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In-Space Cryogenic Propellant Depot Potential Commercial and Exploration Applications

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Abstract

The key goals and objectives for an In-Space Cryogenic Propellant Depot are to support a safe, reliable, affordable and effective future human and robotic space exploration initiative.

Previous studies have been conducted at the NASA Marshall Space Flight Center to determine technical requirements and feasibility for exploration and commercial potential of an in-space cryogenic propellant depot in low-Earth-orbit (LEO), low-Lunar-orbit (LLO) and/or on the lunar surface. Results indicate that in-space cryogenic propellant depots are technically feasible given continued technology development and that 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 requires large amounts of power which is enabled by Space Solar Power technologies. Recent analysis 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.

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Presentation to

Space Power & Infrastructure Working Group

2006 Japan-U.S. Science, Technology & Space Applications Program (JUSTSAP)

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Outline

- Reasons for developing an In-Space Cryogenic Propellant Depot
- Technical feasibility of an In-Space Cryogenic Propellant Depot
- Commercialization of an In-Space Cryogenic Propellant Depot

Water to Cryogen Production Concept

- Development of depot technology will enable sustainable human missions at any location where water can be found, (i.e., Moon, Mars, Europa, etc..).
- A cryogen production facility in low-Earth-orbit would 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
- The basic concept for production of hydrogen and oxygen is through an electrolysis process such as the one currently on Space Station
- Production capabilities would enable new commercial markets for reusable high-energy upper stages, satellite services, and water and oxygen for ongoing human operations.

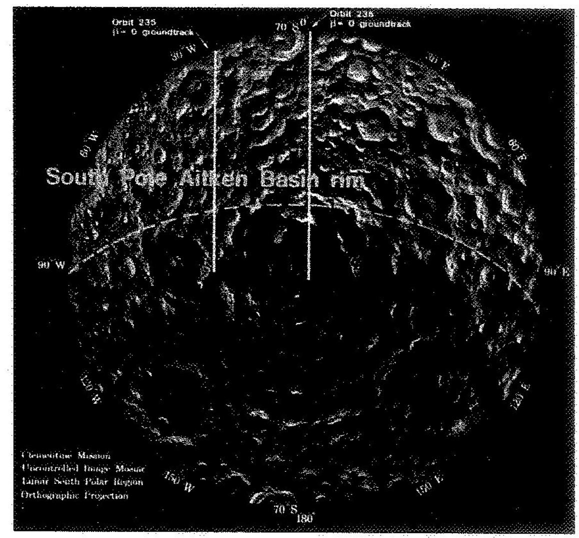
"Stepping Stone to Lunar Ice Utilization"

Relevancy

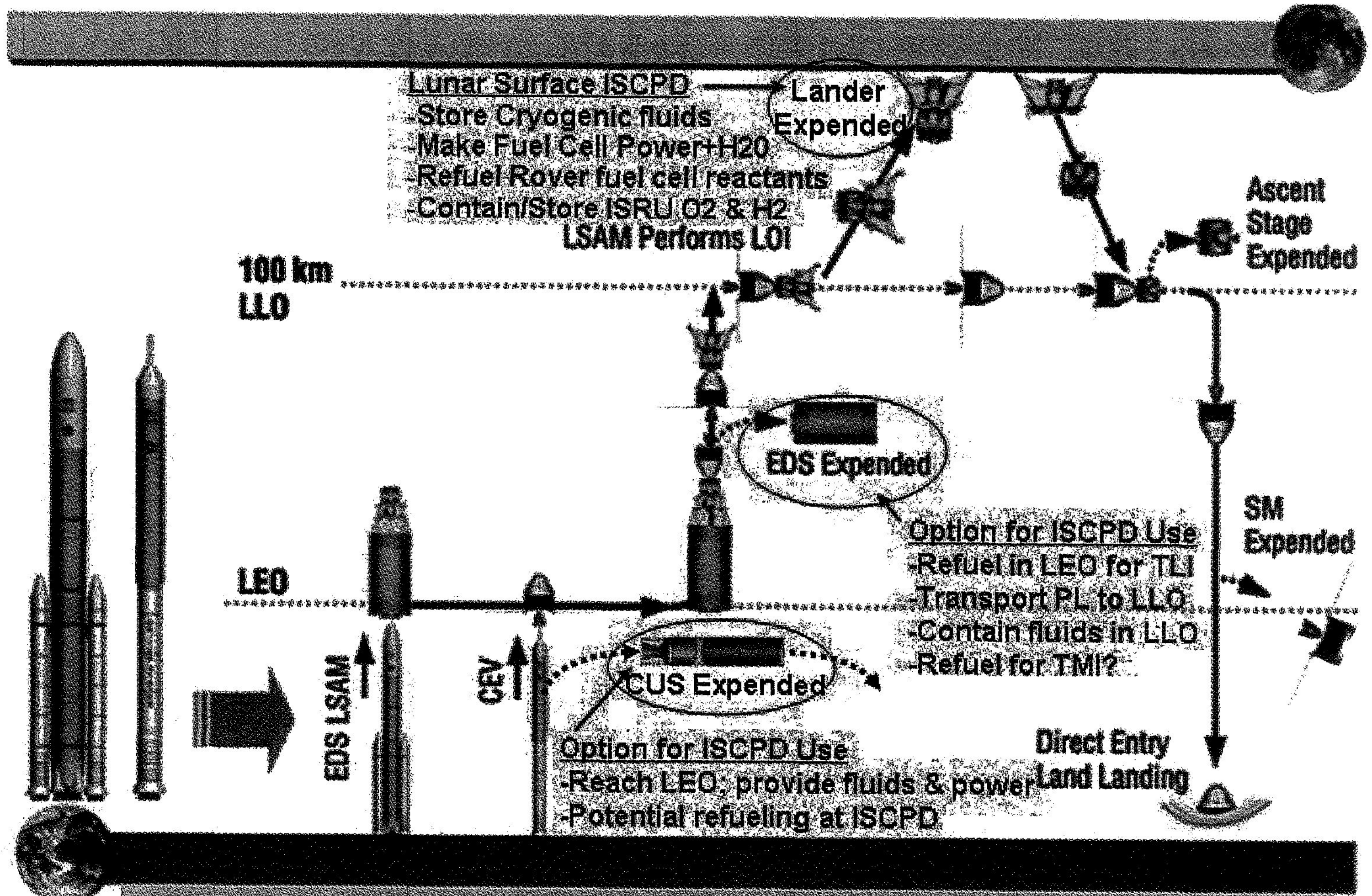
The long-term management, storage and transfer of cryogenic and non-cryogenic propellants is one potentially important architecture-level approach to reducing the cost while expanding the operational robustness of future exploration and commercial space endeavors. This approach in conjunction with lunar resource utilization opens up new options for future human/robotic exploration and development of space while advancing the emergence of key capabilities that will be required.

Products/Benefits

- Advanced In-Space Cryogenic Propellant Depot concepts
- Smaller packaging for electrolysis
- Lunar resource utilization
- Utilize Space Solar Power Technology
- Depot location trade study
- Identification of technology requirements in support of ground and flight experiments and demonstrations



Possible In Space Cryogenic Propellant Depot Uses with NASA's ESAS-Recommended Architecture



(estimates)	Earth Departure Stage		CEV Upper Stage		Lunar Lander	
Dry Mass (kg, *lbm*)	19,345	*42,645*	17,467	*38,507*	6,137	*13,529*
Propellant (kg, *lbm*)	207,704	*457,884*	163,538	*360,519*	25,105	*55,344*
Residual (kg, *lbm*)	2,719	*5,995*	2,955	*6,515*	486	*1,071*

Systems-Technology Challenges

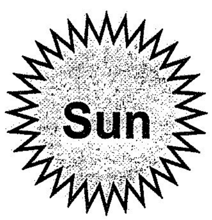
Long-duration, low-loss transfer, management and storage of key cryogens, including hydrogen, for use in a wide variety of gravitational and other environments.

