

Cryogenic Propellant Depot Experiments, Demonstrations and Applications

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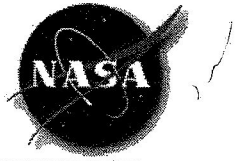
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Abstract. Cryogenic Propellant Depots have been assessed over many years in terms of architectures, system configuration trades, related technologies, economic assessments, etc., to enable more ambitious and affordable human and robotic exploration of the Earth Neighborhood and beyond. These activities have identified architectures and concepts that produce, preposition and store propellants in space for exploration and commercial space activities. Commonalities across mission scenarios for these architecture definitions, depot concepts, technologies, and operations were identified that also best satisfy the Vision of Space Exploration.

The Boeing Company supported the NASA, Marshall Space Flight Center (MSFC) by conducting Architecture Definitions and Systems Studies. The primary objectives were: (1) determine high leverage propellant depot concepts and related technologies; (2) identify commonalities across mission scenarios of depot concepts, technologies, and operations; (3) determine the best depot concepts and key technology requirements and (4) identify technology development needs including definition of ground and space demonstration requirements.

This presentation briefly summarizes potential ground and flight experiments and demonstrations as well as discusses various commercial and exploration applications of Cryogenic Propellant Depots.

STAIF 2007



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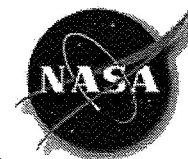
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February 11-15, 2007

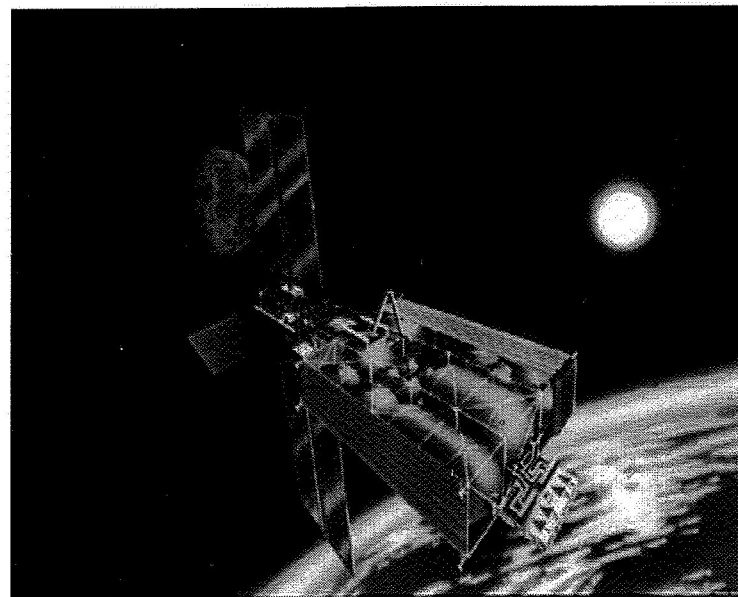
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Objectives of an Cryogenic Propellant Depot

