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Abstract


The cost of access to space beyond low Earth orbit may be reduced if vehicles can refuel in orbit. The cost of access to low Earth orbit may also be reduced by launching oxygen and hydrogen propellants in the form of water. To achieve this reduction in costs of access to low Earth orbit and beyond, a propellant depot is considered that electrolyzes water in orbit, then condenses and stores cryogenic oxygen and hydrogen. Power requirements for such a depot require Solar Power Satellite technologies.

A propellant depot utilizing solar power technologies is discussed in this paper. The depot will be deployed in a 400 km circular equatorial orbit. It receives tanks of water launched into a lower orbit from Earth, converts the water to liquid hydrogen and oxygen, and stores up to 500 metric tons of cryogenic propellants. This requires a power system that is comparable to a large Solar Power Satellite capable of several 100 kW of energy. Power is supplied by a pair of solar arrays mounted perpendicular to the orbital plane, which rotates once per orbit to track the Sun. The majority of the power is used to run the electrolysis system. Thermal control is maintained by body-mounted radiators; these also provide some shielding against orbital debris. The propellant stored in the depot can support transportation from low Earth orbit to geostationary Earth orbit, the Moon, LaGrange points, Mars, etc.

Emphasis is placed on the Water-Ice to Cryogen propellant production facility. A very high power system is required for "cracking" (electrolyzing) the water and condensing and refrigerating the resulting oxygen and hydrogen. For a propellant production rate of 500 metric tons (1,100,000 pounds) per year, an

average electrical power supply of 100's of kW is required. To make the most efficient use of space solar power, electrolysis is performed only during the portion of the orbit that the Depot is in sunlight, so roughly twice this power level is needed for operations in sunlight (slightly over half of the time). This power level mandates large solar arrays, using advanced Space Solar Power technology. A significant amount of the power has to be dissipated as heat, through large radiators.

This paper briefly describes the propellant production facility and the requirements for a high power system capability. The Solar Power technologies required for such an endeavor are discussed.



Utilizing Solar Power Technologies for On-Orbit Propellant Production

**Presentation to The 25th Annual International Space
Development Conference**

Los Angeles, Ca

May 4-7, 2006

**John C. Fikes, Marshall Space Flight Center
Joe T. Howell, Marshall Space Flight Center
Mark W. Henley, The Boeing Company**

Introduction



Water to Cryogen Production Concept

- 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 depot technology will enable sustainable human missions at any location where water can be found, (i.e., Moon, Mars, 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.
- The basic concept for production of LH2 and LOX is through an electrolysis process commonly used in fuel cells. The process cracks the water into hydrogen and oxygen gasses. These gasses are separated and refrigerated at cryogenic temperatures to convert the gasses to liquid propellants.
- Production capabilities would enable new commercial markets for reusable high-energy upper stages, satellite services, and water and oxygen for ongoing human operations.



Assumptions/Guidelines

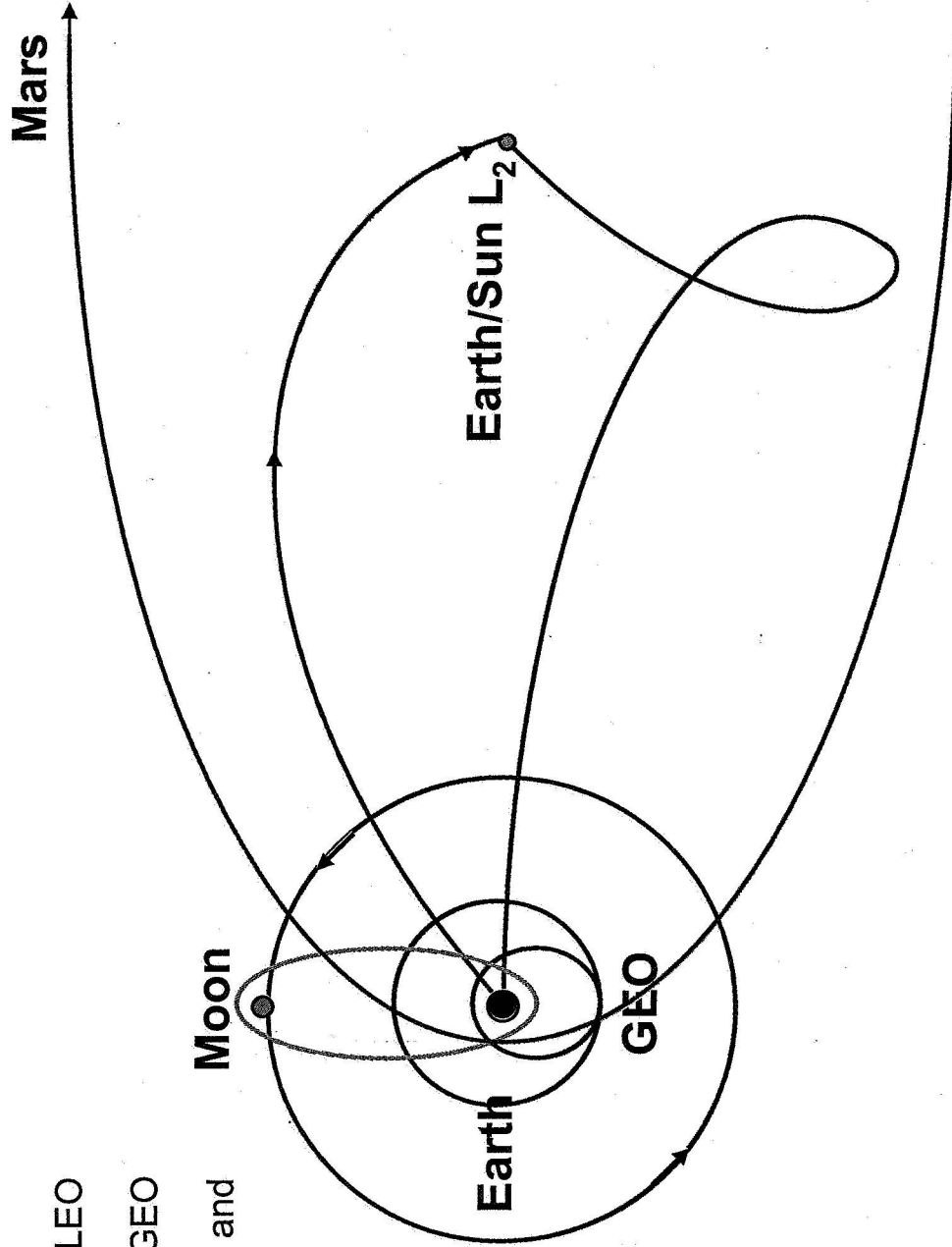
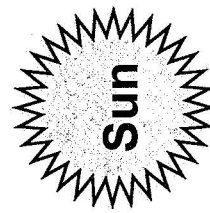
- Design of a water to propellant production capability
- Production rate base-lined at ~ 500 metric tons (MT) per year
 - One depot for a Lunar or L2 mission
 - Two depots for a Mars mission
- Water delivery options:
 - ELV/OMV
 - RLV/OMV
- Equatorial Orbit
- 400 km altitude
- ELV or RLV launch of depot components from equatorial sites
- Automated assembly and maintenance with minimal human interaction
- Requires Solar Power Satellite technology development

