission scenario. Over the next twenty years, communication satellites will continue to dominate the space industry, despite investment to bring down the cost of space access. Even if launch costs were to drop to $500/lb to LEO, emerging non-satellite markets would constitute only about 1.5 percent of the propellant requirements forecasted here.

Regardless of the technical specifications of the selected depot, any realization of the markets identified both qualitatively and quantitatively in this report would require concerted coordination between depot and orbital tug developers and the satellite manufacturers themselves. The system interface requirements are extensive, necessitating significant commitments by all parties over a lengthy development schedule. Moreover, reliance on an orbital tug introduces a measure of risk and uncertainty into the business plans of satellite manufacturers and operators for which savings or revenues must aggressively compensate.

This analysis sets the stage for an overall assessment of the economic arguments for and against an in-space propellant depot. The costs of building, servicing, and fueling a depot should be contrasted against the economic value the depot brings to its customer base. Such an analysis should include an explicit treatment of the business case risks inherent in the introduction of depot reliance to traditional space businesses such as satellite communications.

Bibliography

"An Analysis of Potential Markets and Their Fuel Requirements for an In-Space Propellant Depot," Futron Corporation, NASA Contract NAS8-99134, Marshall Space Flight Center, 2001.

"Space Solar Power Platform Technologies for In-Space Propellant Depots," The Boeing Company in Cooperation with NASA Marshall Space Flight Center, NASA Contract NAS8-99140, Mod.2, Task 3, 2000.