IAC-06-D3.3.08

IN-SPACE CRYOGENIC PROPELLANT DEPOT (ISCPD) ARCHITECTURE DEFINITIONS AND SYSTEMS STUDIES

Mr. John Fikes
National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center, Huntsville, Alabama, United States, john.fikes@nasa.gov

Mr. Joe T. Howell
National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center, Huntsville, Alabama, United States, joe.howell@nasa.gov

Mr. Mark Henley
The Boeing Company, Canoga Park, California, United States, mark.w.henley@boeing.com

ABSTRACT

The objectives of the ISCPD Architecture Definitions and Systems Studies were to determine high leverage propellant depot architecture concepts, system configuration trades, and related technologies to enable more ambitious and affordable human and robotic exploration of the Earth Neighborhood and beyond. This activity identified architectures and concepts that preposition and store propellants in space for exploration and commercial space activities, consistent with Exploration Systems Research and Technology (ESR&T) objectives. Commonalities across mission scenarios for these architecture definitions, depot concepts, technologies, and operations were identified that also best satisfy the Vision of Space Exploration. Trade studies were conducted, technology development needs identified and assessments performed to drive out the roadmap for obtaining an in-space cryogenic propellant depot capability.

The Boeing Company supported the NASA Marshall Space Flight Center (MSFC) by conducting this Depot System Architecture Development Study. The primary objectives of this depot architecture study 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 test article requirements.

INTRODUCTION AND BACKGROUND

An in-space cryogenic propellant depot capability represents a key element of NASA's visions. The servicing of propellants and consumables in space enables a multitude of mission scenarios, otherwise unavailable due to costs or operational constraints and/or inefficiencies. Cryogenic Fluid Management (CFM) technology applications are particularly suited in evolving capabilities for commercialization and solar system science missions. These applications cut across all human exploration missions, including depots, orbital transfer vehicles such as the Crew Exploration Vehicle (CEV) and other in-space stages.

At the core of the depot capability is the economic management of cryogens without undue or complicated impositions on infrastructure, other systems, or mission operations. This technology leads to autonomous fluid management operations without the complications of propellant settling and without extravehicular activity (EVA) support. The basic goal is to enable automated zero-g storage and transfer of cryogenic fluids from supply tanks (Figure 1) to user tanks: safely, reliably, and with minimum loss of propellant.

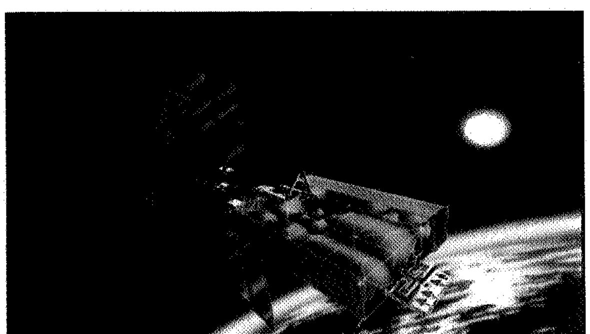


Figure 1. In-Space Cryogenic Propellant Depot Artist Concept.

ARCHITECTURE DEFINITIONS

Recommendations for ISCPD Architectures were developed based on prior studies and NASA's concurrent Exploration Systems Architecture Study (ESAS). ESAS recommended use of cryogenic hydrogen and oxygen on two upper stages for Shuttle-derived launch vehicles as well as a lunar Lander. While the final architecture may vary, these are good candidate vehicles for ISCPD refueling, and Table 1 summarizes their expected quantities of cryogenic propellant. In addition, ESAS recommended use of cryogenic methane and oxygen on an Ascent Stage, including storage of these cryogens for at least two weeks in space. ESAS did not specifically require use of an ISCPD, but the NASA Administrator recommended commercial ISCPD development, with a market value of 2.5 billion dollars per year to refuel the ESAS Earth Departure Stage (EDS), thereby increasing lunar payload mass, and providing even greater value for Mars exploration.

Table 1. Cryogenic ESAS vehicles could refuel or offload residuals at an ISCPD.

Approximate mass derived from ESAS report in metric tonnes	**Earth Departure Stage**	**CEV Cryo Upper Stage**	**Lunar Lander**
Dry Mass	19	17	6
Propellant	208	164	25
Residual Fluids	2.8	2.9	0.5

Such vehicles may be refueled at a depot or deliver residual propellants (to re-fill depot tanks) and might even store cryogenic propellant in space. Figure 2 illustrates these vehicles in the recommended ESAS scenario and how they may fit ISCPD applications.