Utilizing Solar Power Technologies for On-Orbit Propellant Production Applications

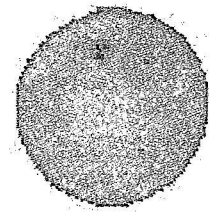


Propellant Depot Missions

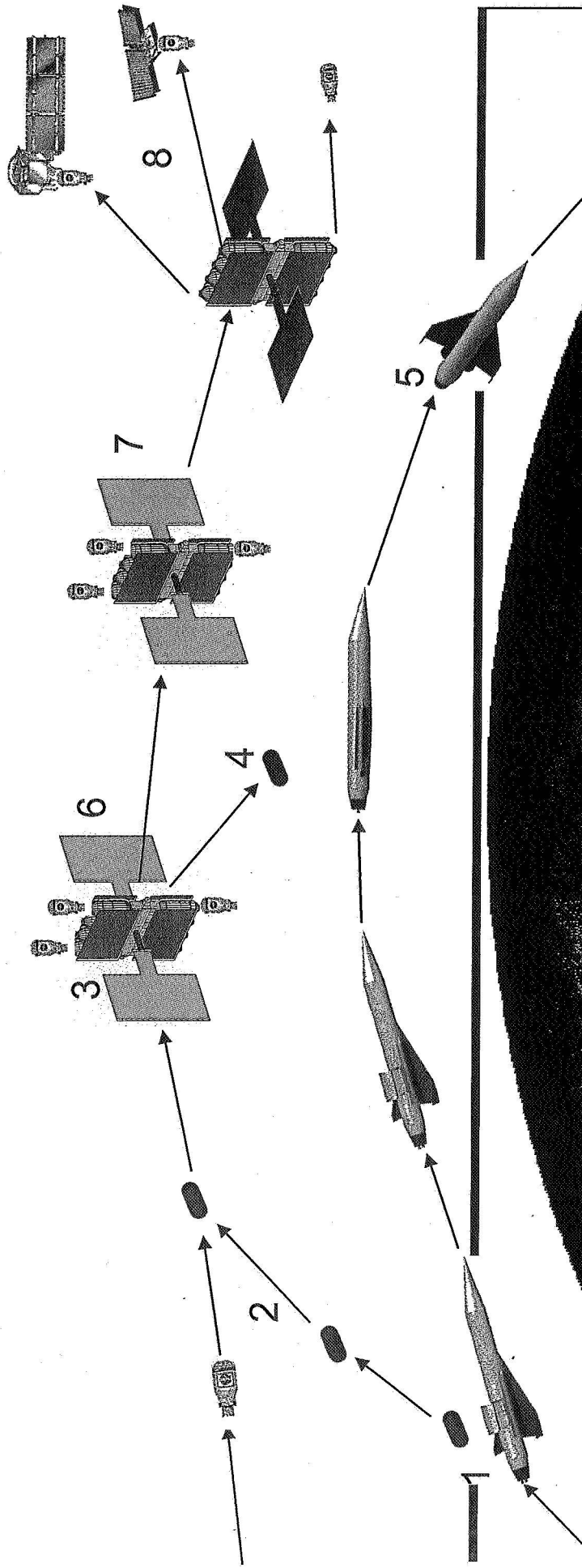
- Refuel OMVs for transfers in LEO
- Refuel OTVs for transfers to GEO
- Refuel Storage Depots for L2 and Lunar missions



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



Utilizing Solar Power Technologies for On-Orbit Propellant Production Mission Scenario



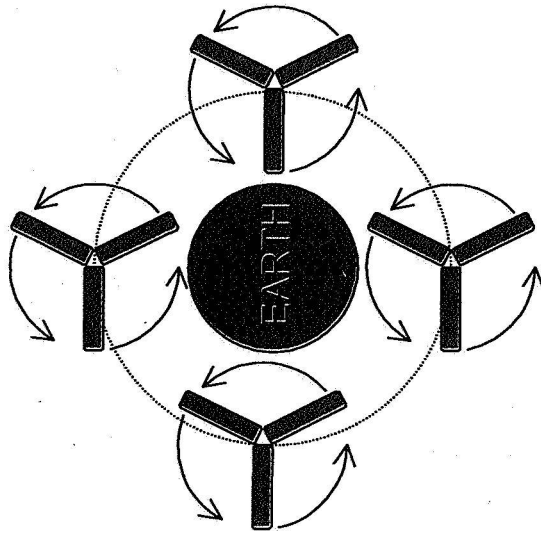
1. RLV/ELV delivers water tank to orbit
2. OMV captures water tank and transfers to Depot
3. Water is transferred to holding tanks at Depot
4. Transfer tank is returned to RLV or de-orbited (ELV)

5. RLV returns to launch site
6. Water is cracked into LH2 and LOX for propellants
7. Propellants are transferred to OMV's, OTV's and storage depots
8. OMV's, OTV's and storage depots transfer to other destinations via chemical, electric or solar thermal propulsion

Utilizing Solar Power Technologies for On-Orbit Propellant Production
Approaches for Cryogenic Settling

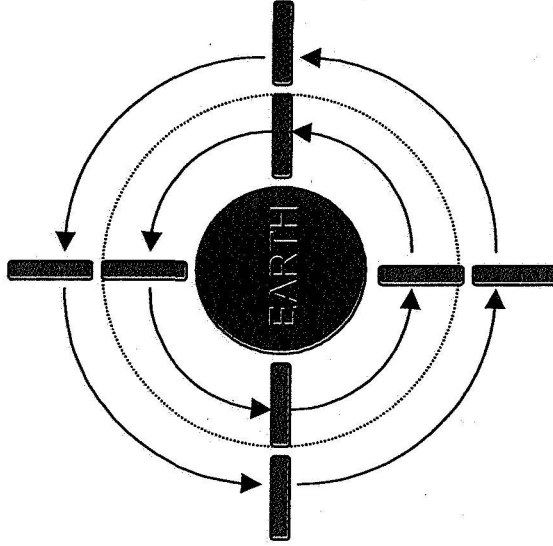


Rotating Depot



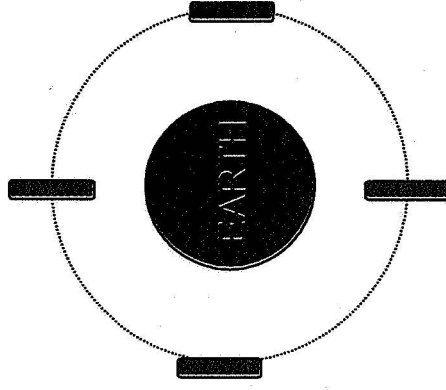
- Suitable for Deep Space
- Requires de-spun docking