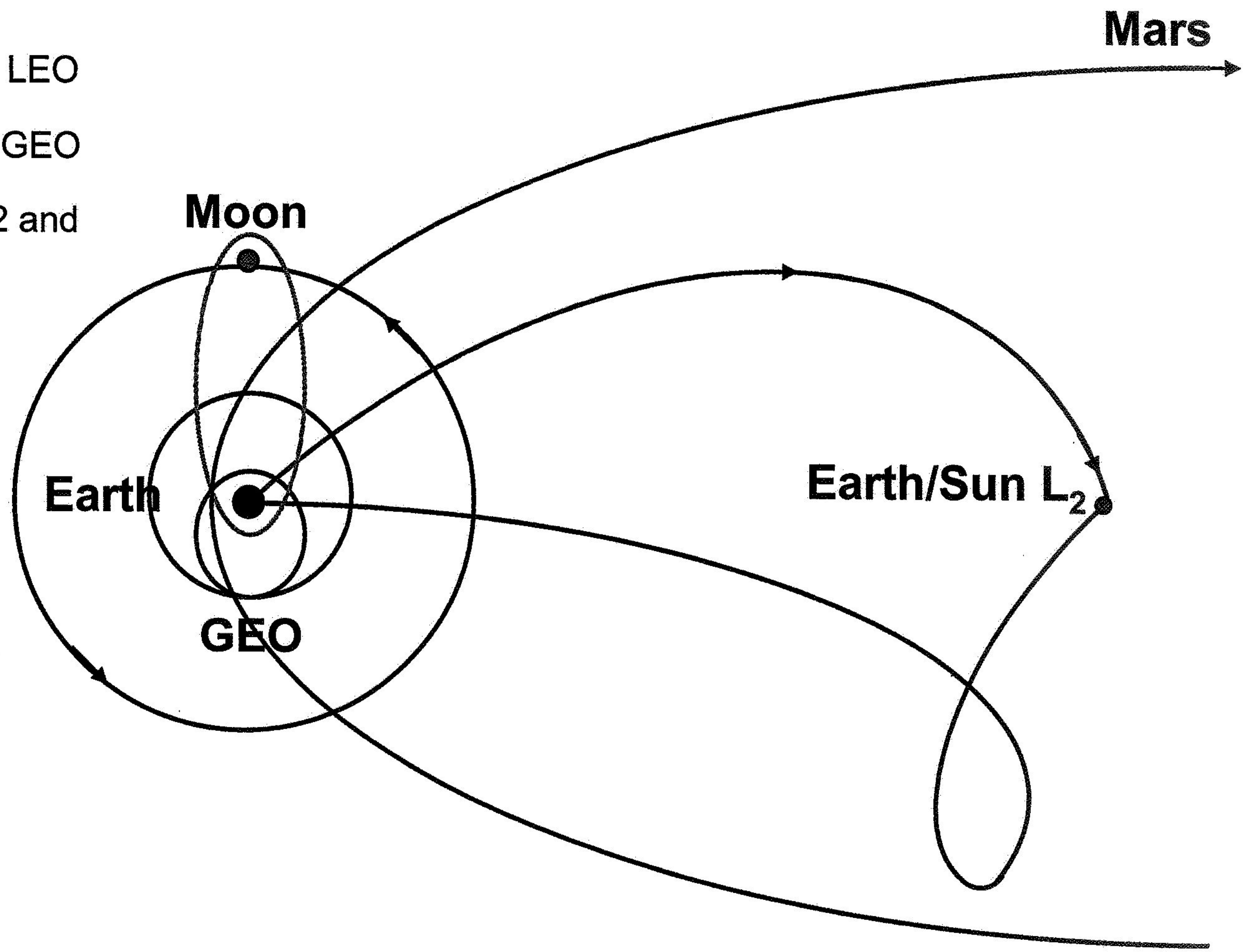
- **Long-duration, Very Low Gravity Cryogenic Fluid Storage**
  - LH_2, O_2, etc.
- **Passive and Active Thermal Control**
- **Liquid Acquisition for LH_2, O_2, etc.**
- **Micro-Gravity Cryogenic Fluid Transfer**
  - Gravity Gradient Assist
  - Propulsive Thrust Assist
  - Tank Change-out
- **Micro-Gravity Fluid Management**
  - Liquid Acquisition for LH_2, O_2, etc.
  - Zero-g Pressure Control/Venting
  - Mass Gauging
  - Cryogenic Fluid Distribution
- **Water Storage**
- **Alternate Propellants**
- **Depot/Proximity Operations**
- **Cryogenic Propellant Depot Technology Demonstrations/Flight Experiments**

Applications

Propellant Depot Missions

- Refuel OMVs for transfers in LEO
- Refuel OTVs for transfers to GEO
- Refuel Storage Depots for L2 and Lunar missions

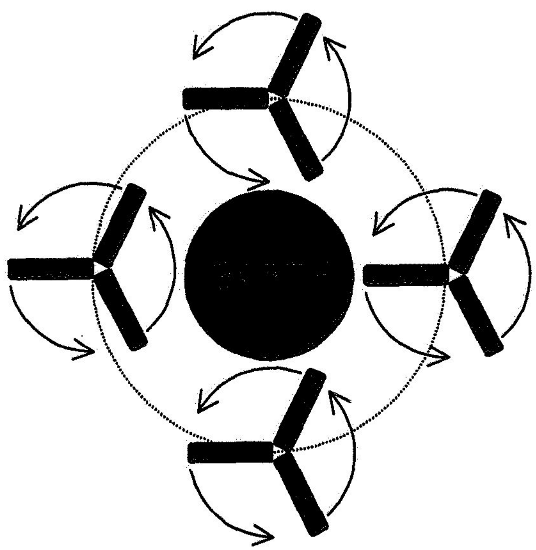




- Propellant for Mars Missions
- Commercial Missions
  - Satellite transfers
  - Satellite servicing
  - Orbital debris removal

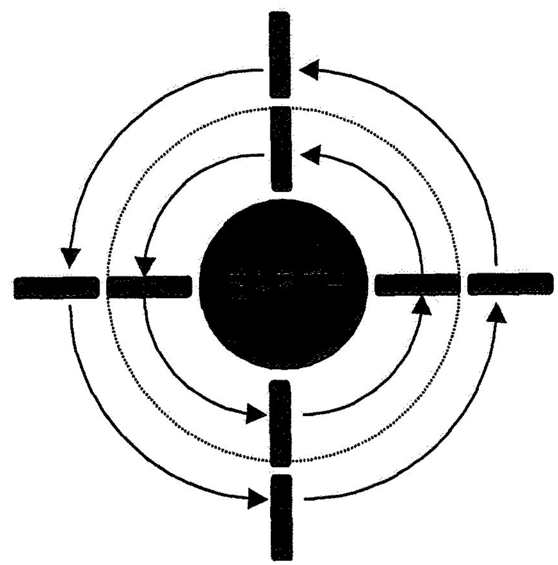
Approaches for Cryogenic Settling

Rotating Depot



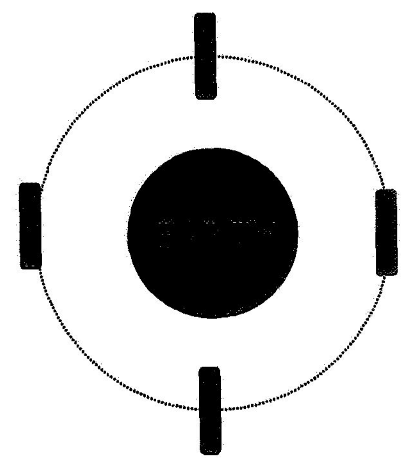
- Suitable for Deep Space
- Requires de-spun docking

Gravity Gradient Depot



- Any orbit
- Marginal settling for H2
- Docking at Ends or Center

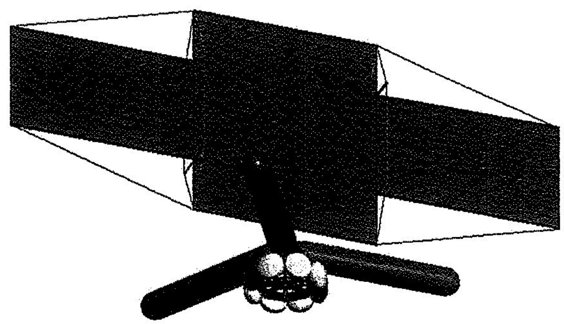
Solar Inertial



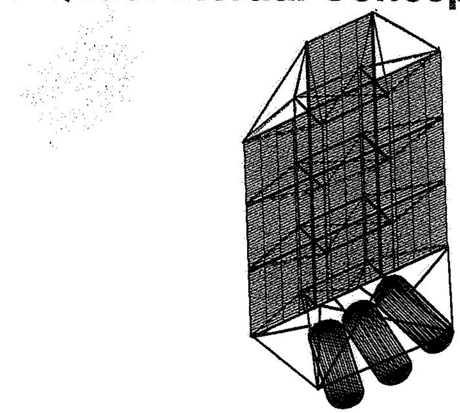
- Sun Pointing
- No alpha/beta joints
- Requires zero-g propellant acquisition