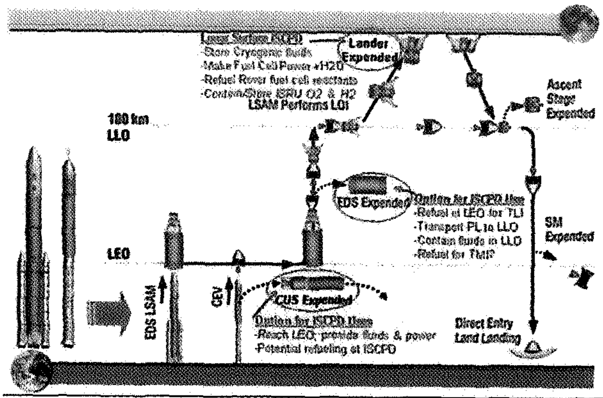


Figure 2. The ESAS-recommended architecture offers opportunities for ISCPD uses.

In the ESAS-recommended lunar architecture, the EDS would use roughly 123,000 kg of cryogenic propellants to reach Low Earth Orbit (LEO) where it would mate with the CEV and burn its remaining propellant (~85,000 kg) for Trans-Lunar Injection (TLI). If the EDS were refueled in LEO as Dr. Griffin suggested, it could more than double the payload to TLI. A refueled EDS could also potentially carry payload into lunar orbit (or initiate Lander descent). Such scenarios could double or triple the payload mass to the lunar surface.

The Cryogenic Upper Stage for CEV launches is planned for suborbital flight, with re-entry over the Pacific Ocean, but it may also be able to reach orbit carrying the CEV. In orbit, the remaining tons of cryogenic propellants could provide low thrust propulsion, fuel cell power, and Environmental Control and Life Support System (ECLSS) consumables to support the CEV. If this upper stage is carried to orbit, it could off-load residual propellants at an ISCPD, or be refueled and re-used.

The lunar Lander will be designed for longer-term storage and management of cryogenic fluids: roughly one week for propulsive maneuvers and two weeks for fuel cell reactants. The Lander's cryogenic propellant storage system must withstand daytime lunar surface heating, and the Lander design includes radiators for heat rejection. Fuel cells on the Lander provide power generation from Earth launch until lunar ascent, with oxygen reactant stored in the oxygen propellant tanks, while hydrogen reactant is stored in the hydrogen propellant tanks. In this way, the Lander serves as an ISCPD and it could continue to store cryogens after the humans return to Earth, supplying reactants to refuel rovers using fuel cell power, and receiving and storing oxygen and hydrogen produced from resources found on the lunar surface (in lunar regolith and/or polar ice).

Oxygen and hydrogen production from water has the potential to provide great benefits for Space Exploration. Water may be launched from Earth at low cost or found on Earth's moon, and the moons and surface of Mars. Water electrolysis systems have been developed for the International Space Station (ISS) and one was launched on the last Space Shuttle mission, to produce gaseous oxygen (for breathing) and hydrogen (vented overboard). With refrigeration and heat exchange, we can convert such gases into cryogenic liquids, and store them at In-Space Cryogenic Propellant Depots.

The exploration architecture is expected to grow in capabilities over time. Initially, ISCPD cryogenic propellant may be delivered from Earth, using chemical propulsion to reach a depot in LEO. Launch systems may deliver cryogenic propellants in dedicated launches as well as by scavenging of residual and reserve propellants from cryogenic upper stages. Initial ISCPD capabilities may be limited to passive storage (with no refrigeration, but using boil-off gas to provide propulsion, power and water), however the architecture will evolve, with increasing power requirements to allow for zero boil-off (refrigeration), and eventually allow for cryogenic propellant production from water launched to the depot from Earth or carried from extraterrestrial sources using advanced propulsion and/or aero-braking.