Gravity Gradient Depot



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

Solar Inertial

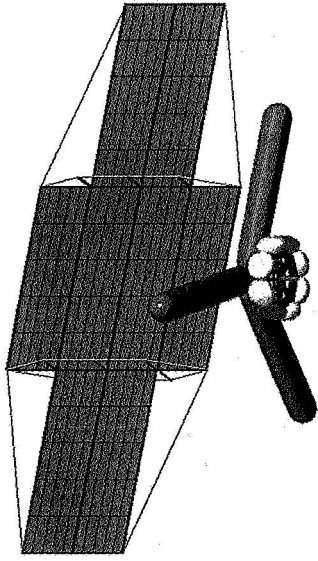


- Sun Pointing
- No alpha/beta joints
- Requires zero-g propellant acquisition

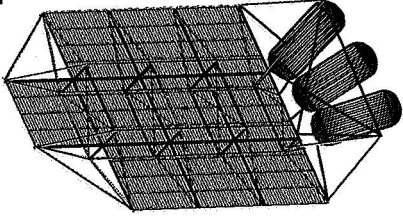
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Concepts for Cryogenic Propellant Depots



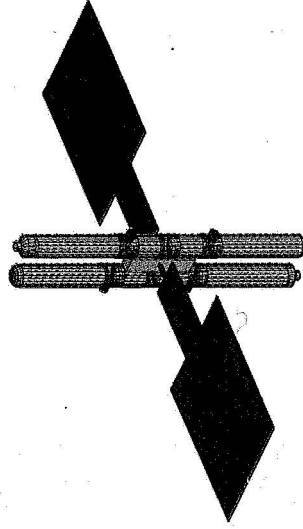
Spinner Concept



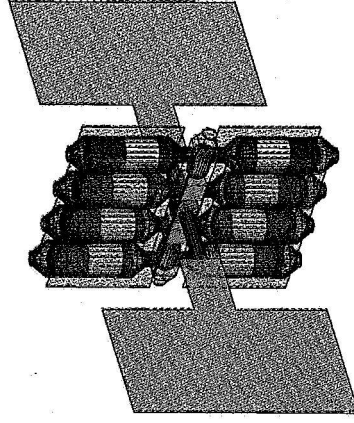
Abacus Quasi-Inertial Concept



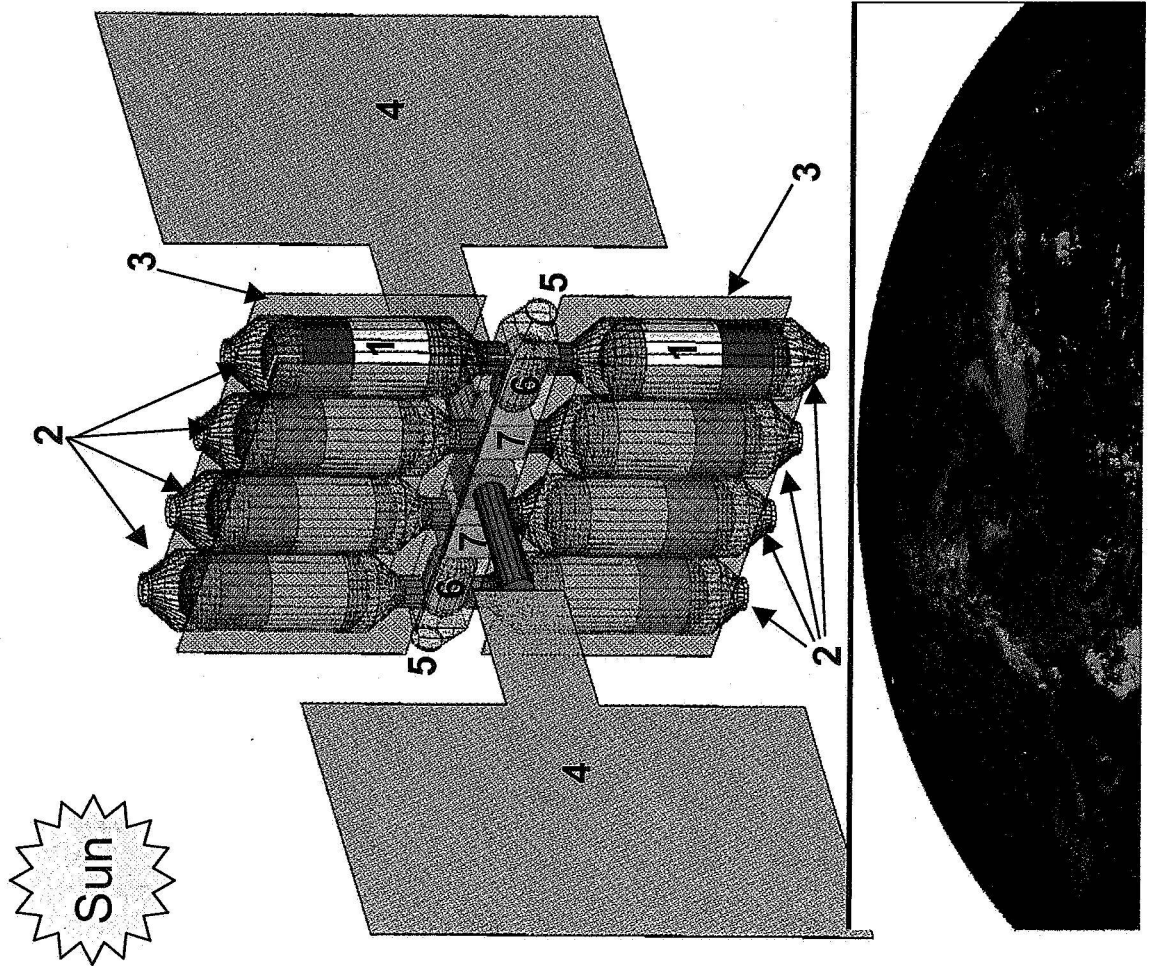
Preliminary Gravity Gradient Concept



Gravity Gradient Concept



Utilizing Solar Power Technologies for On-Orbit Propellant Production
On-Orbit Propellant Production Design