Concepts for Cryogenic Propellant Depots

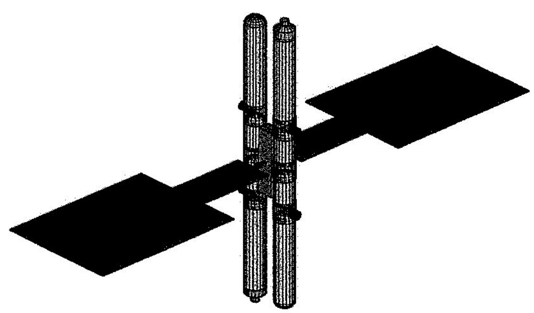
Spinner Concept



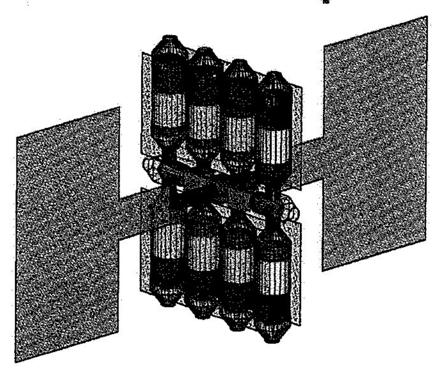
Abacus Quasi-Inertial Concept



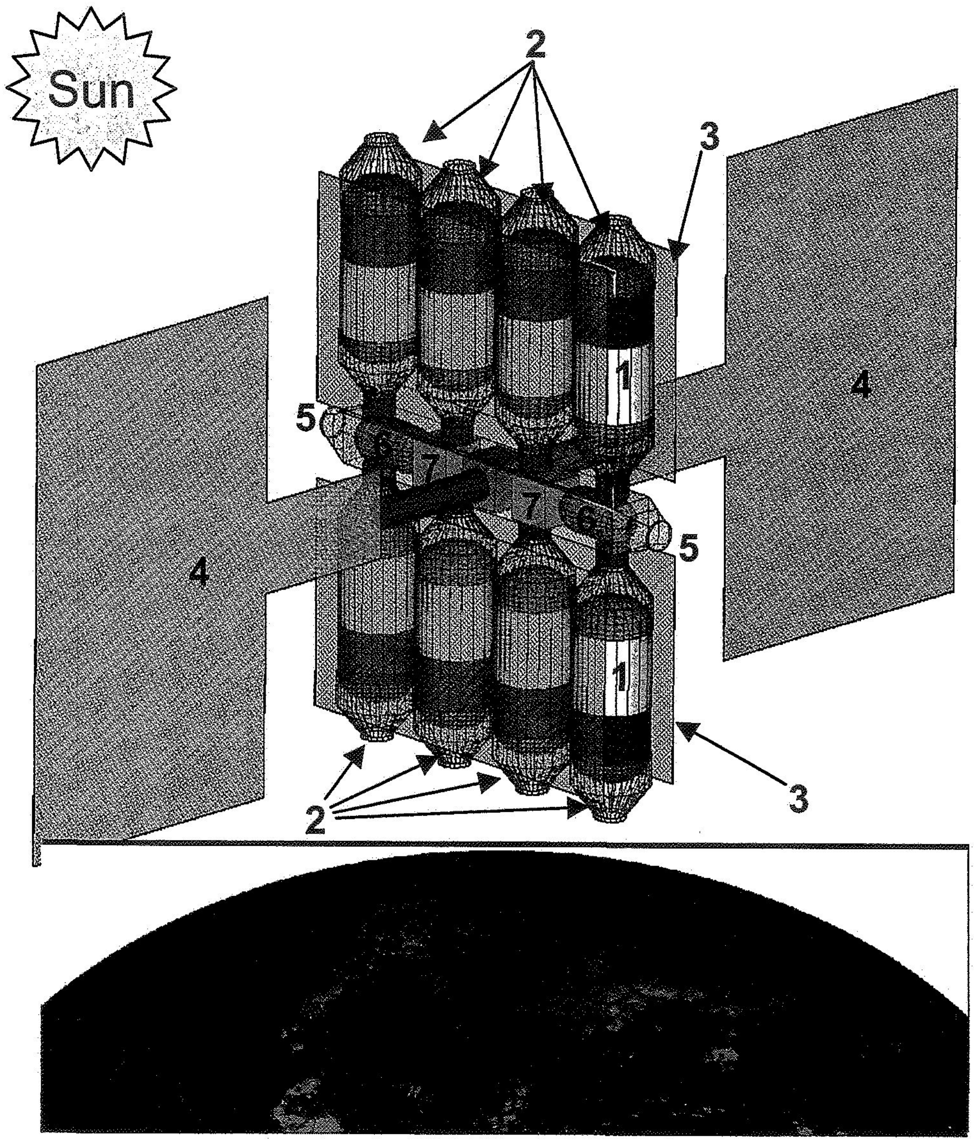
Preliminary Gravity Gradient Concept



Gravity Gradient Concept

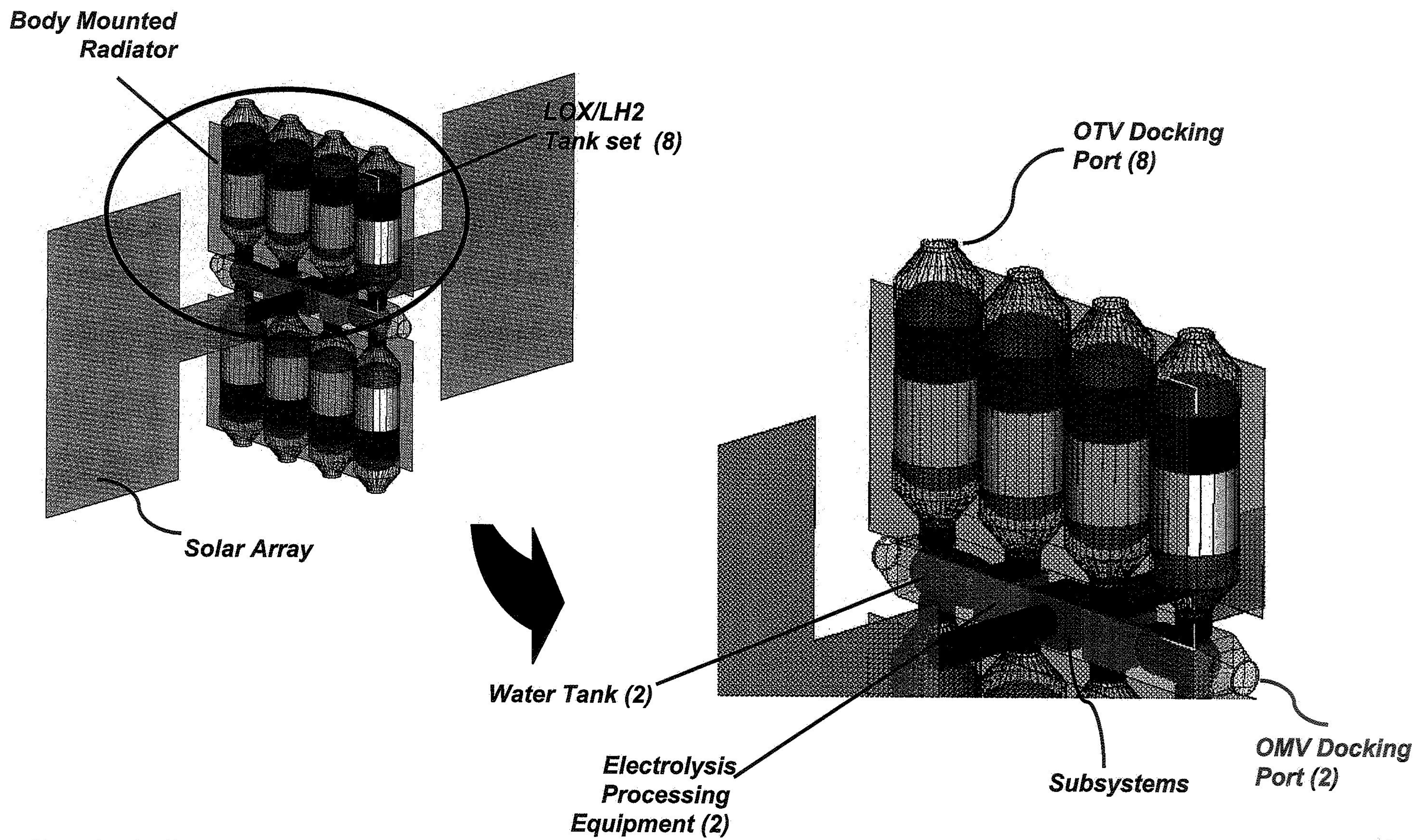


On-Orbit Propellant Production Design

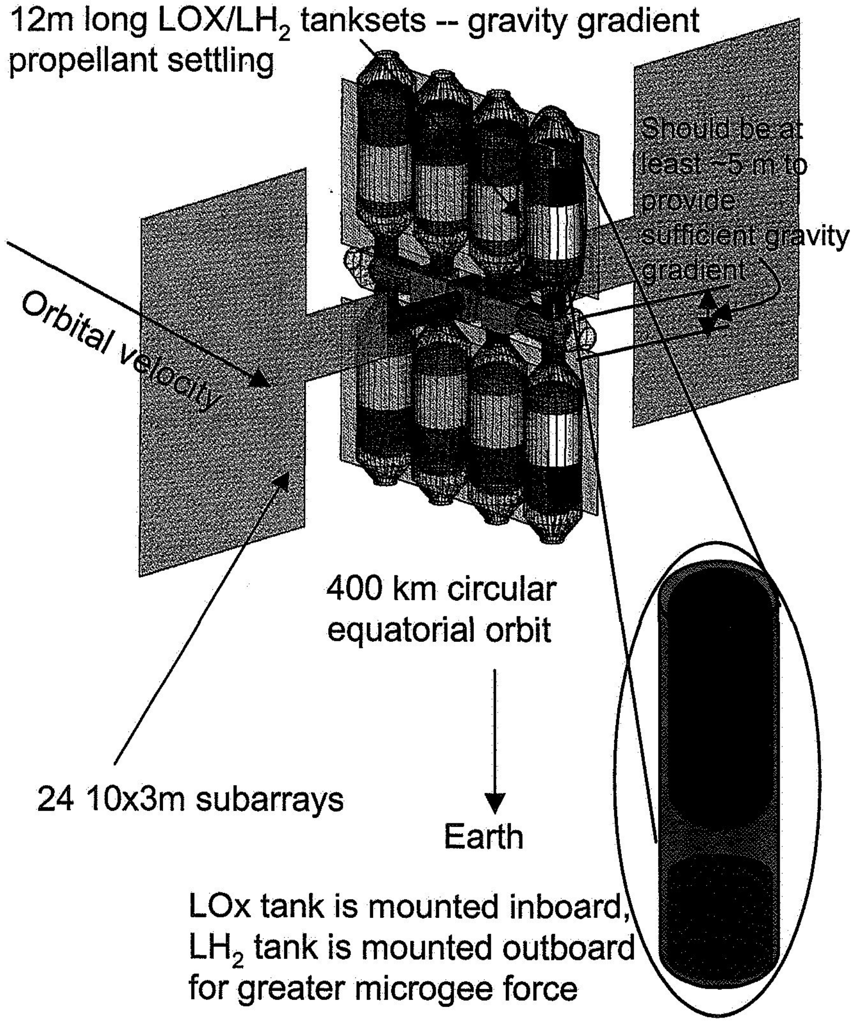


1. LOX/LH2 Storage Tanks
2. Transfer Vehicle Docking Ports
3. Radiators
4. Solar Arrays
5. Water Docking Port
6. Water Storage Tanks
7. Electrolysis System