The amount of energy needed to launch mass from the moon to LEO or L-1 is much less than that to launch from Earth, so it may eventually be economical to use lunar resources to make cryogenic propellants for use in cis-lunar space and Trans-Mars Injection (TMI). One potential approach would carry cryogenic propellant from production facilities on the moon to an ISCPD at L-1, Low Lunar Orbit (LLO) or LEO. In this scenario, cryogenic oxygen and hydrogen are made from ice found in cold, permanently shadowed areas near the moon's poles. A lunar Lander is refueled and launched from the moon's surface to low lunar orbit, with further propulsion to reach L-1 or a trans-earth injection trajectory (TEI). From TEI, multiple pass aero-braking could gradually lower the perigee to reach LEO without an aerobrake shield (a technique previously used at Venus and Mars). In the distant future, a more advanced approach might produce small "vehicles" filled with water from lunar resources; launch them via propellantless rail-gun to reach L-1 or TEI, and then convert the water into cryogenic propellants to be stored in an ISCPD.

Human missions to Mars will use larger quantities of propellant, requiring significant growth in ISCPD propellant capacity. The payload sent to Mars may also include significant amounts of liquid hydrogen (e.g., 18,700 kg), thus the payload itself may include an ISCPD for cryogen storage throughout the long journey, with continuing storage in orbit around Mars and on the surface. On Mars, hydrogen from Earth may be combined with carbon dioxide from the atmosphere to make cryogenic methane and oxygen propellants for return to Earth ($2H_2+CO_2 => CH_4+O_2$ via the Sabatier process and electrolysis), along with excess oxygen for breathing, and water and power from fuel cells ($O_2+2H_2 => 2H_2O$+Power). Such an In-Situ Propellant Production (ISPP) strategy may significantly reduce the mass launched from Earth and the cost of the associated Mars Exploration program, and this scenario influenced the ESAS selection of oxygen and methane propellants for lunar ascent, as a precursor to use for Mars ascent.

CONFIGURATION AND SYSTEM TRADES

ISCPD capabilities are expected to evolve over time, starting with relatively simple initial systems, and improving upon these as technologies mature and confidence grows. For example, an initial ISCPD configuration may use passive storage of modest quantities of propellant in LEO, to serve human lunar exploration systems, with growth to use active refrigeration and store very large quantities of propellant for human missions to Mars. To the extent practical, ISCPD systems should be designed for pre-planned product improvement, with configurations allowing a wide range of applications. Initial ISCPD facilities may operate in a micro-gravity environment in LEO, with additional facilities emplaced later on the moon, at Earth-Moon or Earth-Sun libration points, and in lunar orbit. As the architecture evolves to include In-Situ Propellant Production, depots may also operate in a high gravity environment on the Moon, Mars, and the moons of Mars. Table 2 summarizes the expected order of priority for ISCPD applications and their different environments.

Table 2. Order of priority for ISCPD applications and their different 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%, bi-weekly variation (3 sec delay)	100% (3 sec delay)	100% except at opposition (40 min.delay)	Up to 100% (at poles) (40 min.delay)
Micro-meteroid & 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	Gravity gradient settling option	Gravity ~1/6 g	Gravity gradient settling option	No gravity field	Gravity gradient settling option	Gravity ~1/3 g

ISCPD tanks are expected to be quite large. We considered using extremely-large tanks, launched as a monolithic structure, as well as moderately-large tank modules, joined to other modules in space to create a depot. Small tanks were only considered briefly, as their mass is higher for a given quantity of propellant (due to a higher surface area to volume ratio), however small tanks may be needed for high pressure (supercritical) fluid. The main issue for larger tanks is access to orbit, and the favored design solutions are to launch ISCPD tanks as upper stages using only some of their cryogenic propellants to reach LEO, and continuing to store propellants in orbit. The ISCPD tanks were based on Delta Expendable Launch Vehicle (ELV) stages, but the same general logic could apply to other launch systems, including variants of the ESAS architecture.

It would be possible to place a very large ISCPD in orbit with a single launch. As is shown in Figure 3, a depot could be created with a capacity for 400 tons of cryogenic propellant by using Delta IV ELV "Common Booster Core" (CBC) tank-sets in both the launch vehicle and as the payload (replacing the fairing). During launch, propellant is transferred from the upper CBC task-set to the lower tank-set, and the engine burns longer with this added propellant, to place the entire monolithic structure into orbit. Such large tank-sets allow simple "gravity gradient" settling of their cryogenic propellants, as the related forces are much less than forces of surface tension in large tanks. [The "Bond number" is very large, Bo = Bond Number = $(2\rho aR)/\sigma$, where a = acceleration, R = tank radius, ρ = density, and σ = surface tension]. Gravity gradient orientation, however, is undesirable for atmospheric drag and debris impact hazards, and other techniques tend to settle propellant to the same end of the depot (vs. opposite ends). The large monolithic depot would also require a single dedicated launch, adding a risk of losing the entire depot in a single failure, and it would arrive in LEO nearly empty.