1. LOX/LH2 Storage Tanks

2. Transfer Vehicle Docking Ports

3. Radiators

4. Solar Arrays

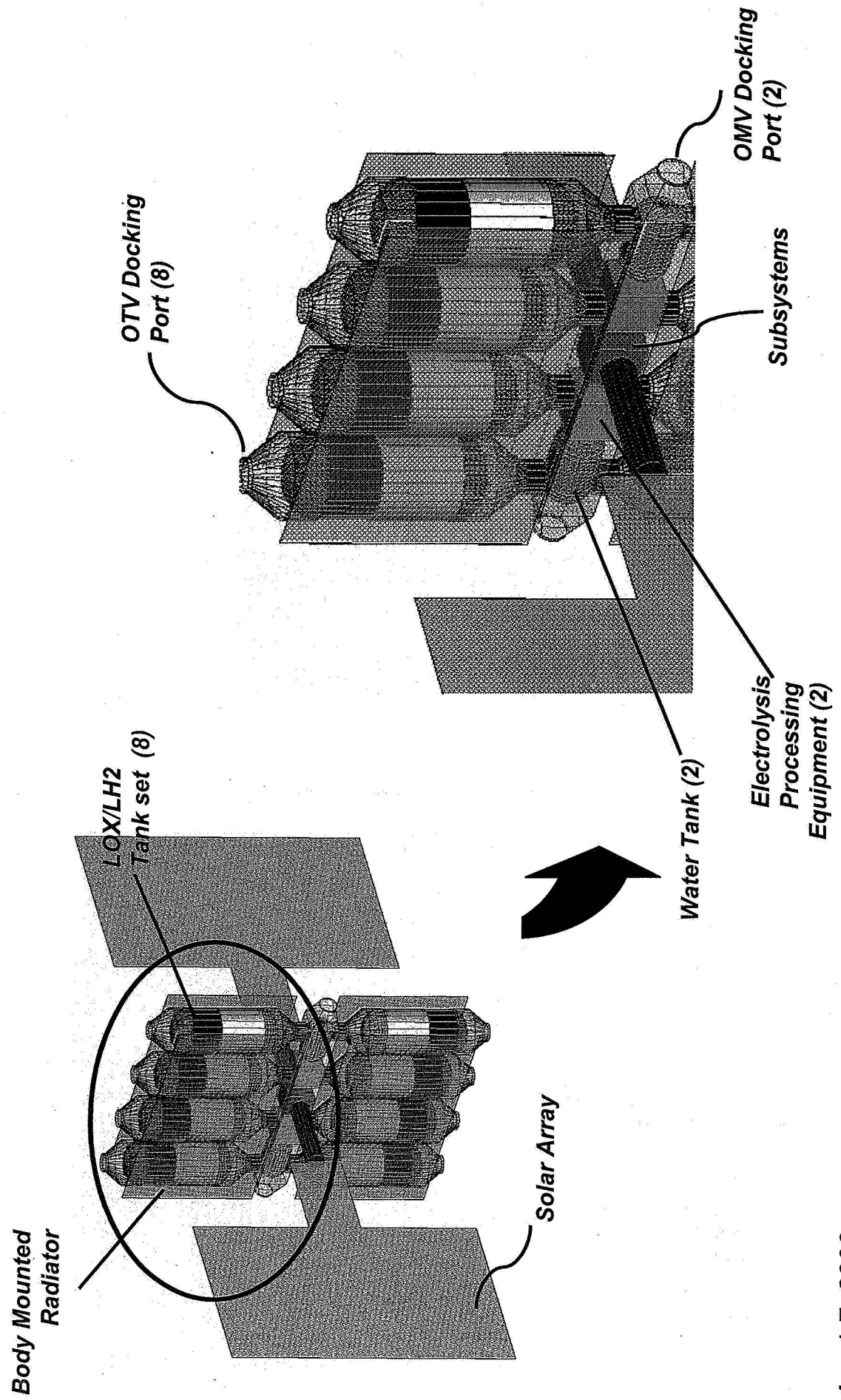
5. Water Docking Port

6. Water Storage Tanks

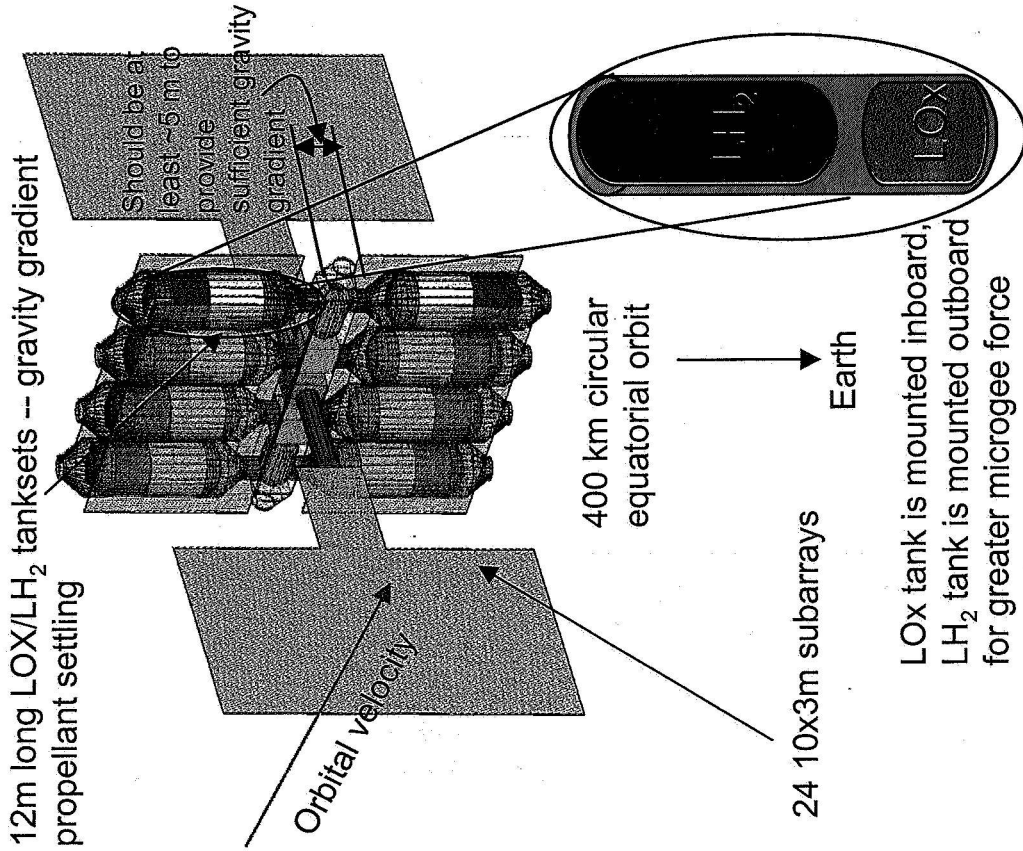
7. Electrolysis System



Utilizing Solar Power Technologies for On-Orbit Propellant Production On-Orbit Propellant Production Schematic