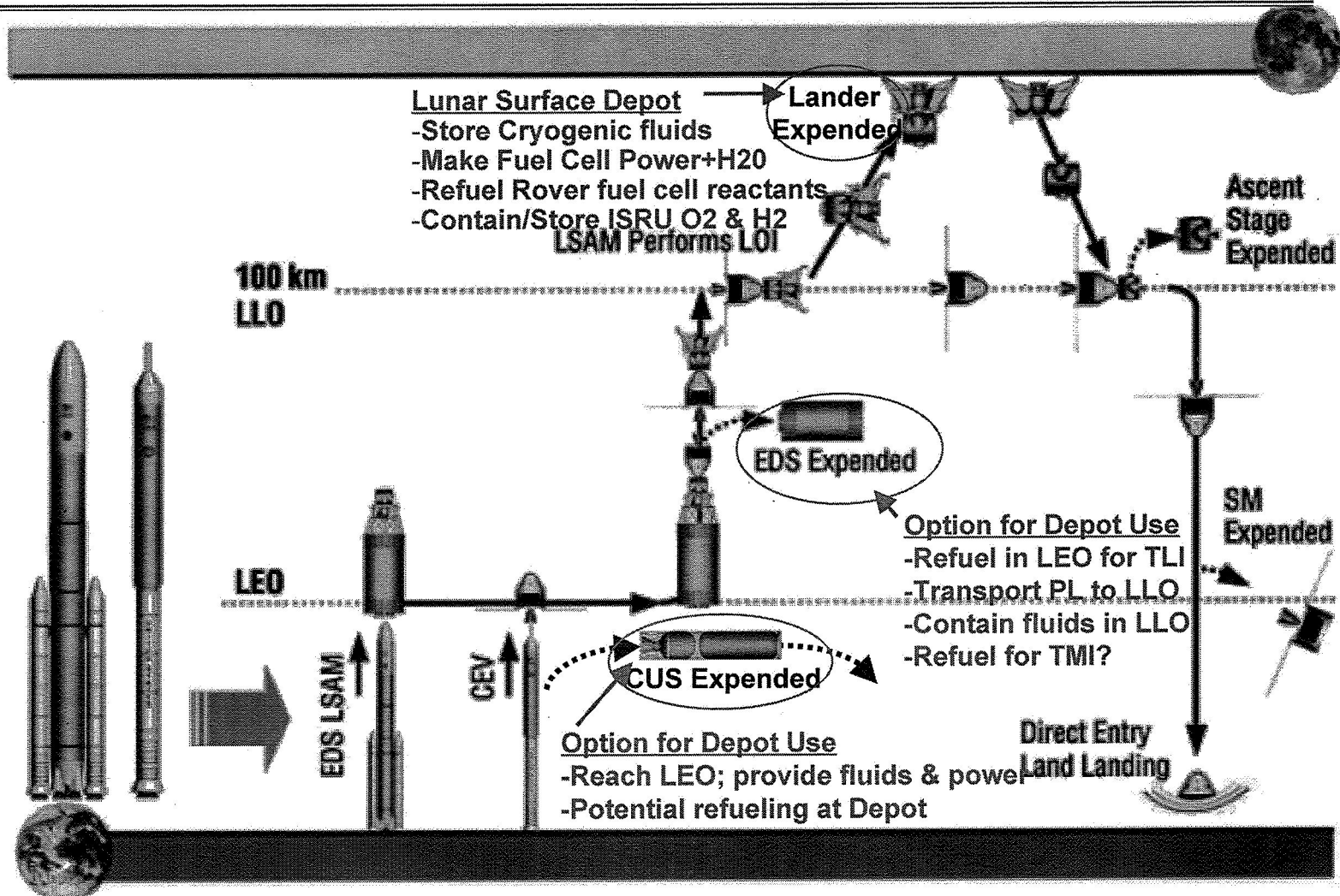


- Servicing of propellants and consumables in space
- Manage the economics of cryogenics without undue or complicated impositions on infrastructure, other systems, or mission operations
- Autonomous fluid management operations without the complications of propellant settling and without extravehicular activity (EVA) support



The basic goal: enable automated zero-g storage and transfer of cryogenic fluids from supply tanks to user tanks: safely, reliably, and with minimum loss of propellant.

Possible 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

Configuration and System Trades

Effects of Location on Depot Design Environments



LOCATION FACTORS	Low Earth Orbit (LEO)	Lunar Surface (e.g., Polar)	Lunar Orbit (e.g., Polar)	L-Point (e.g. E-M L-1)	Mars Orbit (& moons)	Mars Surface
Priority	1	2	2 or 3	2 or 3	3	4
Exposure to Sunlight (Boil-off & solar power)	~ 60% of the time	Near 100% on polar mountain & 0% in crater	~60-100%, bi-weekly variation	Near 100% (occasional 1.5 hr eclipse)	Near 45% of solar constant at Earth	24 hr day; dust-storms; Year-long day & night at Pole
Secondary Heating	Earth Albedo ~300K	~400K in day ~40-100K in polar craters;	Lunar Albedo ~100-400K	Albedo is insignificant	Less than Earth	Atmosphere & local albedo
Heat Rejection	Radiate to deep space	Heat exchange with lunar ice?	Radiate to deep space	Radiate to deep space	Radiate to deep space	Dust issues; Clouds
Comm. Link Availability	~100% (TDRSS) (~ 1 sec delay)	Up to 100% (on near-side) (3 sec delay)	~60-100%, monthly cycle (3 sec delay)	100% (3 sec delay)	100% except at opposition (40 min.delay)	Up to 100% (at poles) (40 min.delay)
Micro-Meteoroids & Orbital Debris	No "up" flux, gravity increase Debris impacts front & sides	Large increase from lunar meteor ejecta (top & sides)	No "up" flux, gravity increase Lunar ejecta impacts front	Natural deep space flux Orbital debris absent	Increased flux of meteoroids No orbital debris	Protected by atmosphere
Propellant Settling	G. gradient settling option	Gravity ~1/6 g	G. gradient settling option	No gravity field	G. gradient settling option	Gravity ~1/3 g

Key Technology Challenges



- **Tele-supervised (and eventually autonomous) highly resilient deep space systems operations** (in this case, 'deep space' operations includes all ambitious mission operations beyond LEO).
- **Reconfigurable and self-adaptive modular systems.**
- **Space assembly, maintenance and servicing** (from the systems level, down to the subsystem level).
- **Highly fuel-efficient, high reliability, re-startable propulsion**, such as high-power electric propulsion for cargo and **cryogenic engines** for time critical mission (such as those involving astronaut crews).
- **High-energy propellants for long-duration missions (particularly cryogenic propellants such as liquid oxygen, liquid hydrogen, etc.)**
- **Long-term storage and management, as well as the highly reliable and low-loss transfer (including transfer in micro-gravity) of cryogenic propellants.**
- **High-power, but low-mass space power generation and management systems**