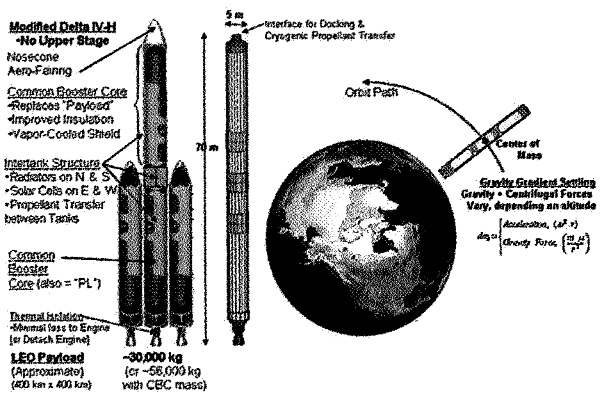


Figure 3. A large monolithic depot could reach LEO with a single launch with near-empty tanks.

More modestly sized depot tanks could reach LEO nearly full of propellants, requiring only a small propulsive maneuver for orbit circularization after release in a sub-orbital trajectory. Figure 4 illustrates such a depot tank-set launched in place of a cryogenic upper stage. In this scenario, a main engine, typically required for upper stages, is not needed, as lower thrust H2-O2 thrusters are sufficient to perform a circularization burn over a long time interval at apogee. A single launch provides initial depot capabilities, including the delivery of propellants. The configuration can grow with the modular addition of more tank-sets, as well as additional power and thermal radiation systems for refrigeration and zero boil-off. The modular approach allows tailoring of depot propellant capacity to meet re-supply needs that change depending upon time and depot location with improved debris protection. While configuration details may vary, such a modular approach is recommended as the most practical course for gradual development of ISCPD capabilities.

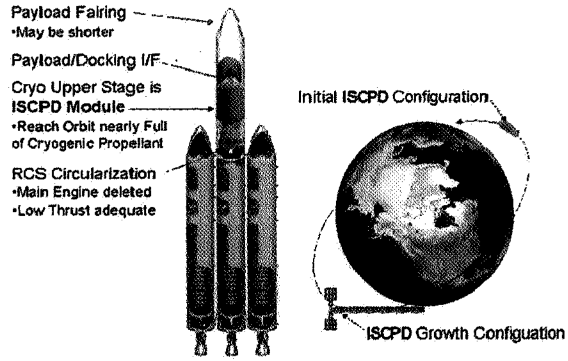


Figure 4. Modular depot tanks can launch as upper stages, reaching LEO nearly full.

A wide range of techniques could settle cryogenic propellants for acquisition and transfer in zero gravity. We expect ISCPD settling techniques to also evolve with time: initial settling could use boil-off gas from a receiving vehicle's hydrogen tank as a propellant to provide a low thrust. Techniques without propulsive thrust will be required when ISCPD capabilities grow to include "zero-vent fill" (with more power and refrigeration). Techniques include tank exchange, use of gravity gradient forces, surface tension, and system rotation or fluid rotation (in tanks). Of these, surface tension systems appear most promising as a baseline. Another advanced technique could use magnetic fields: since liquid oxygen is paramagnetic (attracted to a magnetic field) and liquid hydrogen is diamagnetic (repelled by a magnetic field) (note that the Earth's magnetic field may even need to be considered as an influence on propellant behavior in LEO).

ALTERNATIVE CONCEPT DEFINITION AND ASSESSMENT

Notional ISCPD system configurations were defined for comparison purposes and alternative conceptual designs also assessed. A reference depot module was defined, as summarized in Figure 5. The module uses a thermodynamic vent system for hydrogen boil-off, with H_2 gas passing through a vapor cooled shield on the tank wall, then conducting heat away from the oxygen tank before venting. A contingency vent system is included in the oxygen tank. The module shown in Figure 5 has a deployable multi-layer insulation blanket, which also provides protection for the hydrogen tank against micrometeoroids and orbital debris. Rigid insulation alternatives also have merit. Pressurization is autogenous, using small tanks of supercritical H2 and O2 gas, which also provide fuel cell reactants and RCS propellants. The module includes accommodations for autonomous docking and fluid transfer on both the forward and aft ends.