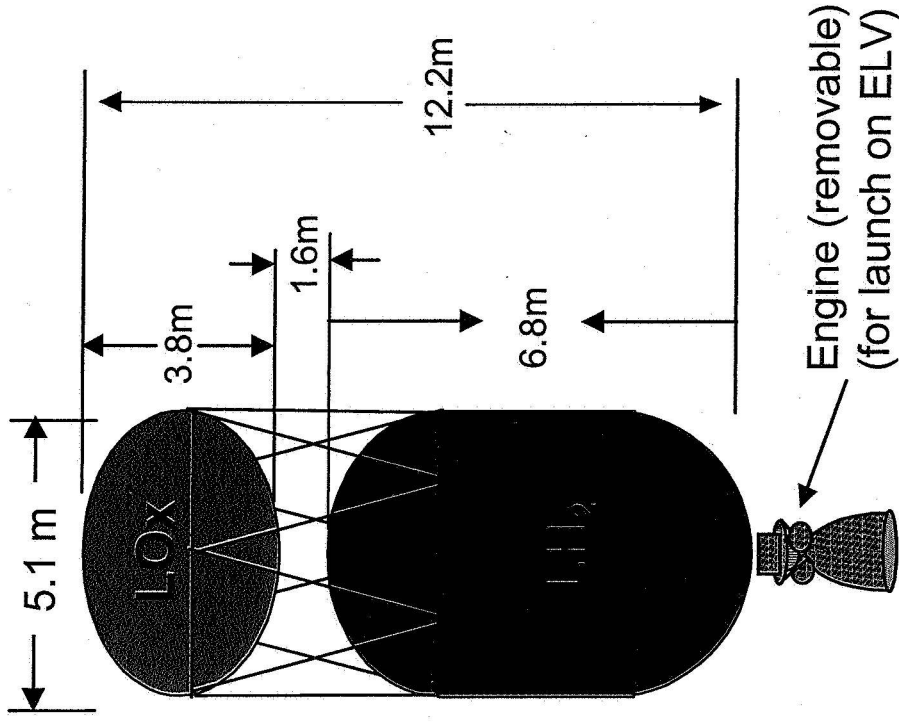


Utilizing Solar Power Technologies for On-Orbit Propellant Production Propellant Production Depot Key Features



- 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 & LH₂ 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

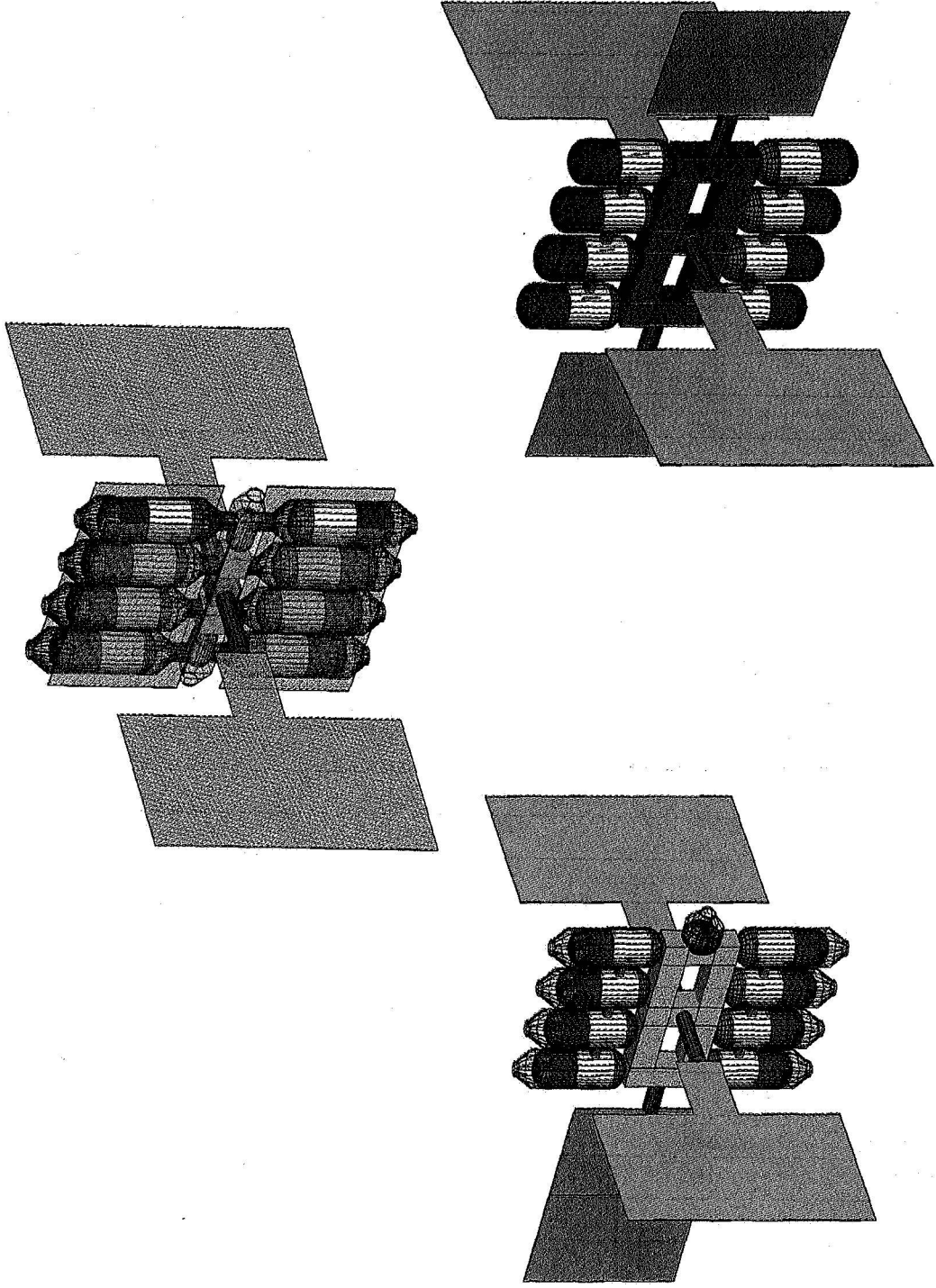
Utilizing Solar Power Technologies for On-Orbit Propellant Production
Propellant Production Depot Tank-Set



- **Total length per tankset = 3.80 m + 6.8 m + 1.6 m = 12.2 m.**
- **Total propellant mass stored per tankset = 60,914 kg + 7614 kg = 68,528 kg**
- **Number of tanksets needed to meet 500 MT depot requirement $\geq 500/68.528 = 7.3 \sim 8$.**