Key Functional Challenges

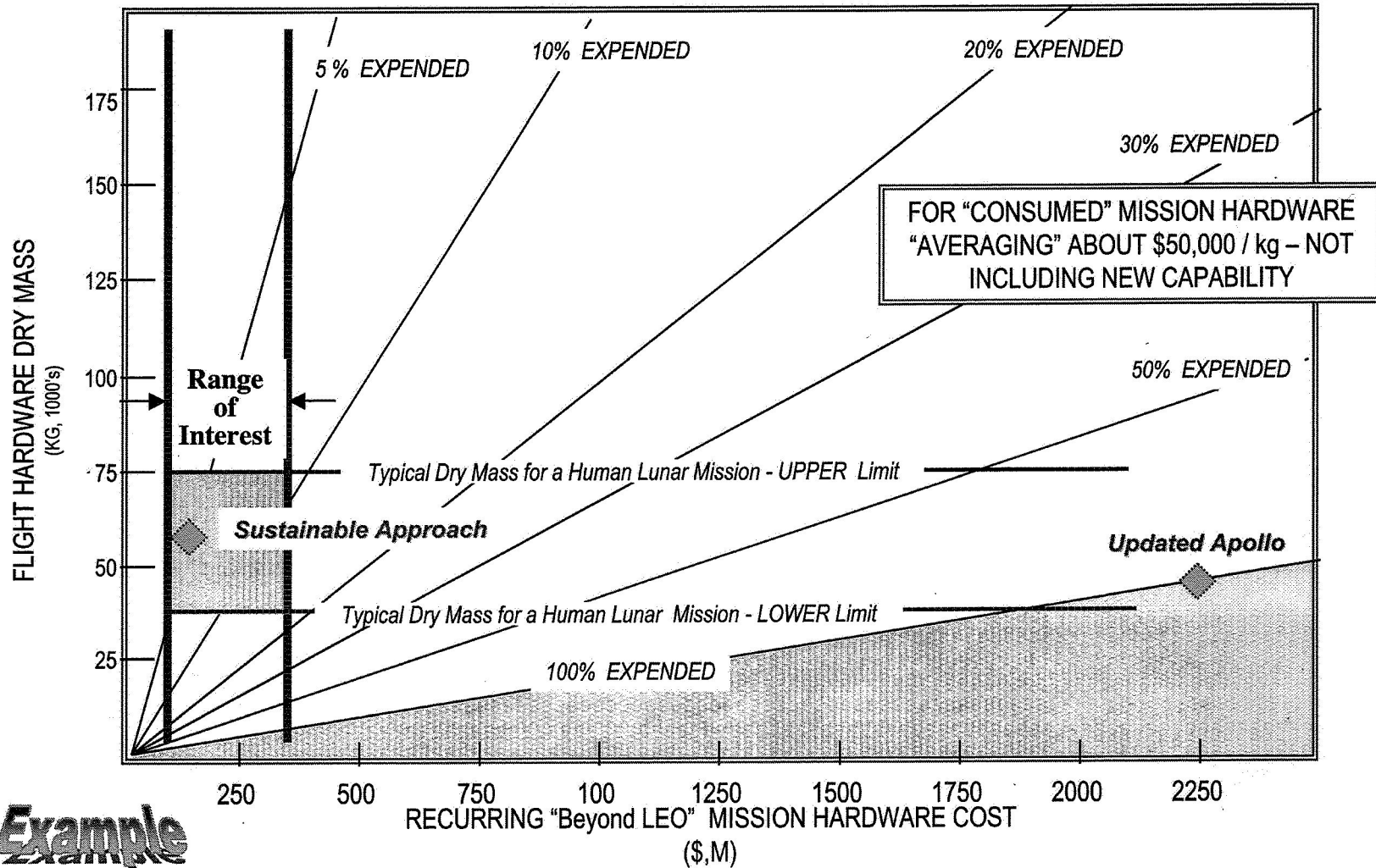


- Lower cost ETO transport (perhaps by enabling a transition to launchers that are more similar to those used by other government organizations or by commercial sectors; and in the long term by transitioning to reusable launch vehicles);
- Highly-autonomous assembly, maintenance and servicing of systems in space and on planetary surfaces (including both robotic and crew-assisted operations),
- Affordable and timely pre-positioning of fuel, systems and other materiel throughout the Earth-Moon system (including to the surface of the Moon); and,
- Reusable, highly reliable and high-energy in space transportation (and for lunar missions, excursion transportation systems).

Cryogenic Propellant Depots are critical to the Affordable and timely pre-positioning of fuel throughout the Earth-Moon system (including to the surface of the Moon)

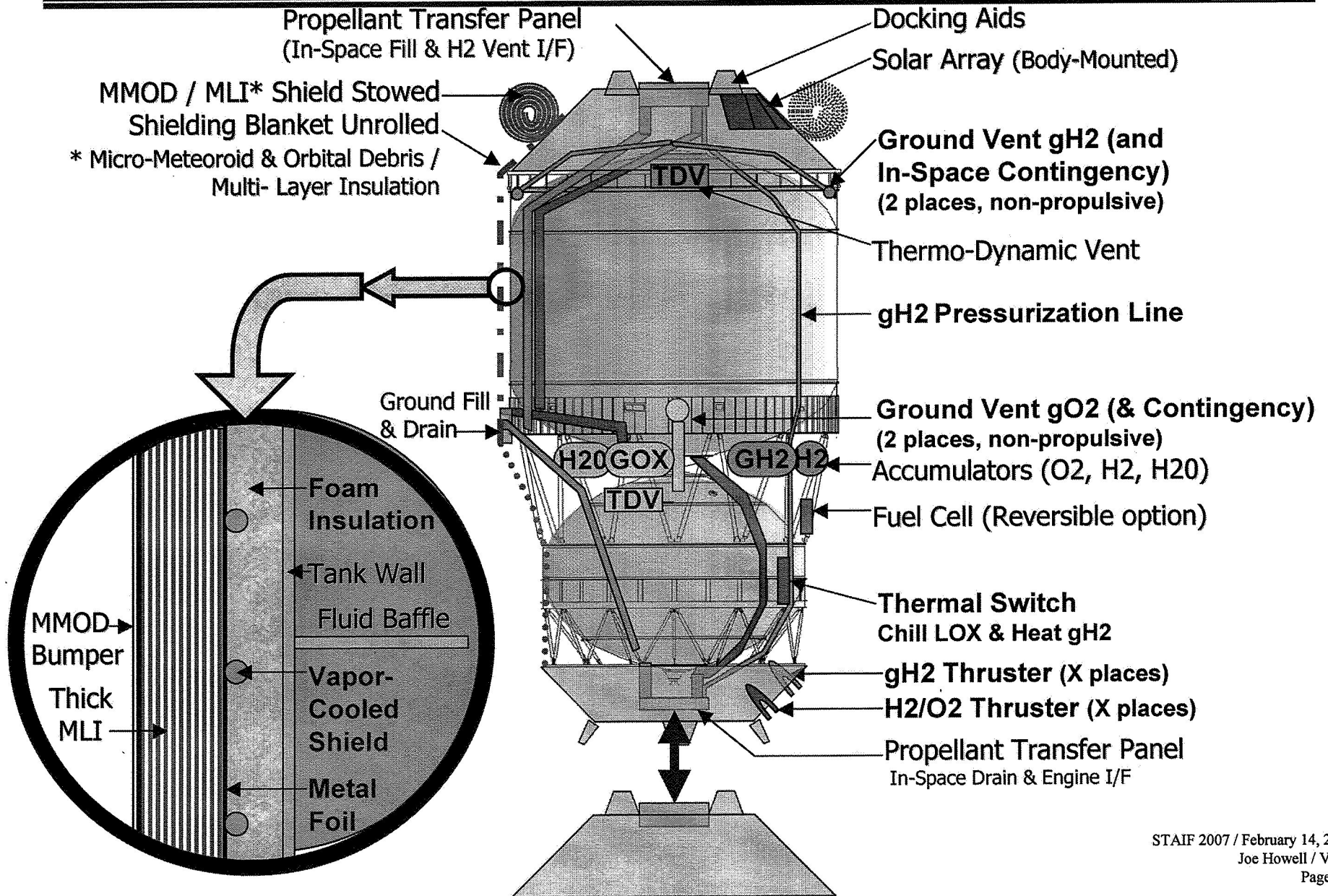
The Challenge of Affordability

The High Cost of Expendable Space Systems

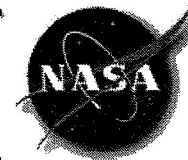


Reusable Space Systems are critical to reducing excessive 'expendable hardware' costs of Apollo-derived architectures.