On-Orbit Propellant Production Schematic

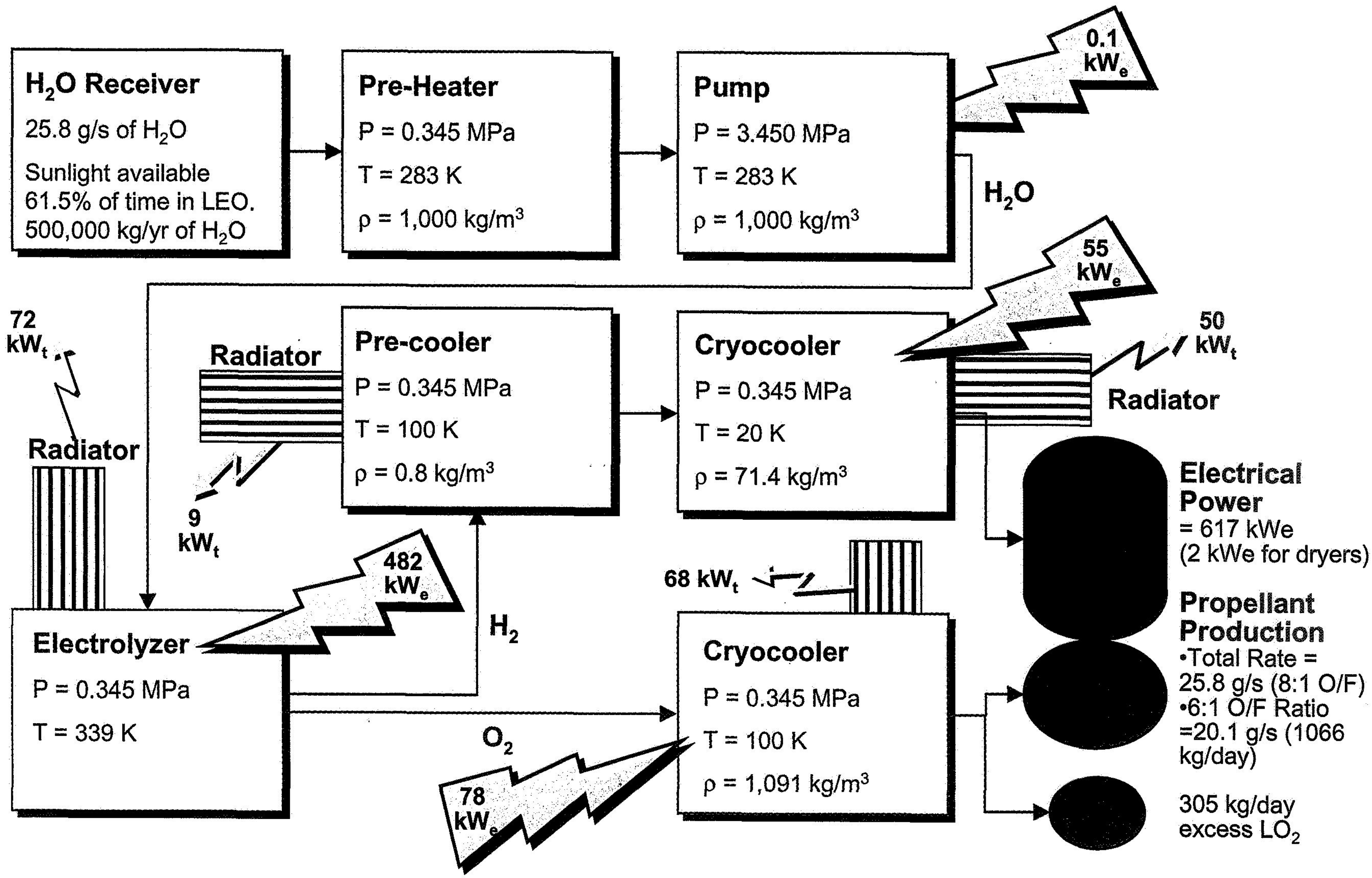


Propellant Production Depot Key Features

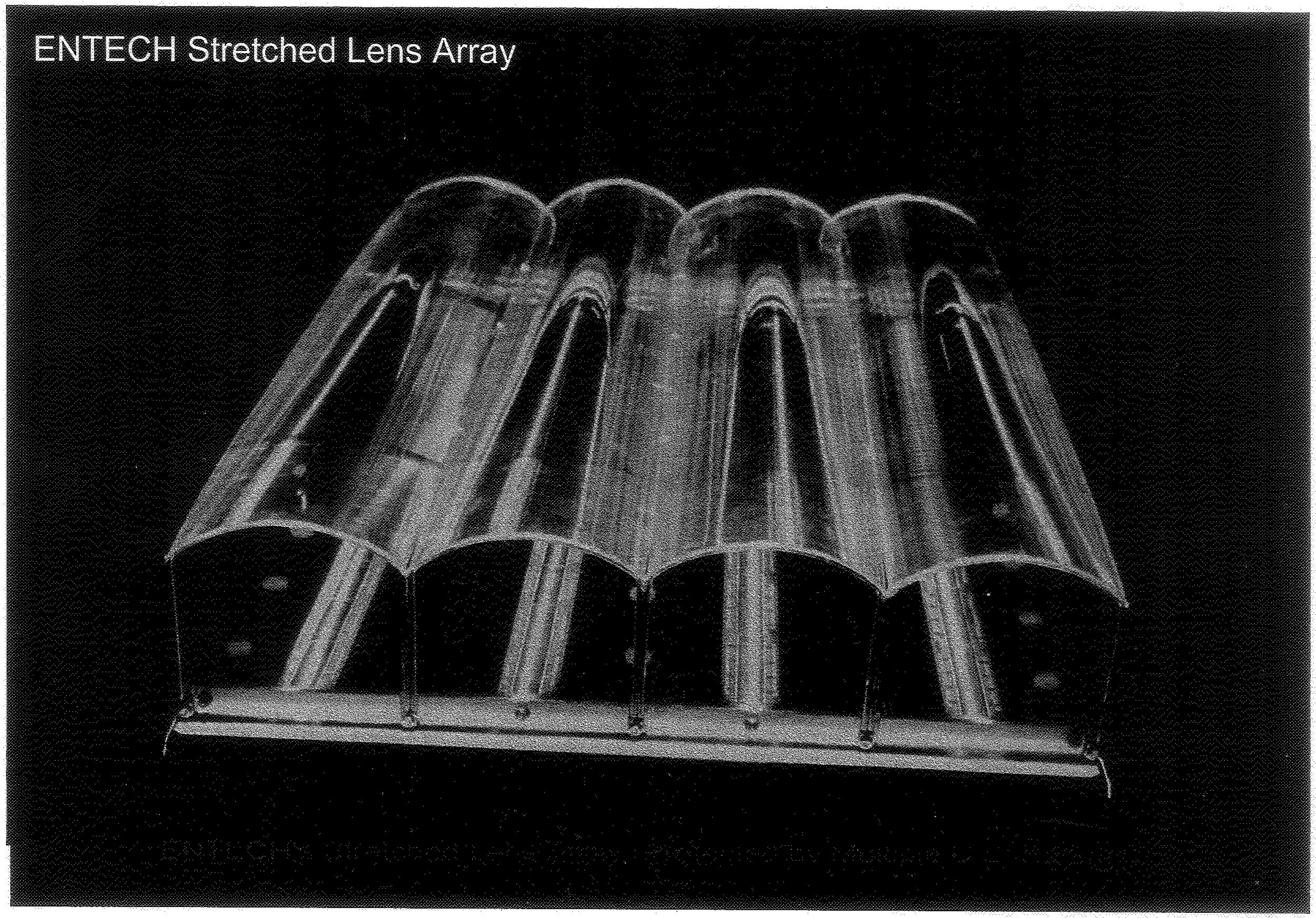


- •ENTECH Stretched Lens Array (SLA's)
  - Sized for 706kWe (635kWe delivered to bus)
  - Inflatable abacus structure
- •Power Management & Distribution (PMAD)
  - 150V
  - No converters at the arrays
  - Two power conducting slip rings
- •8 Delta IV Heavy-class tanksets
  - 500 MT LOX & LH_2 per year
  - 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