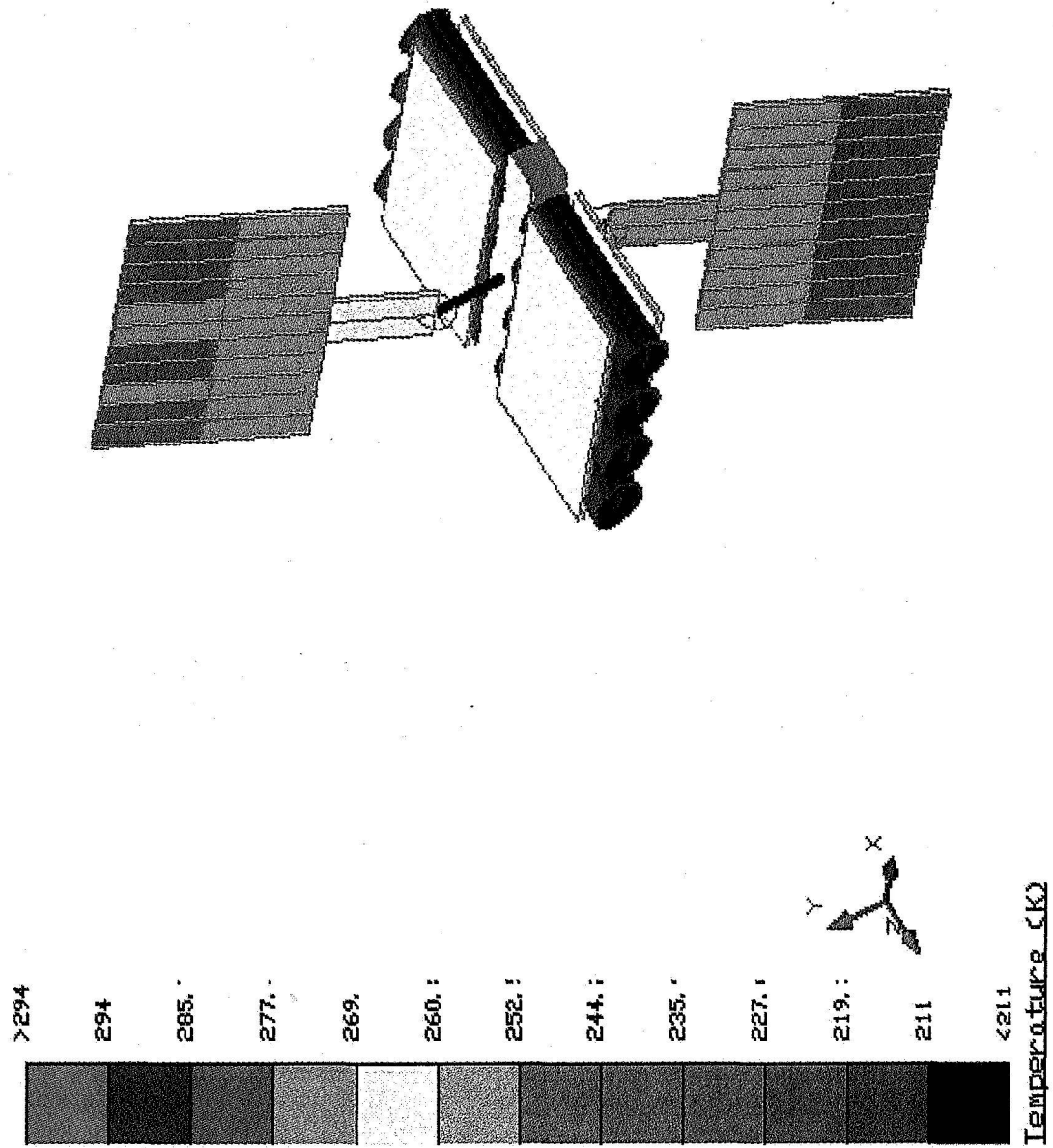
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Possible Thermal Radiator Configurations



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Baseline Thermal Configuration



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Thermal Assessment on Radiator Location



Radiator Location	Process			
	Tankset Housing Temp. (K)	Equipment Housing Temp. (K)	Equipment Plate Temp. (K)	Solar Array Radiator Temp. (K)
Body-Mounted Option	233	274	294	261 268/260
On Solar Arrays	224	273	293	256 279
Axial	218	270	290	251 275
Axial, Articulated	218	270	290	253 272
Lateral	216	269	289	240 275
Lateral, Articulated	216	269	289	253 273

Utilizing Solar Power Technologies for On-Orbit Propellant Production

Single Wall Penetration



Estimated per year probability of no penetration:

- 400 km circular zero inclination orbit
- Year = 2020, ORDEM96 default solar & debris growth
- Single-sheet aluminum wall

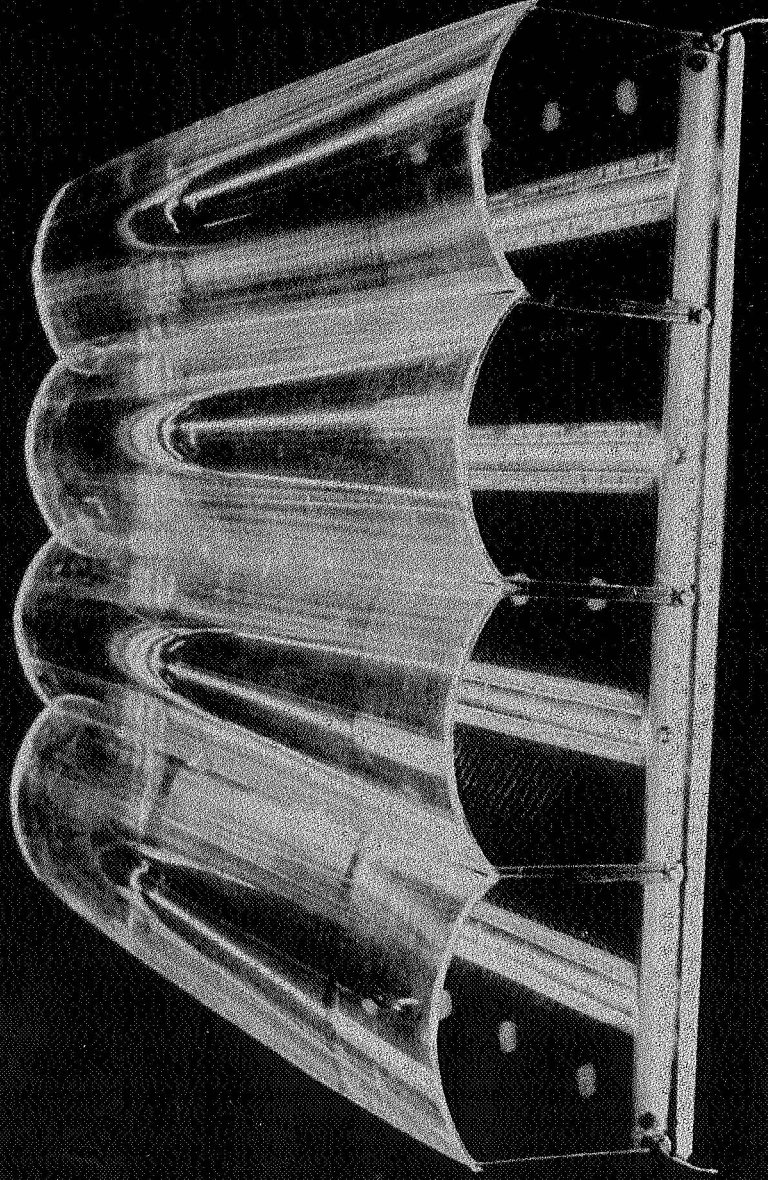
Thickness (in)	1	10	30	100
0.08	.89	.30	.03	0.0
0.12	.967	.71	.36	.03
0.24	.996	.96	.88	.66
0.50	.999	.994	.98	.94