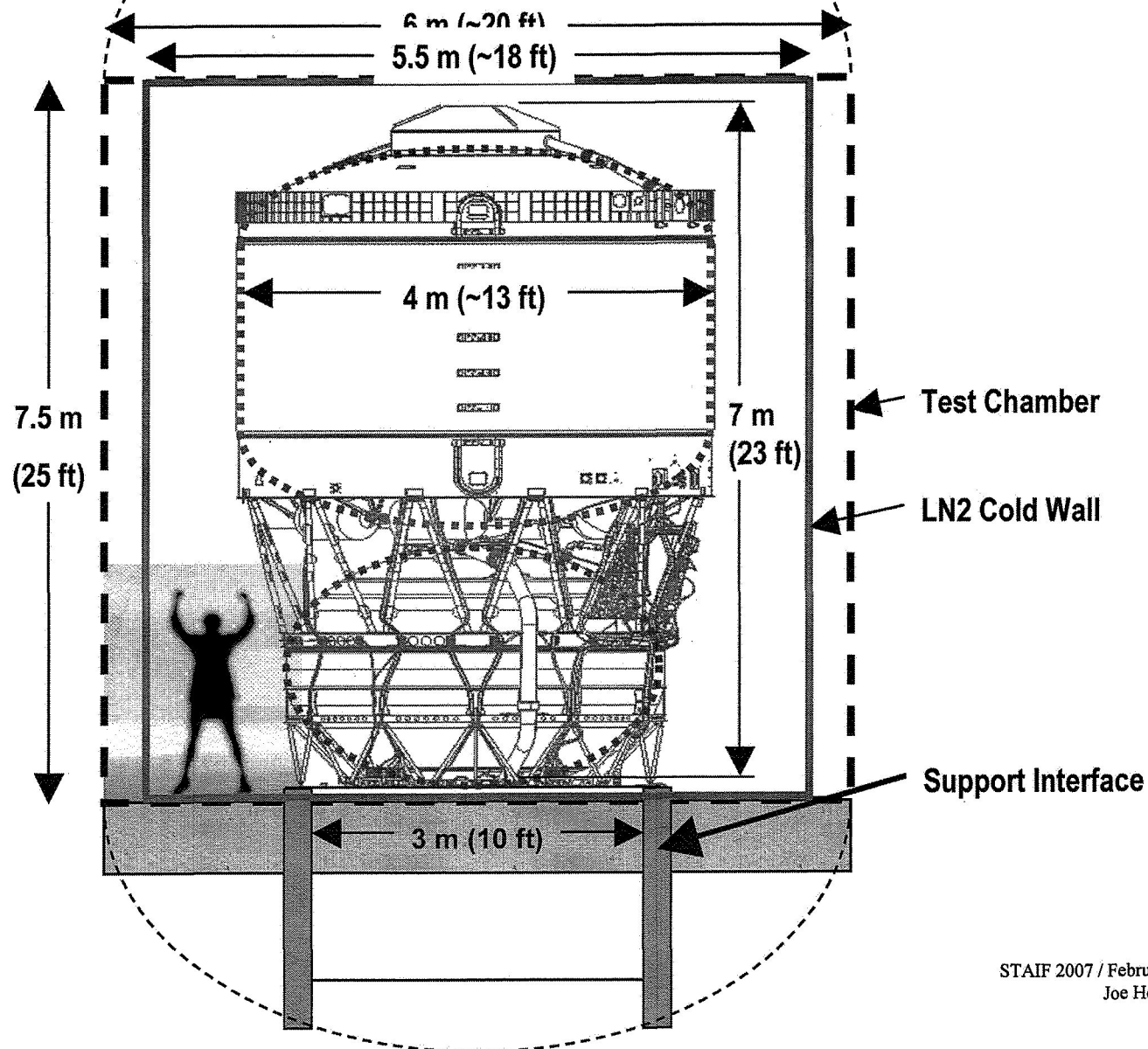
Reference Depot Module Concept



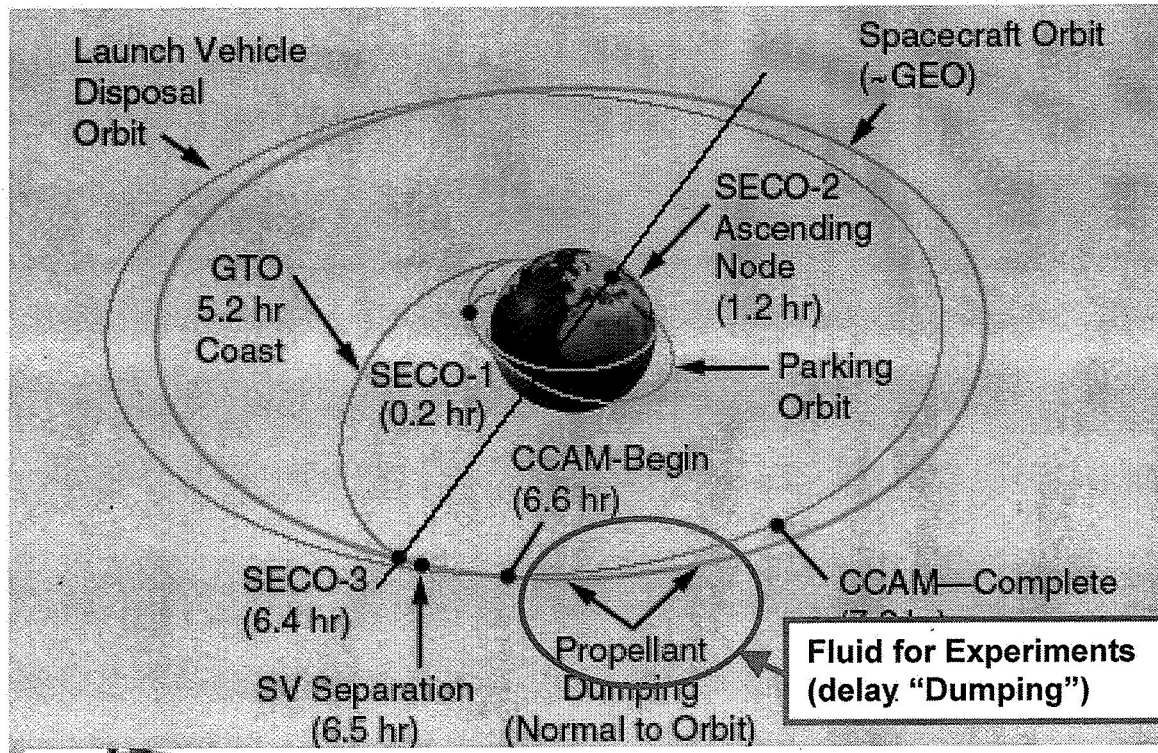
Example Use of Delta III Tanks in Vacuum Chamber



Ground Test of Integrated Depot Module System-level Checkout for Experimental Hardware prior to Secondary Space Flight Demonstration