Electrolysis System

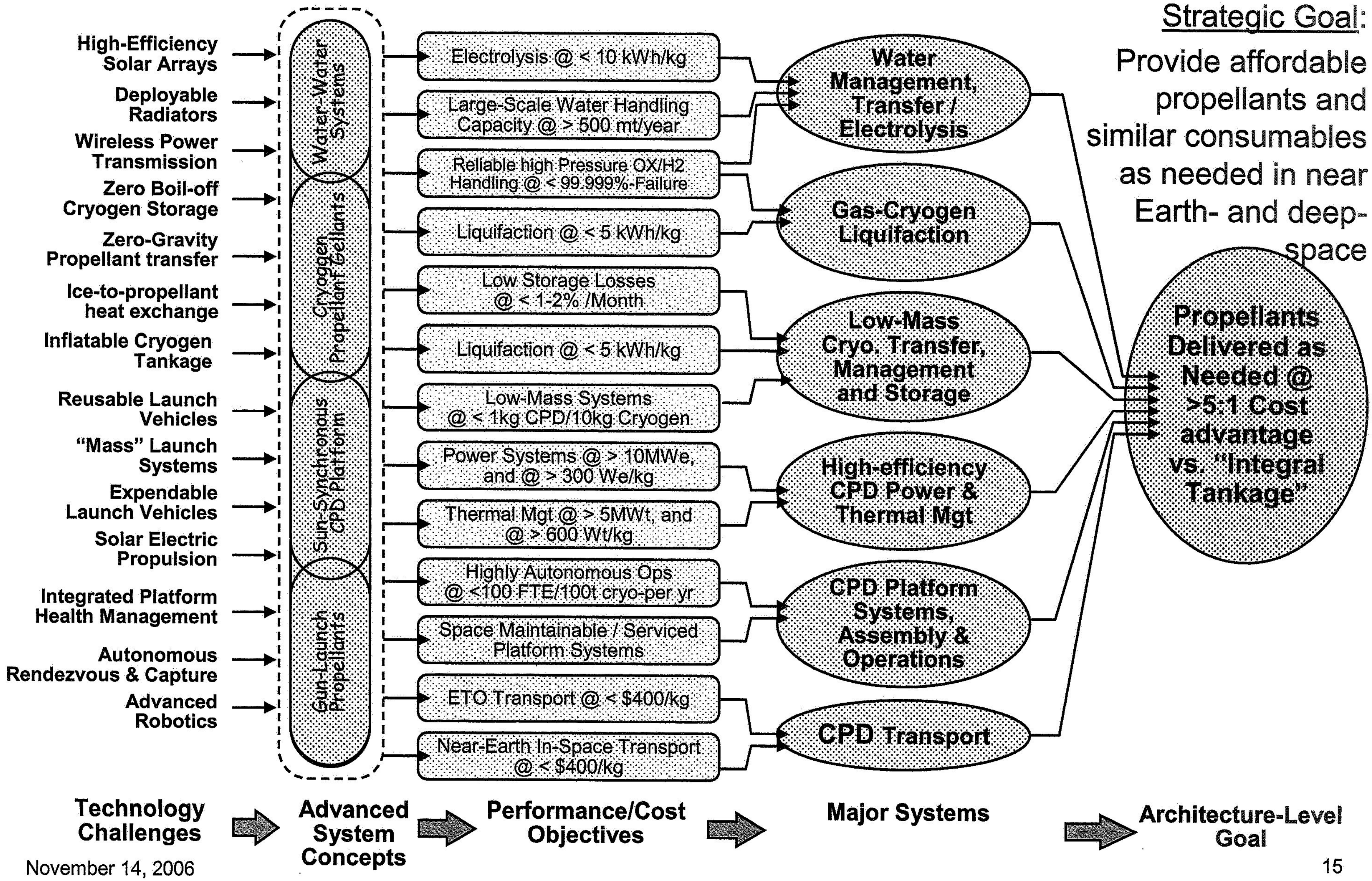


Power System



In-Space Cryogenic Propellant Depot Potential Commercial and Exploration Applications

Technology



Market Study

Study consisted of:

- Initial canvassing of potential markets for a propellant depot
- Systematic evaluation of candidate markets for technical feasibility
- 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

Market Study

LEO to GEO transfer for both government and commercial markets:

- Large fuel requirements for satellite transfer from LEO to GEO make this market perhaps the most likely commercial user of a propellant depot

- Market is characterized by the delivery of a satellite to the Depot orbit and the ferrying of the satellite to GEO by a reusable orbital transfer vehicle (OTV).

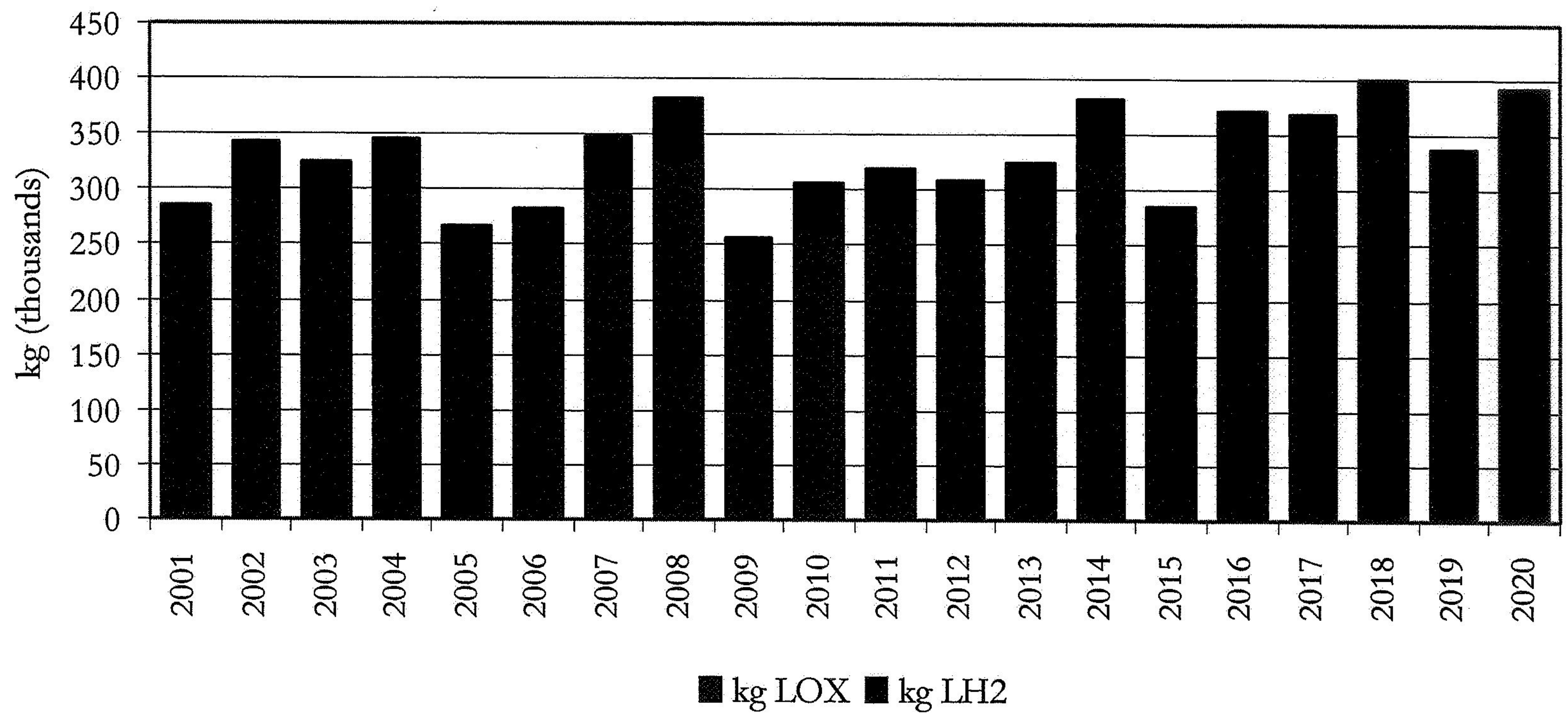
In order to determine the propellant required for each of these markets:

- A 20-year demand forecast was made of the orbital assets

- ΔV required to carry out the indicated maneuvers was calculated

- Total propellant required given reference technical specifications of the propellant, OTV, and OMV was determined