- Unshielded tanks would have 34% chance of being penetrated within a year
- Micrometeoroid/Space Debris shield is required
- Integrate tank, vapor cooled shield, radiator, and launch vehicle aeroshell to provide shielding

Utilizing Solar Power Technologies for On-Orbit Propellant Production Power System



ENTECH Stretched Lens Array

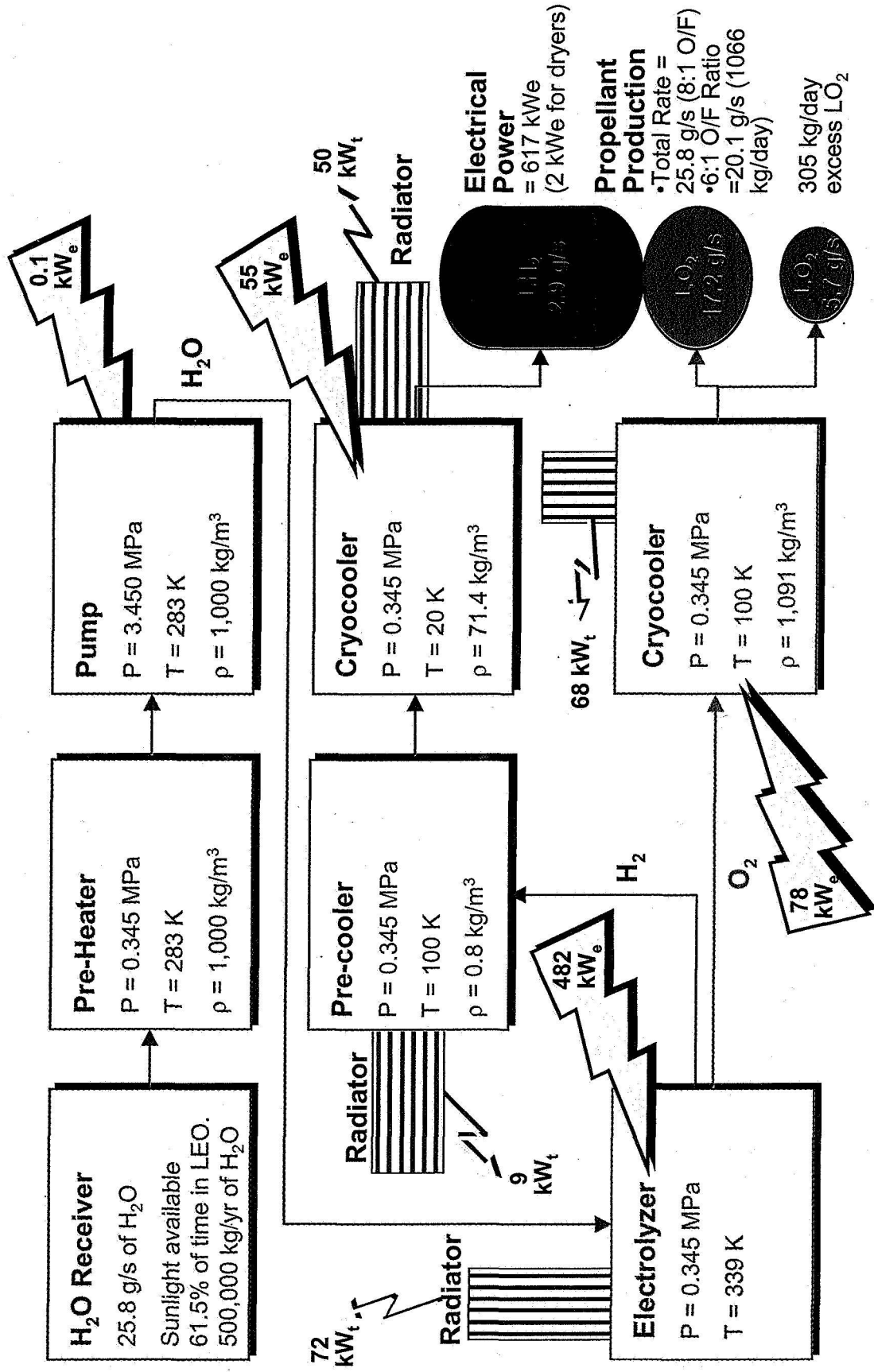


ENTECH's Stretched Lens Array (Protected by Multiple U.S. Patents)