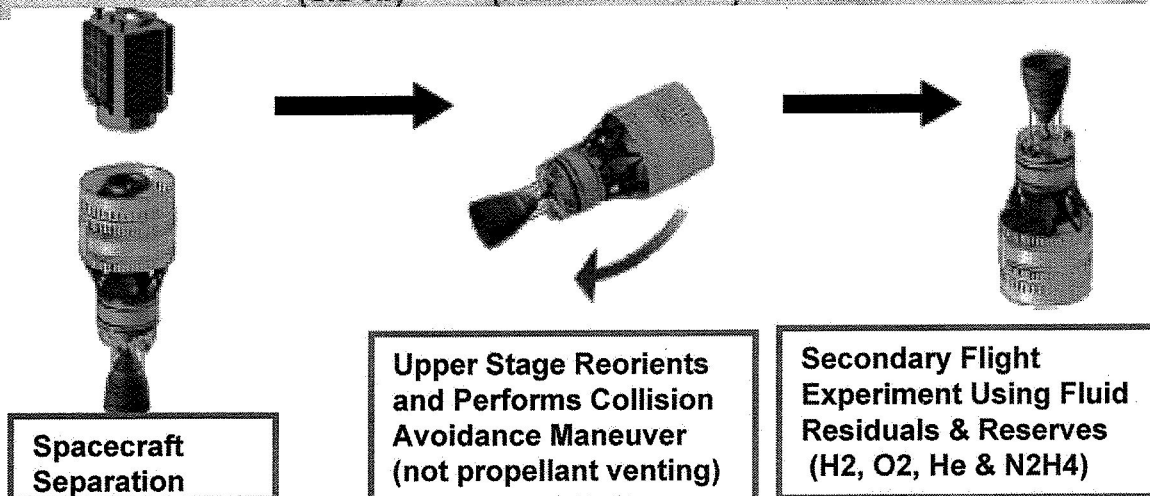


Secondary Flight Experiment Opportunities

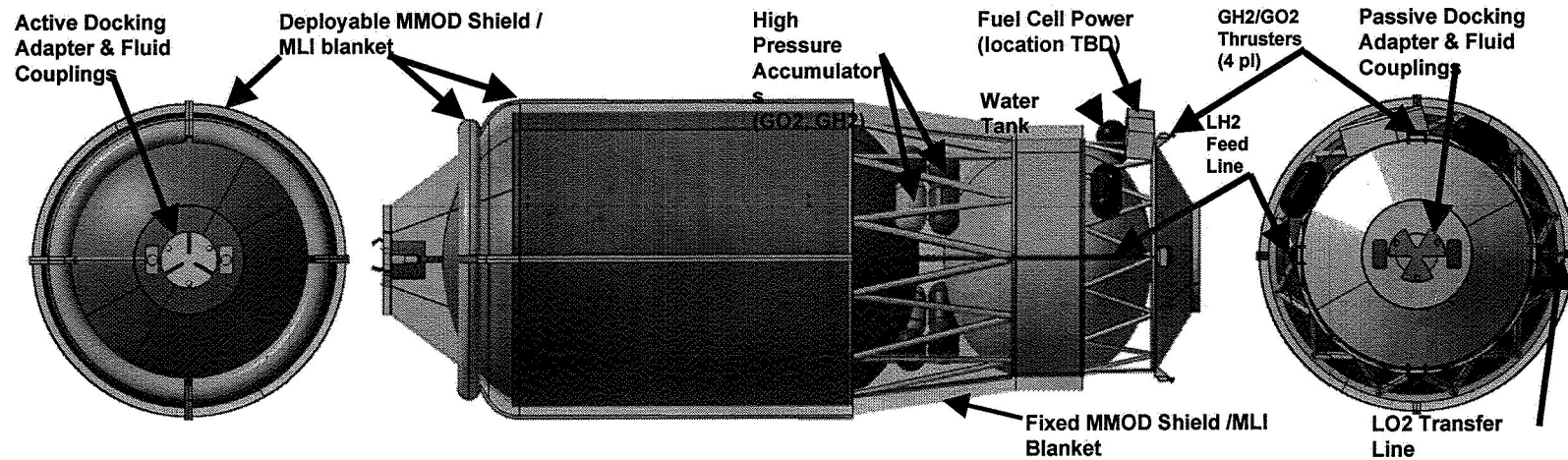


Cryogenic Fluid Flight Experiment Objectives

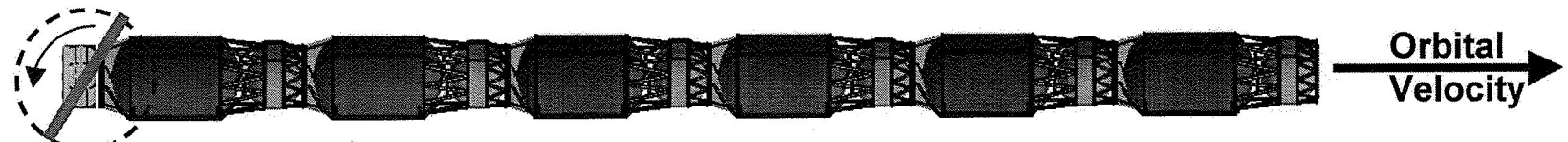