Propellant Requirements for Government Forecast

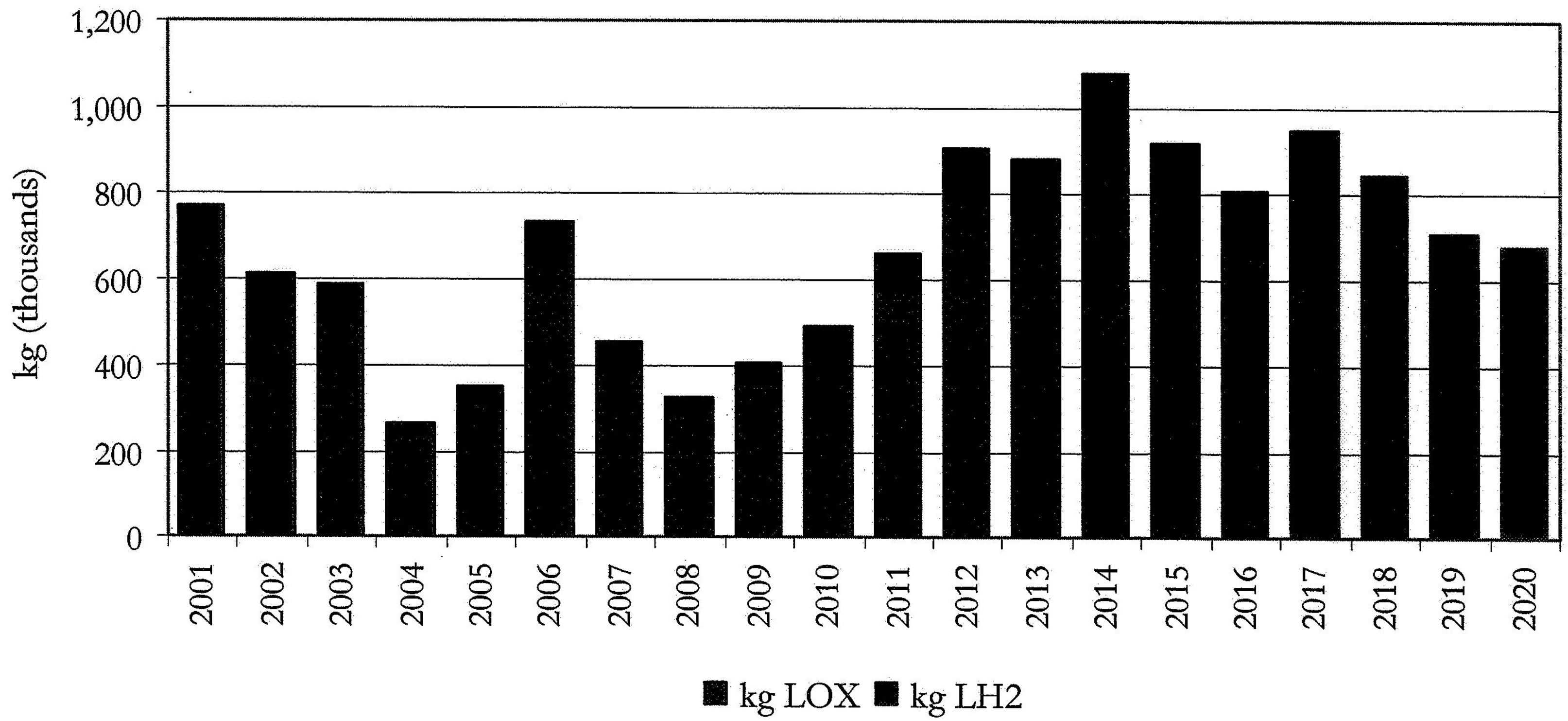


- Used available government and industry launch forecasts for the next 10 to 20 years

- Estimates were prepared for the amount of propellant that would be required if a reusable transfer vehicle replaced the expendable upper stages

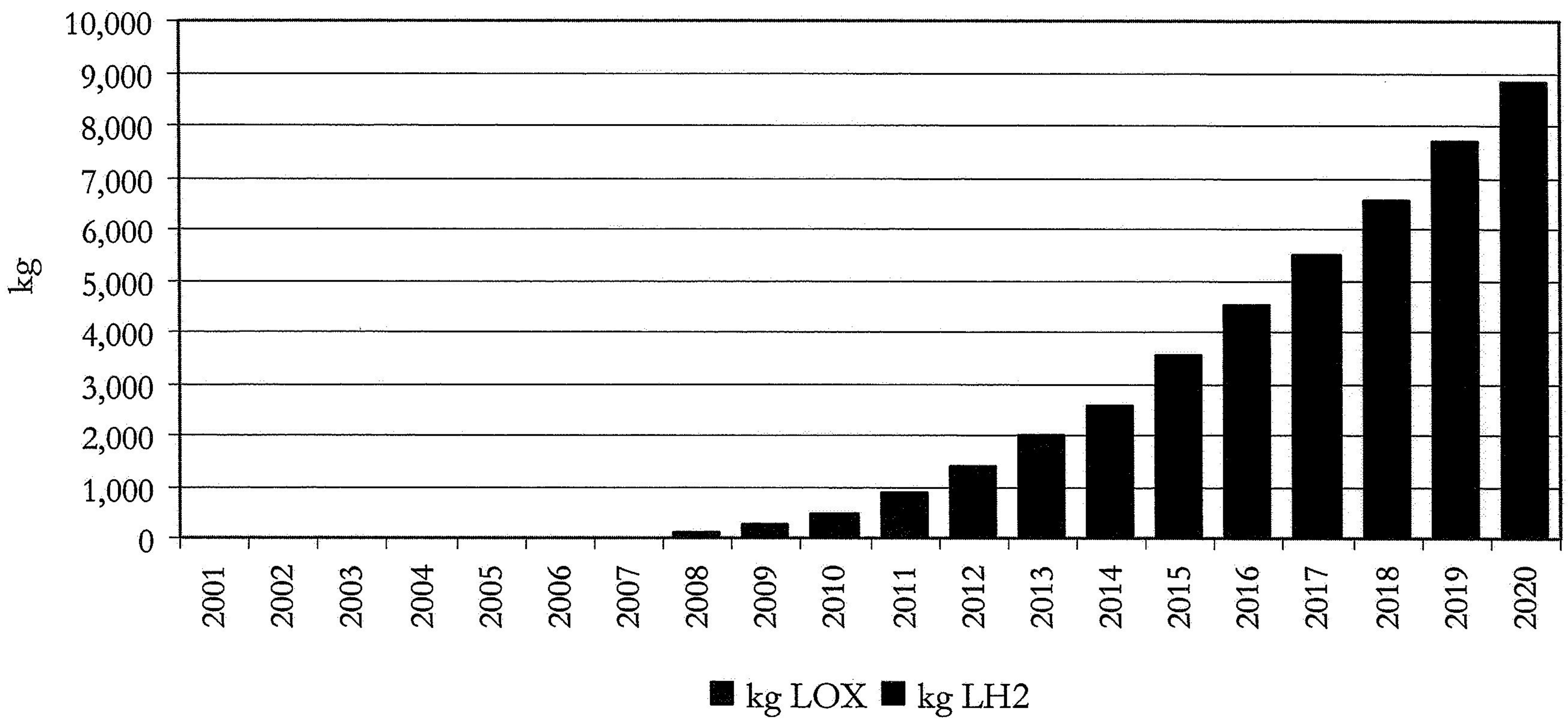
- Calculated for the government forecast

Propellant Requirements for Commercial Market Forecast



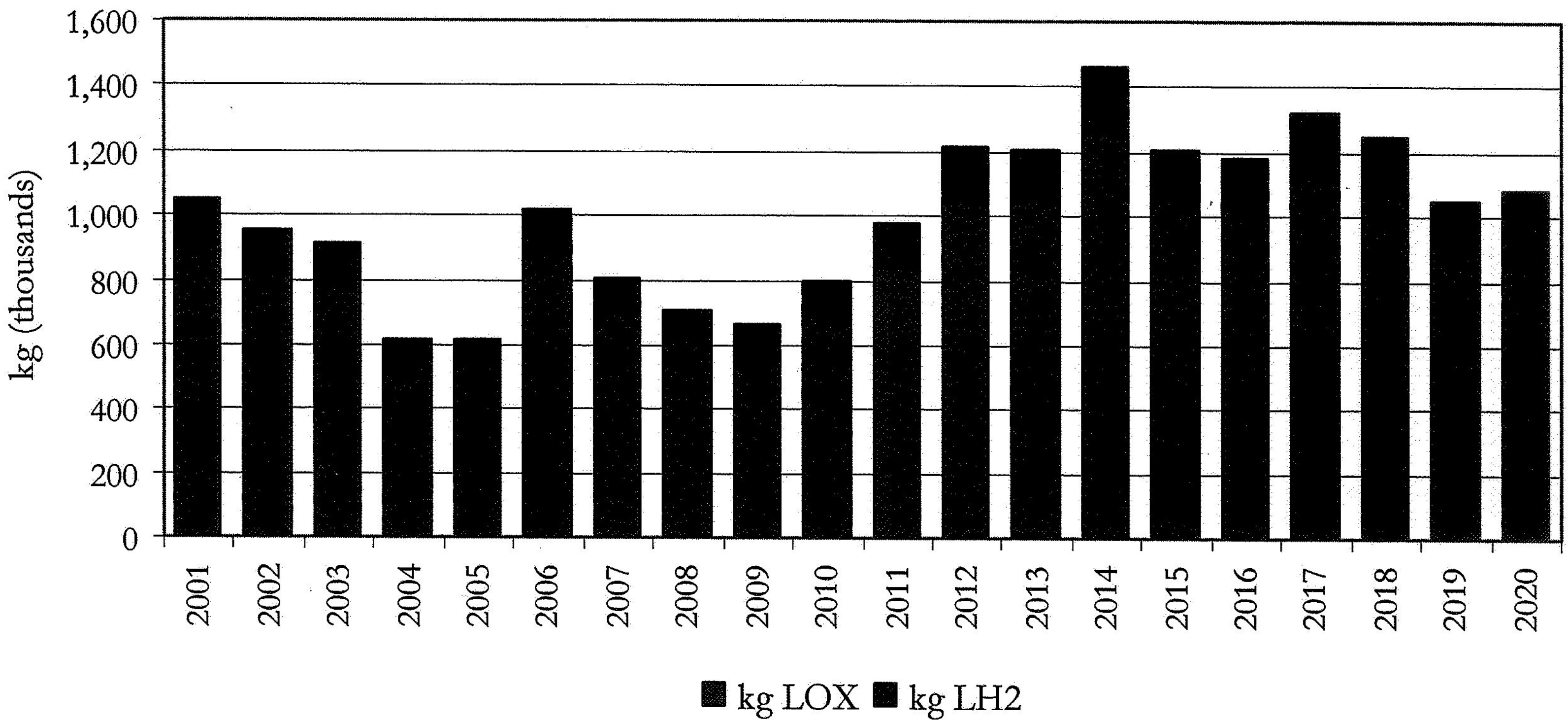
- Used available government and industry launch forecasts for the next 10 to 20 years
- Estimates were prepared for the amount of propellant that would be required if a reusable transfer vehicle replaced the expendable upper stages
- Calculated for the GEO commercial transfer propellant forecast