Utilizing Solar Power Technologies for On-Orbit Propellant Production

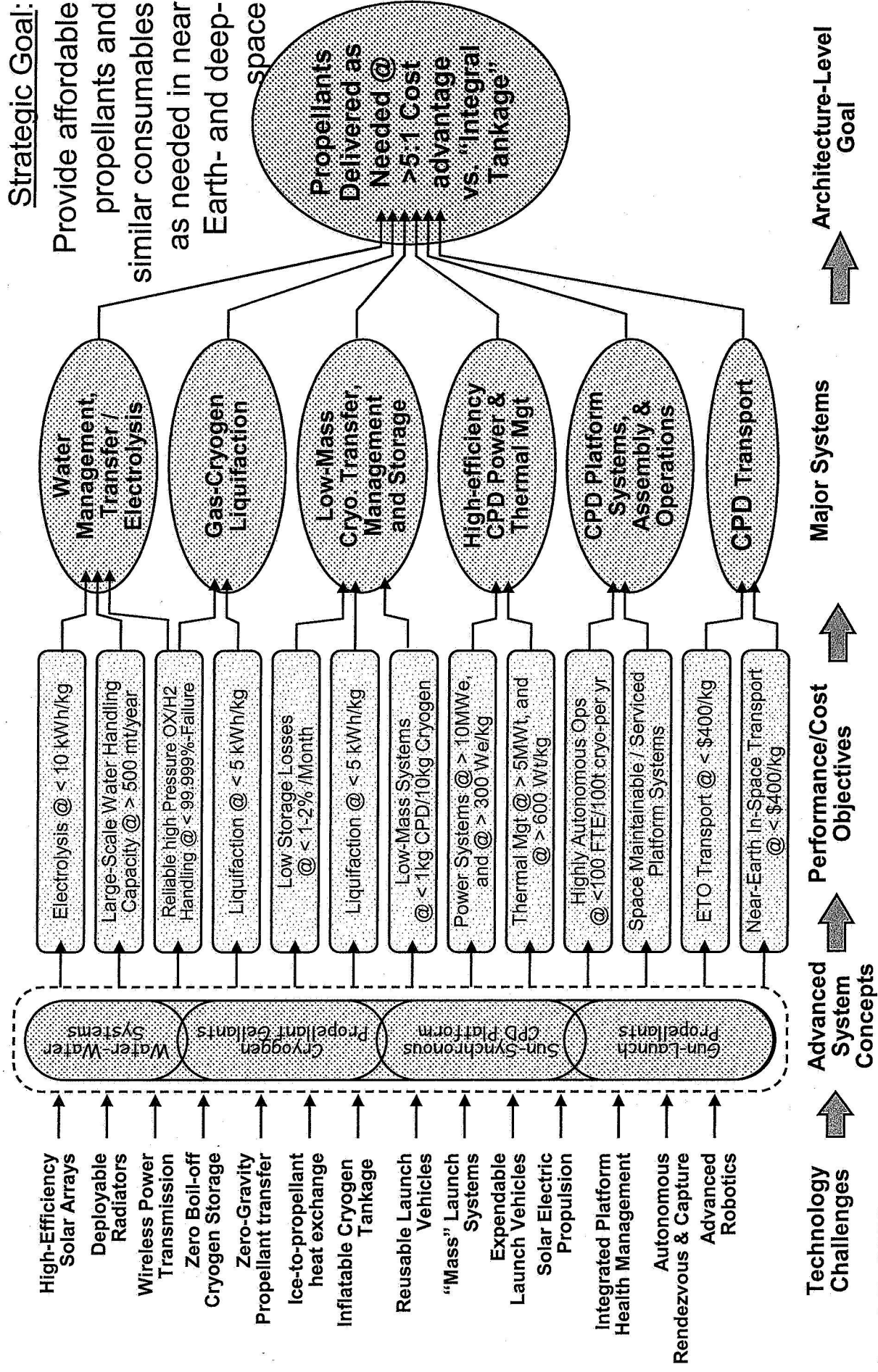
Electrolysis System



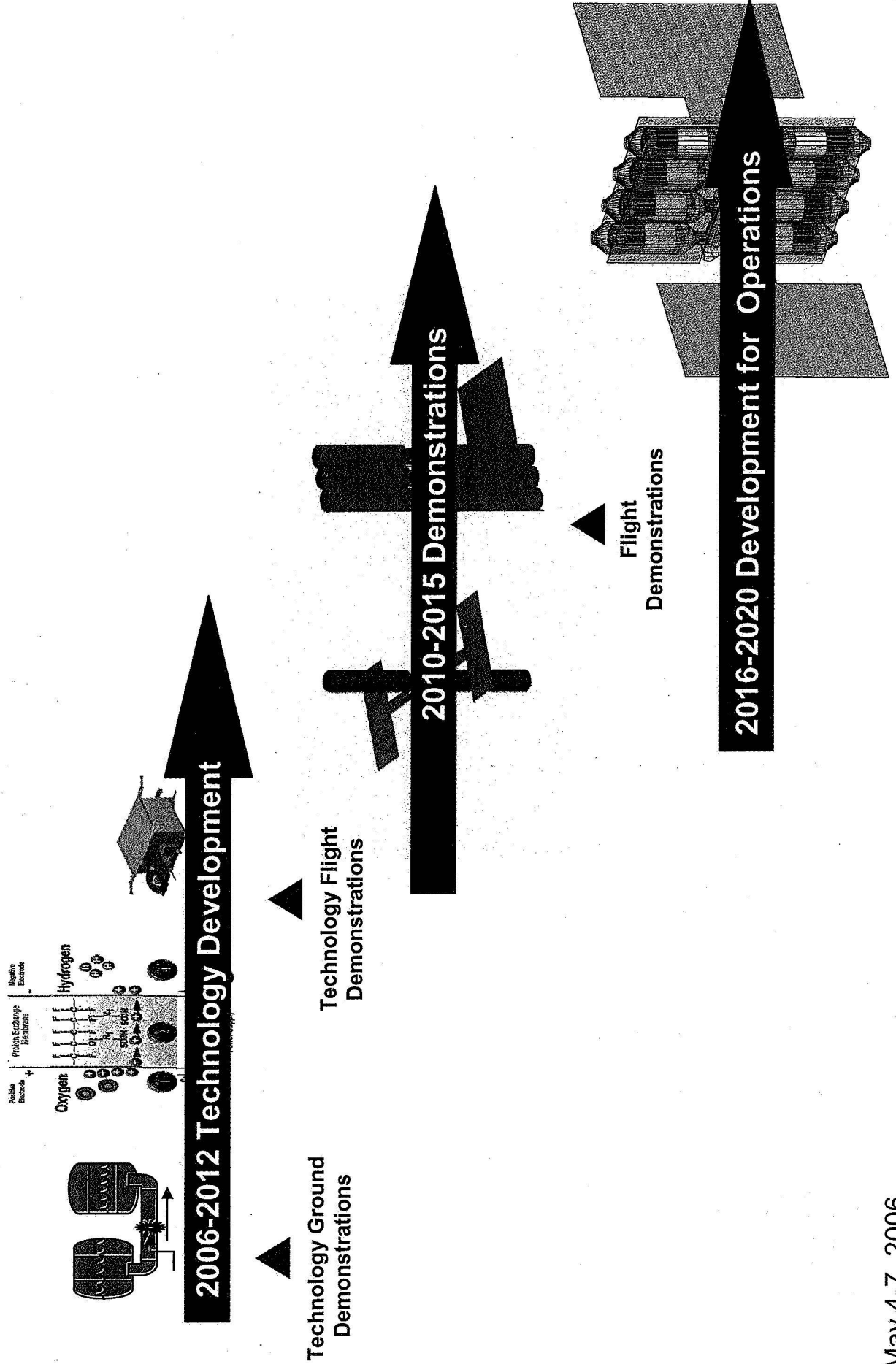
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Technology



Utilizing Solar Power Technologies for On-Orbit Propellant Production Technology Roadmap





Summary

- Large-scale cryogenic production from H₂O in Earth orbit is technically feasible
 - Avoids volume and safety issues related to containment of cryogenics during launch
 - Allows high acceleration of payload(H₂O/Ice) during launch
- Solar Power Technologies enables efficient cryogenic propellant production from H₂O
- Variations of the system studied initially here should be considered in more detail
 - Smaller scale facilities in LEO/L2/Lunar
 - Technology use for surface-based propellant production