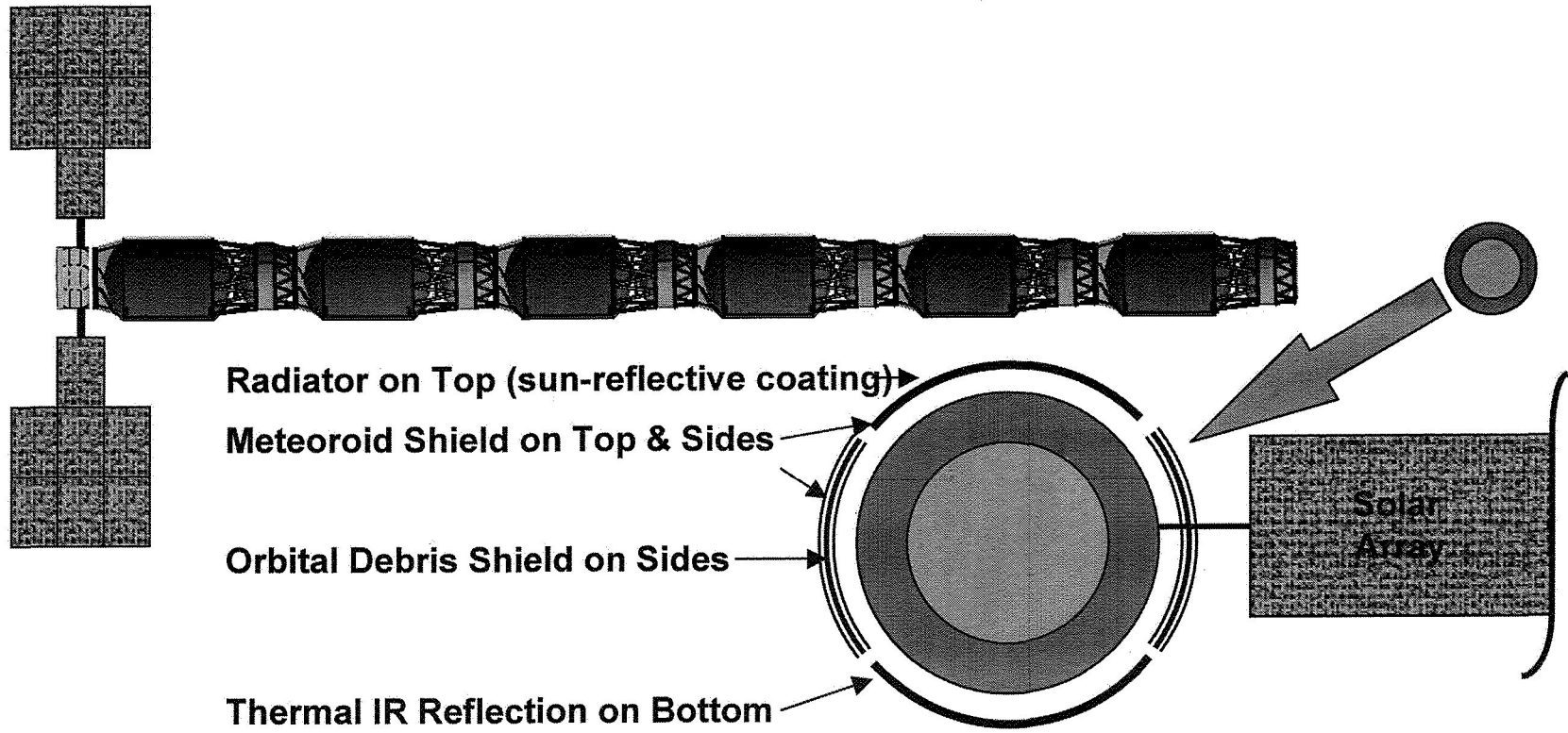
- Test or demonstrate technology
- Demonstrate operational concepts
- Develop or emplace infrastructure
- Advance commercial opportunities
- Collect engineering data (support ESAS)