Propellant Requirements for Emerging Market Forecast



- Used 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
- Calculated for the emerging markets forecast

Aggregate Propellant Forecast Through 2020



- Commercial, government and emerging markets 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

Comments on Cryogenic Propellant Depots from NASA Administrator Mike Griffin

- **No Depot in ESAS Architecture**
  - Recommends Commercial ISCPD Development
    -$2.5 B/year market for ESAS LEO Stage Refueling
  - NASA might develop first unit for commercial operation/growth
- **Recommends Lunar In Situ Propellant Production**
  - Liquid Oxygen
  - Hydrogen, if available (e.g., ice)
  - Possible transport of products to LEO Depot
- **ESAS Cryogenic Lunar Lander is "Very Notional"**
  Expendable, but secondary use on the moon is encouraged

Mike Griffin's Comments on a Commercial Cryogenic Propellant Depot 52nd AAS Conference,15 Nov. 2005

...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 SDHLV for carrying high-value cargo.

But NASA's architecture does not feature a fuel depot. Even if it could be afforded within the budget constraints which we will likely face – and it cannot – it is philosophically the wrong thing for the government to be doing. It is not "necessary"; it is not on the critical path of things we "must do" to return astronauts to the Moon. It is a highly valuable enhancement, but the mission is not hostage to its availability. It is exactly the type of enterprise which should be left to industry and to the marketplace.

So let us look forward ten or more years, to a time when we are closer to resuming human exploration of the Moon. The value of such a commercially operated fuel depot in low Earth orbit at that time is easy to estimate. Such a depot would support at least two planned missions to the Moon each year. The architecture which we have advanced places about 150 metric tons in LEO, 25 MT on the Crew Launch Vehicle and 125 MT on the heavy-lifter. Of the total, about half will be propellant in the form of liquid oxygen and hydrogen, required for the translunar injection to the Moon. If the Earth departure stage could be refueled on-orbit, the crew and all high-value hardware could be launched using a single SDHLV, and all of this could be sent to the Moon.

There are several ways in which the value of this extra capability might be calculated, but at a conservatively low government price of $10,000/kg for payload in LEO, 250 MT of fuel for two missions per year is worth $2.5 B, at government rates. If a commercial provider can supply fuel at a lower cost, both the government and the contractor will benefit. This is a non-trivial market, and it will only grow as we continue to fly. The value of fuel for a single Mars mission may be several billion dollars by itself. Once industry becomes fully convinced that the United States, in company with its international partners, is headed out into the solar system for good, I believe that the economics of such a business will attract multiple competitors, to the benefit of both stockholders and taxpayers.

Continued

Best of all, such an approach enables us to leverage the value of the government system without putting commercial fuel deliveries in the critical path. If the depot is there and is full, we can use it. But with the architecture we have advanced, we can conduct missions to the Moon without it. The government does not need to have oversight, or even insight, into the quality and reliability of the fuel delivery service. If fuel is not delivered, the loss belongs to the operator, not to the government. If fuel is delivered and maintained in storage, the contractors are paid, whether or not the government flies its intended missions. If long-term delivery contracts are negotiated, and the provider learns to effect deliveries more efficiently, the gain is his, not the government's. Since fuel is completely fungible, it can be left to the provider to determine the optimum origin, size and method of a delivering it. And **finally, though I would rather not do it, it is even possible that we could develop such a market in stages, with the first fuel tank provided by the government, and then turned over to a commercial provider to store and maintain fuel for future missions, and to expand the tank farm as warranted by the market.**

To maintain and operate the fuel depot, periodic human support may be needed. Living space in Earth orbit may be required; if so, this presents yet another commercial opportunity for people like Bob Bigelow, who is already working on developing space habitats. So the logistics needs of the fuel depot may provide more of the same opportunities that we will pioneer with ISS.

Fuel and other consumables will not always be most needed where they are stored. Will orbital transfer and delivery services develop, 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. This might well be left to specialty suppliers who know nothing of the storage and maintenance of cryogenic tank farms, but who know a lot about how to generate and store power. Could these be standard power modules, developed and delivered for a fee to locations specified by the user?

In the course of conducting many fuel replenishment missions and associated operations, commercial launch and orbital systems of known and presumably high reliability will be developed and evolved. Government mission planners will be able to take advantage of these systems, which will become "known quantities" by virtue of their track record rather than through the at best mixed blessings of government development oversight.

Continued

There will also be a private sector role in supporting a variety of lunar surface systems and infrastructure, including lunar habitats, power and science facilities, surface rovers, logistics and resupply, communications and navigation, and in situ resource utilization equipment. There may or may not be gold on the Moon – I'm not sure we care – but we may well witness a 21st century gold rush of sorts when entrepreneurs **learn to roast oxygen from the lunar soil**, saving a major portion of the cost of bringing fuel to the lunar surface. Will a time come when it is more economical to **ship liquid oxygen from the lunar surface to low Earth orbit**, then to bring it up from Earth?

This will all start to become "really real" in 10 years or so. As I see it, these are exactly the kinds of enterprises to which government is poorly suited, but which **in the hands of the right entrepreneur can earn that person a cover on Fortune magazine**. But it will take enlightened government management to bring it about, management as much in the form of what not to do, as to do. In the coming years and decades, NASA must focus on its core government role as a provider of infrastructure broadly applicable to the common good, and too expensive for any single business entity to develop. NASA must remain on the frontier, and must conscientiously architect its plans to favor the inclusion of entrepreneurs through arms-length transactions wherever possible, restricting the use of classic "prime contracts" to situations where they are the right tool, not the default tool.

With the beginning of space station operations five years ago, we are now at a point children born at the beginning of the 21st century will live their lives knowing that there will always be people living and working in space. And the number of people who will be engaged in such activity will grow by leaps and bounds if we in government are faithful in executing our role in helping the private sector to step up to these new opportunities. I hope there are many entrepreneurs in this audience who have the vision to help us help them pioneer the commercial space frontier. You, and all those engaged in the quest that we are undertaking, have my sincere thanks and appreciation.

Other Related Comments from Mike Griffin

NASA HQ NEWS CONFERENCE; ESAS, SEPTEMBER 19, 2005;

http://www.nasa.gov/pdf/133896main_133896main_ESAS_rollout_press.pdf

- "…**if the availability of either water ice or hydrogen in other forms at the lunar poles is ultimately confirmed, then we will be able to extract hydrogen from the moon and would have the constituents of the most important propellant combination** for at least the next several decades right there on the moon".

