

Cryogenic Propellant Depots in Space

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1. Introduction

One of the problems that seems to confuse discussions of future space missions is the difference in perspective of visionaries and realists. Visionaries tend to be far-sighted and look well beyond the current limitations and challenges to a conceptual realm where many things not presently possible, can be imagined. Nevertheless, without a clear pathway leading from here to there, envisaging a bright future is not very useful. By contrast, realists (like myself) face up to the immediate difficulties, but the danger is that realists can easily get bogged down by the enormity of current limitations and challenges, and end up concluding that nothing is possible.¹

In regard to propellant depots, the visionaries hold sway. For example, a Georgia Tech team² has proposed the use of LEO propellant depots and an innovative launch system for a futuristic space environment in which they plot performance metrics vs. number of flights per year, with the number of flights per year measured by hundreds up to 1000.

2. Mr. Griffin's Views

In a presentation³ given in November 2005, the NASA Administrator said:

"... our mission architecture hauls its own Earth-departure fuel up from the ground for each trip. But if there were a fuel depot available on orbit, one capable of being replenished at any time, the Earth departure stage could after refueling carry significantly more payload to the Moon, maximizing the utility of the inherently expensive Shuttle-derived heavy lift vehicle (SDHLV) for carrying high-value cargo."

He then goes on to say that NASA cannot afford to develop such a fuel depot and "it is philosophically the wrong thing for the government to be doing.... It is exactly the type of enterprise which should be left to industry and to the marketplace."

Mr. Griffin points out that in the future, when the lunar program is in operation, there will be two major missions to the lunar outpost per year, and each of these entails launching the crew on a ~ 25 mT launcher, and the Earth departure stage and additional payload on a ~125 mT SDHLV. About half of the mass sent to LEO consists of propellants for Earth departure. For two missions per year, the annual cost of sending the Earth departure propellants to LEO is estimated to be about \$2.5B based on an estimate of \$10,000/kg. Mr. Griffin suggests that this potential \$2.5B/year market would be attractive to private entrepreneurs.

Mr. Griffin admits that "To maintain and operate the fuel depot, periodic human support may be needed. Living space in Earth orbit may be required.... Fuel and other consumables will not always be most needed where they are stored. Will orbital transfer and delivery services develop,

¹ Reviewing recent NASA planning documents, this may well be the case.

² Tanker Argus: Re-supply for a LEO Cryogenic Propellant Depot, Brad St. Germain, John R. Olds, Tim Kokan, Leland Marcus, Jeff Miller, Reuben Rohrschneider, Eric Staton, IAC-02-V.P.10.

³ NASA and the Business of Space, American Astronautical Society 52nd Annual Conference, Michael D. Griffin, NASA Administrator, 15 November 2005.

with reusable 'space tugs' ferrying goods from centralized stockpiles to other locations? The fuel depot operator will need power for refrigeration and other support systems."

However, from his point of view, these challenges can become opportunities: the need for humans in space would "present yet another commercial opportunity for people like Bob Bigelow, who is already working on developing space habitats."

The Boeing Company has endorsed this view and peered further into the distant future including a lunar water export business, water delivery to propellant stations, lunar hotels, daily scheduled lunar flights, and over 100 hotels and sport centers in Earth orbit to support an orbital population of 70,000.⁴

3. The Big Picture

For lunar and Mars missions, a significant fraction of the total mass that must be transported to LEO from Earth consists of propellants. Assuming use of LOX-LH2 propulsion at a specific impulse of 450 sec, about 50% of the mass in LEO is propellant for Earth departure toward the Moon, and about 60% of the mass in LEO is propellant for Earth departure toward Mars.

There are several conceptual approaches to providing propellants for Earth departure to space vehicles in LEO:

(1) Transport propellants from Earth in large launch vehicles along with Earth departure and other propulsion stages, habitats, ascent and descent vehicles, and other systems needed for human missions. In this scenario, Earth departure propellants are treated as simply one element of the total cargo inventory of a heavy lift launch vehicle. This is the most straightforward approach and since NASA has adopted this approach for lunar transfers, it can be considered to be a baseline, against which other approaches can be compared.