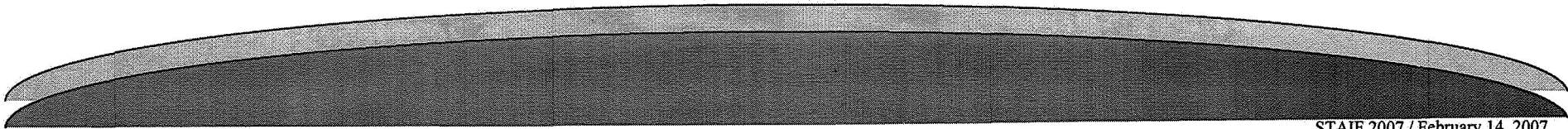
Reference Depot Module Design



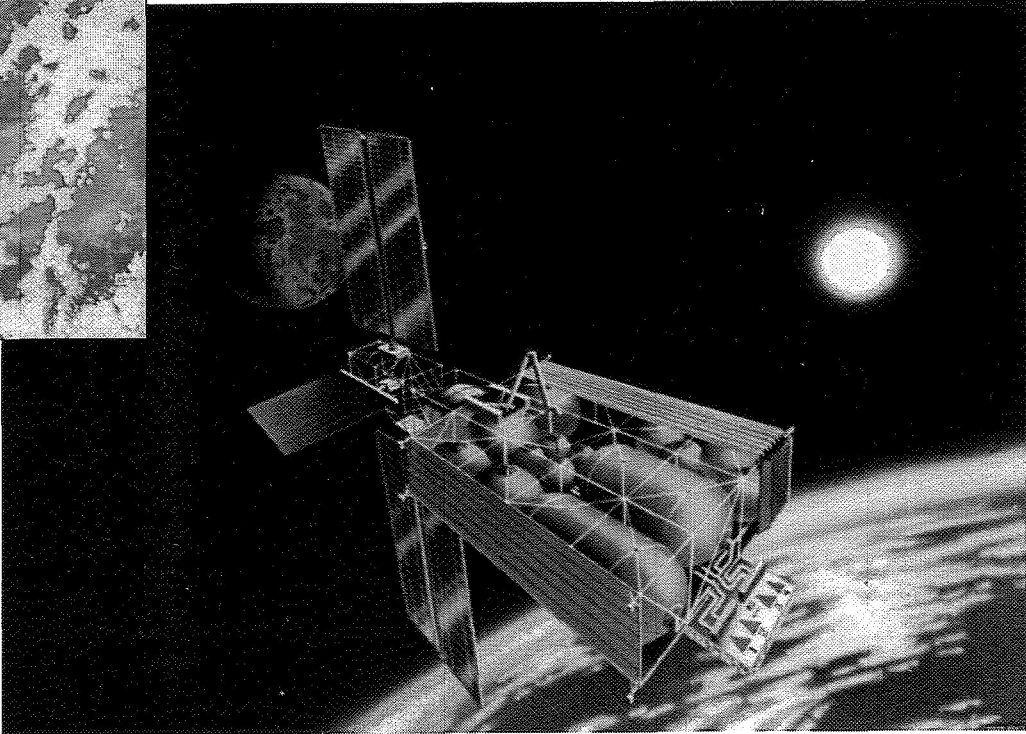
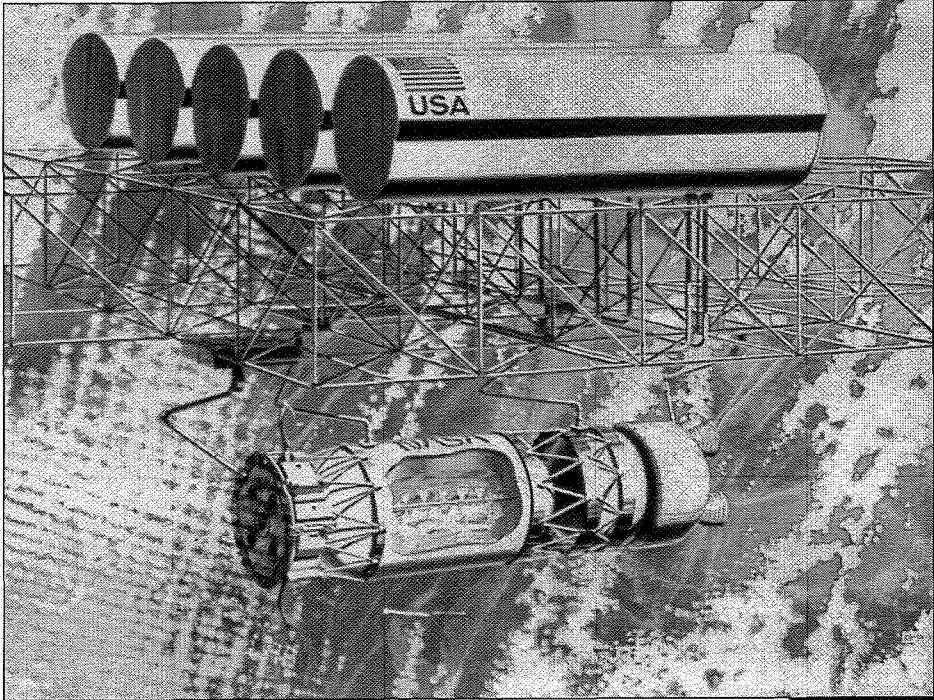
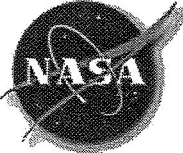
Growth Depot Facility in LEO: Add Propellant and Power for Refrigeration