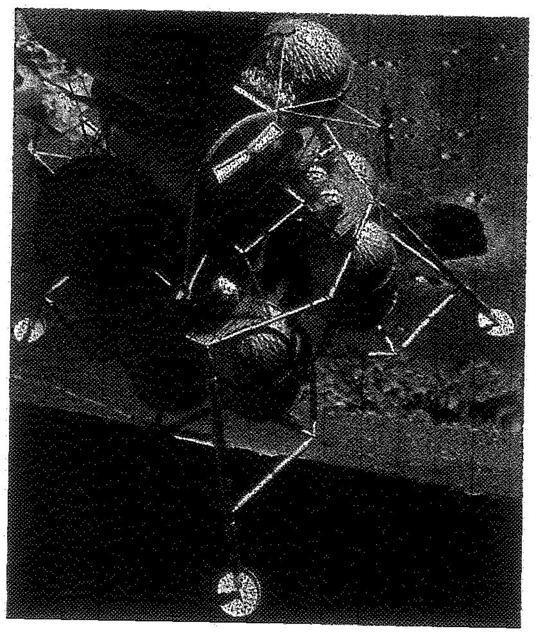
USA Today, October 4, 2005 :

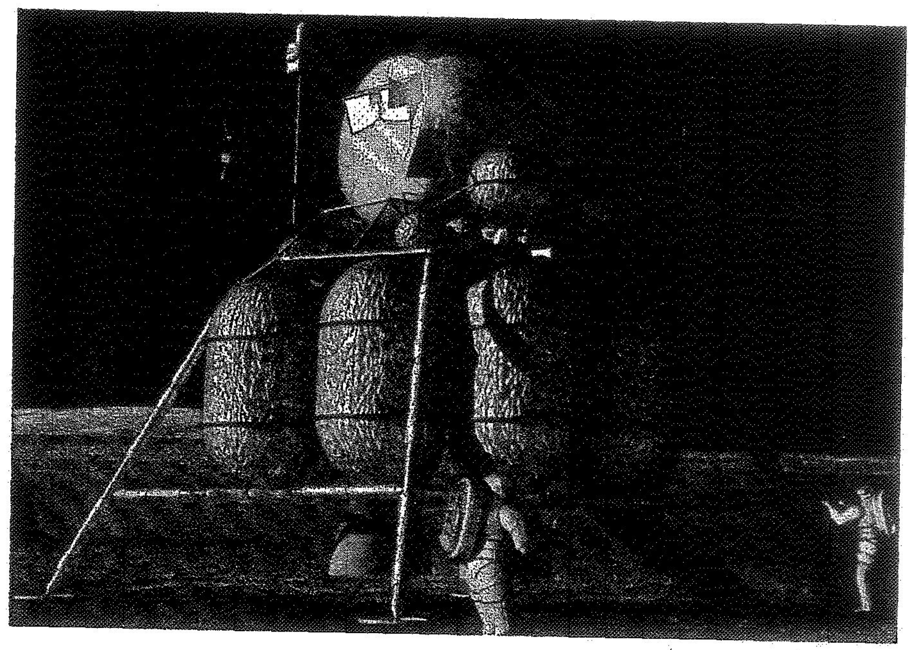
- "I envision the moon being utilized as a source of resources for space activity.
- **Q: What kinds of resources?**
- **A:** Possibly, **one of the most useful (resources) we will get from the moon is liquid oxygen. It can be extracted fairly easily from the lunar soil. If shipped from the moon to other storage depots, it will have very high value because it is half of the propellant needed for any exploration or any other rocketry activity over the next few decades."…**

Other Related Comments from Mike Griffin

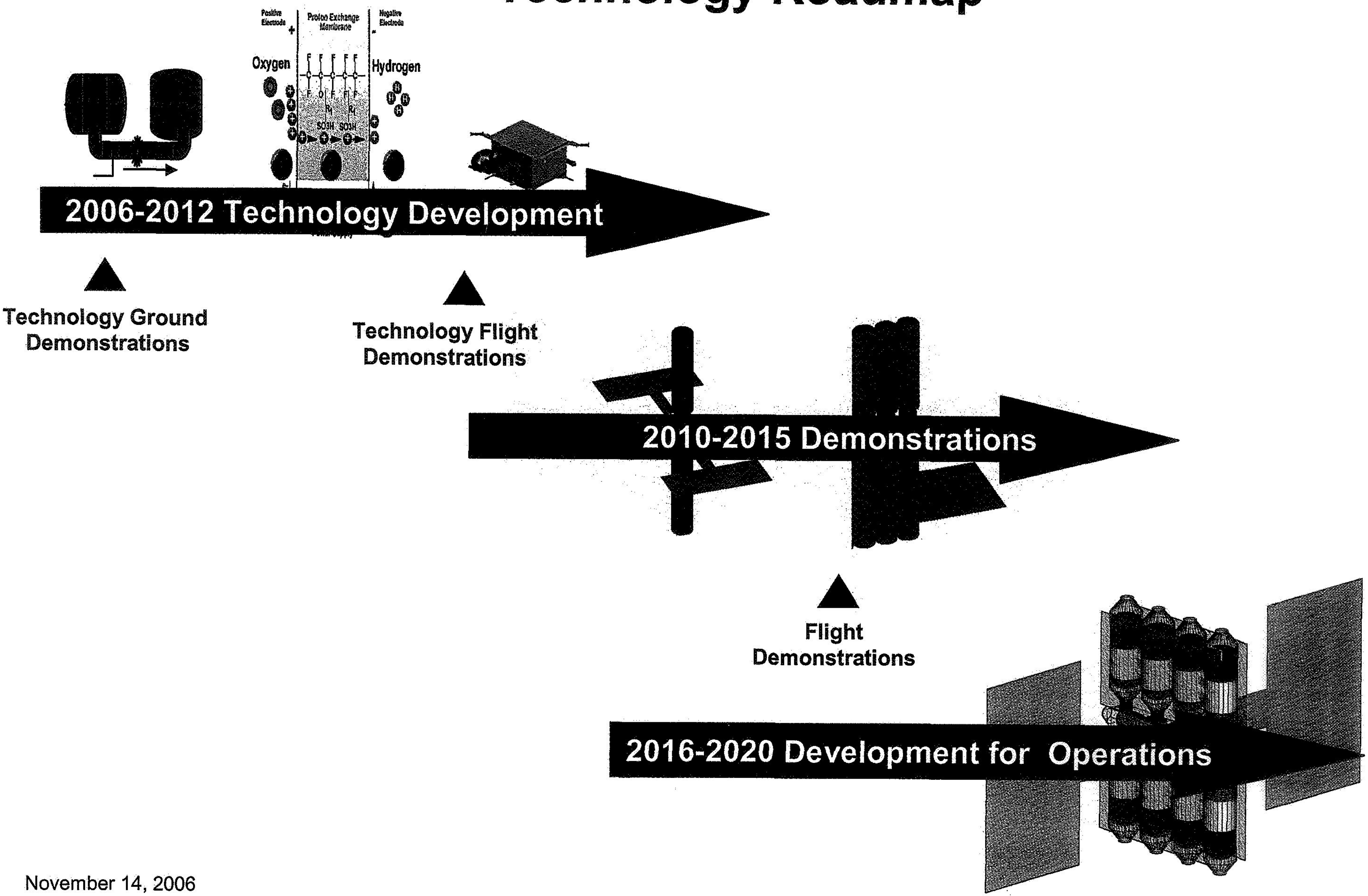
ESAS H2/O2 Lander (http://www.nasa.gov/pdf/133820main_ESAS_Facts.pdf):
"The lander will use a liquid oxygen/liquid hydrogen propulsion system for descent..."

Mike Griffin comments (http://www.nasa.gov/pdf/133896main_ESAS_rollout_press.pdf):
"The lander concept is very notional, because implicit in our requirement is the, we believe the requirement to have a man tended or tenable lunar base capability. That will be best obtained by a lander design, which leaves us much on the surface as possible, because the lander, of course, is expendable. There is no sense expending it to ill purpose. We'd like to leave as much on the surface as we can. So, the lander may well look different from this".





Technology Roadmap



Summary

- In-Space Cryogenic Propellant Depots (ISCPD) can offer significant advantages for NASA's space exploration systems
  - Refueling of in-space transfer stages at an ISCPD can support NASA's ESAS lunar exploration architecture and may be enabling for human exploration of Mars
- Large-scale cryogenic production from H2O in Earth orbit is technically feasible
- ISCPD expected to be modular construction with moderately-sized modules
- Solar Power Technologies enables efficient cryogenic propellant production from H_2O
- For LH2 & LO2 propellant production to be beneficial (for lunar and Mars missions), a lunar surface facility is <u>required</u> (production can't be exclusively in lunar orbit or L-1)
- Location near the North or South pole is needed for repeating launch window to facility in lunar polar orbit
- Technology demonstration may use secondary experiments on cryogenic upper stages for ready access to orbit
- 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
- Government GEO market will continue at about 1/3 of the commercial GEO market throughout the forecast period

Recommendations for the Future

1. Make In-Space Cryogenic Propellant Depots (ISCPD) part of NASA's future architecture plans.
2. Encourage Commercial ISCPD development via commercial launches
   - Contract for delivery of resources derived from residual cryogenic propellants on upper stages (e.g., oxygen and fuel cell power & water)
     - ISS resupply may use this strategy (is ~25% of payload mass)
     - TLI launches could also send stages to lunar orbit or L-1 (pre-position)
   - Fund new "Centennial Challenge" to demonstrate cryogen storage in orbit
3. Design cryogenic upper stages to exchange propellants with ISCPD
   - Define a standard interface panel (physical, electrical & fluid connections)
   - Develop autogenous pressurization systems for future stages and ISCPD
   - Design details of ESAS upper stages and Lander for ISCPD fluid transfer
4. Conducting ground and flight experiments with ISCPD components
   - Examine and test a wide range of technologies in an ISCPD test-bed
   - Perform secondary experiments on every launch of cryogenic upper stages
     - Use remaining fluids (rather just venting those cryogens)
5. Build and test a prototype ISCPD module based on surplus hardware
   - Simulate upper stage for ground tests (before flight experiments)
   - Modify system to become prototype ISCPD module for integrated testing
6. Study a lunar surface ISCPD
   - Define and test systems to store and use remaining Lander propellants
     - Transfer fluids to robots with fuel cells; Retain gO2; Make power + H20
   - Consider cold polar crater environments for cryogenic propellant storage
   - Assess propellant production from H20 & H2 in lunar soil