(2) A second approach would be to transport the lunar-bound or Mars-bound vehicles and systems with dry propellant tanks for Earth departure, and in the same time period, send the Earth departure propellants to LEO with a separate dedicated tanker launch vehicle (LV) to rendezvous and fuel up the vehicle(s) bound for the Moon or Mars. Since Earth departure propellants amount to 50-60% of the mass in LEO,⁵ this would replace one heavy lift launch vehicle with two launch vehicles each with about half the capacity of the single launch vehicle. Presumably, the tanker LV would be less expensive than the cargo LV. However, the total cost to develop and implement two half-size LVs is likely to be greater than the cost of one full-size LV. NASA tends to reduce costs by reducing the number of distinct hardware systems. As an example, in going to the Moon, they used a single propulsion system for both the final sub-orbital burn and Earth departure, rather than staging these with two smaller propulsion systems. Had they used staging, it would not have been necessary to carry the dead weight of the sub-orbital propulsion system during Earth departure, thus reducing the initial mass in LEO. Although staging would be mass-efficient, it is not cost-efficient.

(3) A third approach would be to launch Earth departure propellants separately in smaller, less reliable (and less costly) launch vehicles, and store them in space at powered cryogenic fuel depots. When a human mission is launched from Earth, it would have empty Earth departure

⁴ http://www.boeing.com/defense-space/space/constellation/references/presentations/2.6_Services_Intro.pdf

⁵ <http://www.mars-lunar.net/Reality.or.Fantasy/IMLEO.to.Mars.pdf>

propellant tanks, and it would rendezvous in LEO with the fuel depot, fill its tanks, and then depart for its destination. This approach was advocated by Space Systems/Loral via their "Aquarius system."⁶ The Space review article says:

"For this system to work, the consumables-only launch must be a lot cheaper than the launch of a high-value, possibly irreplaceable payload. Previously published studies⁷ show that allowing launch reliability to be reduced significantly, to between 0.67 and 0.8, can provide a way to cut launch cost by an order of magnitude. While a 0.67 delivery success rate might seem shockingly low from a traditional aerospace perspective, it is accepted routinely in terrestrial low-cost delivery systems. Aqueducts and high-tension power lines, for example, routinely lose one-third of their payloads en route, yet are highly successful."

However, the argument that because some terrestrial systems operate at a delivery success rate of ~67%, therefore it would be acceptable in space can be construed to be equivalent to arguing that since all tables have four legs and all horses have four legs, therefore all tables are horses. When a terrestrial power line or aqueduct operates at 67% efficiency, the side effects are generation of heat and water vapor. When a space system fails, the result is either metal falling out of the sky or clogging up LEO with space debris.

(4) A fourth approach would be to mine putative water ice on the Moon and electrolyze some of it to produce LOX-LH₂ propellants for a round-trip tanker system to transport water from the Moon to LEO, where it would be electrolyzed to produce LOX-LH₂ for Earth departure. This approach would have virtue if the cost of developing and operating the lunar water ferry system is less than the cost of the baseline approach. However, analysis of the requirements for transporting water from the Moon to LEO suggest that this process has a very low efficiency and may be very expensive.⁸ In addition, the prospects for mining polar ice on the Moon are quite uncertain.⁹ Since NASA does not seem inclined to develop a nuclear reactor, operations within the shaded area of a large crater would be ~ 10 km distant from the solar energy source.

(5) A fifth approach would be similar to the fourth approach, except that the source of water ice would be an asteroid, rather than the Moon. The % of water in some asteroids is likely to exceed the indicated ~1% content in polar craters on the Moon, and the Δv for accessing the asteroid could be lower than for the Moon.¹⁰

(6) Within the scope of approaches (4) or (5) one could conceive of establishing fuel depots further out in space than LEO to provide propellants for steps subsequent to Earth departure. Once a supply of propellants is available outside the influence of the Earth's gravity, many favorable possibilities exist for propellant depots. But finding a source of extraterrestrial propellants outside a gravity field is a holy grail like the mice trying to figure out how to put a bell around the cat's neck.

⁶ <http://www.thespacereview.com/article/544/1>

⁷ I have not been able to locate these studies.

⁸ <http://www.mars-lunar.net/Reality.or.Fantasy/Appendix.5.Fueling.pdf>

⁹ <http://www.mars-lunar.net/Reality.or.Fantasy/Polar.Ice.on%20Moon.pdf>

¹⁰ Profitably Exploiting Near-Earth Object Resources, Charles L. Gerlach, 2005 International Space Development Conference National Space Society, Washington DC, May 19–22, 2005.

Obviously, these approaches (other than the baseline) will become more competitive as the Earth departure traffic increases. However, for a few launches per year, it seems doubtful that any alternative can compete with the baseline.