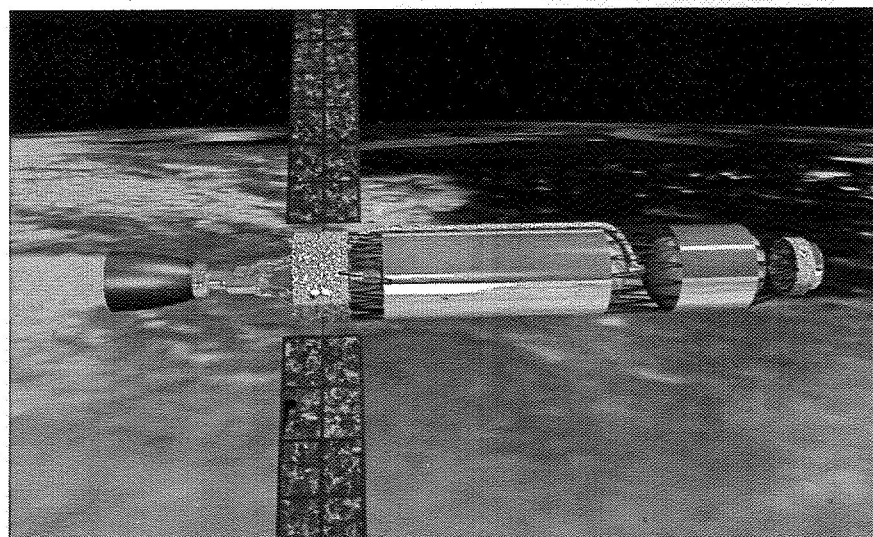
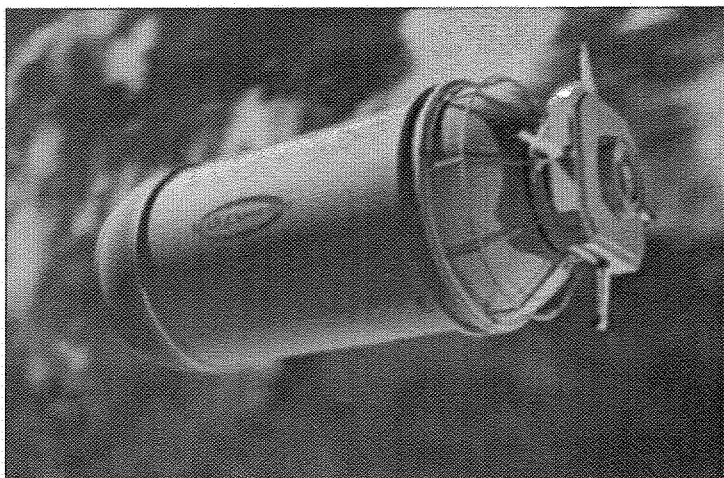
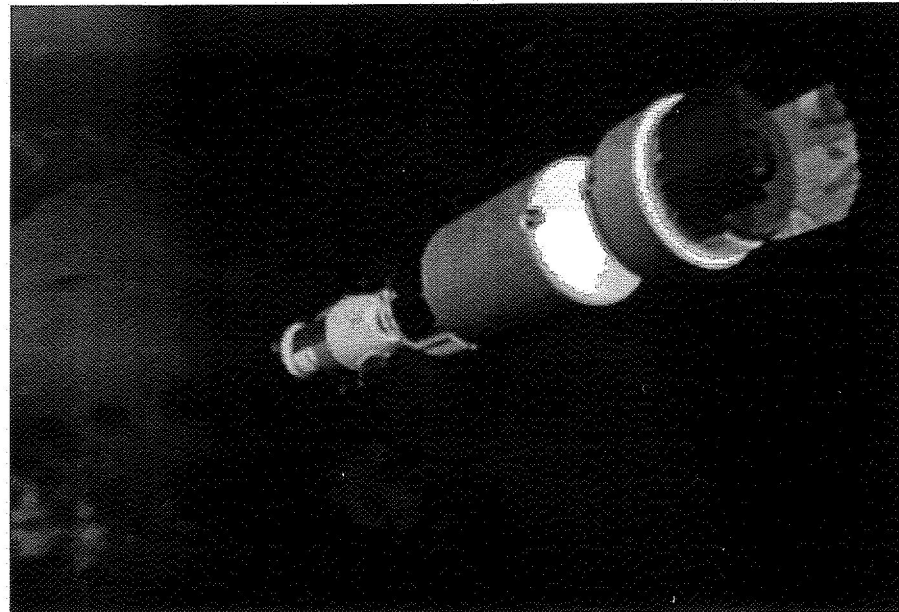
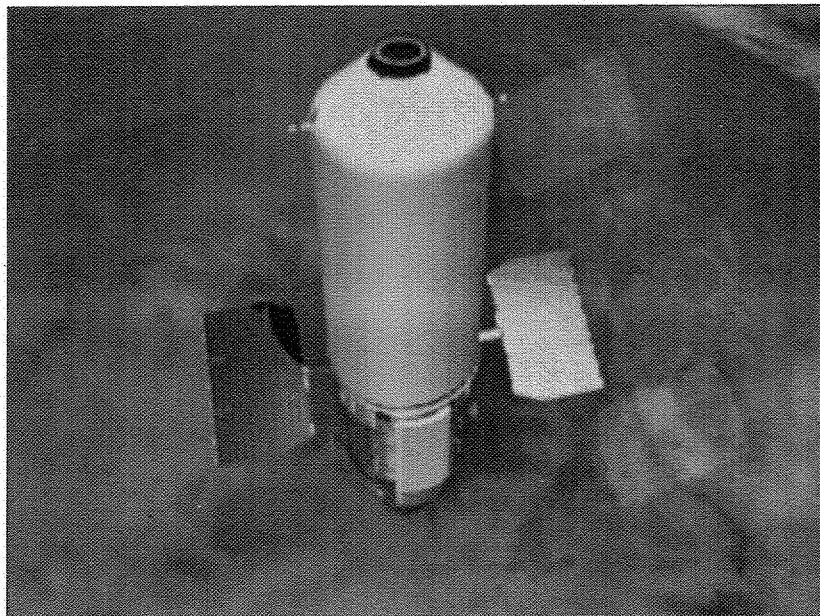
Atmospheric Drag from Solar Array Stabilizes & Settles Propellant "Forward"



Cryogenic Propellant Depots Low Earth Orbit Depot Concepts



Cryogenic Propellant Depots Deployable Orbit Depot Concepts - "HPM"



Summary



- Cryogenic Propellant Depots can offer significant advantages for NASA's space exploration systems
 - Refueling of in-space transfer stages can support NASA's ESAS lunar exploration architecture and may be enabling for human exploration of Mars
- Depot modules are expected to be moderately-sized
 - Allowing deliver of modules to LEO nearly full of propellant (as upper stages without main engines)
- Depot design recommendations include modular construction and autogenous pressurization (no He gas)
- Technology demonstration may use secondary experiments on cryogenic upper stages for ready access to orbit