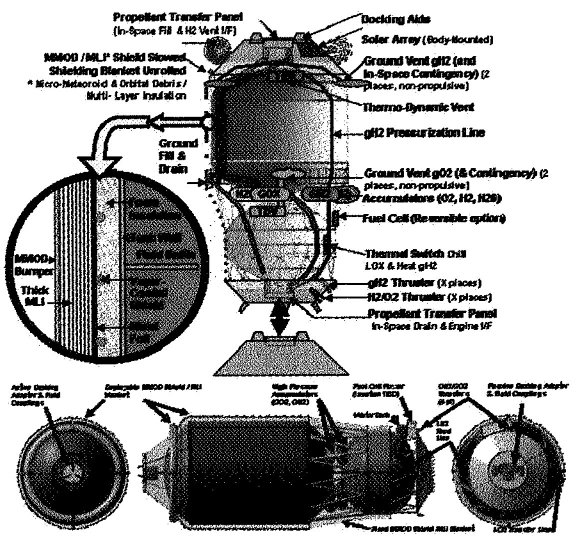


Figure 5. Reference ISCPD module concept.

Figure 6 illustrates growth of the ISCPD with additional modules and solar power. Solar power as shown, is based on existing satellite solar power systems, and is sized for a 20 kWe peak power level (roughly 10 kWe average in LEO). In this view, one can see a preferred orientation with respect to the Earth. This orbital orientation minimizes drag, which tends to settle propellants forward, in the direction of the orbital velocity vector (equivalent to "downward" in the launch orientation). The low drag orientation exposes different parts of the module to different environments; LEO orbital debris hazards are most severe from the sides, meteoroids and sunlight come from above, and the Earth's heating (infrared and albedo) comes from below, thus modules surface details (insulation, thermal shielding, etc.) may be tailored to best meet these differing conditions.

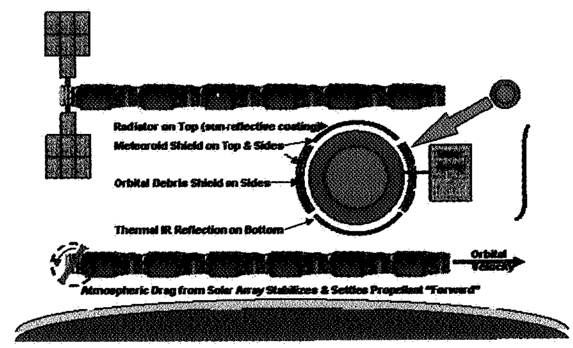


Figure 6. Growth ISCPD Facility in LEO: Add propellant and power for refrigeration.

Autogenous pressurization is important for the depot (and stages that it refuels) to avoid requirements for re-suppling high pressure helium gas, which is difficult to contain and transfer. Cryogenic liquid is transferred to a small "boiler tank" where it is warmed using thermal switches and heat exchangers to reach high pressure, becoming a supercritical fluid. This warmer fluid is then transferred to a Composite Overwrapped Pressure Vessel, and which in turn supplies H2/O2 gas-gas Reaction Control System (RCS), fuel cells, and H2 low thrust propulsion systems as well as providing pressure for the cryogenic liquid tanks (to force fluid to transfer from the depot into lower pressure tanks on the receiving vehicle).

TECHNOLOGY DEVELOPMENT PLANS

Plans for development of critical ISCPD technologies include a potential space flight demonstration program and ground demonstration options that prepare for flight-testing. Cryogenic fluid management in zero- or micro-gravity has been analyzed extensively with few opportunities to verify analytical models in space. The Apollo-Saturn 203 Flight was dedicated as an experiment to monitor cryogenic propellant conditions and dynamics in orbit; however this approach is fairly costly. Relevant space flight data can also be gained without significant cost, however, when flight experiments are performed as a secondary mission objective on a cryogenic upper stage, using its remaining cryogenic propellants after the primary payload is released. The Titan-Cenatur-2 Mission used this approach to perform two additional firings of the engine after storing cryogenic propellants for 1-hour and 3–hour coast intervals, and to demonstrate a "bubbler" system to reduce helium usage (by increasing the oxygen partial pressure). The Titan-Centaur-5 launch of Helios-2 also used this approach to demonstrate a total of seven burns of an RL-10 engine in a variety of conditions and storing cryogenic propellants for 5.25 hours between burns. Many future NASA launches could use a similar strategy to experiment with cryogenic propellants remaining in expended upper stages after their primary payloads are released. Typical cryogenic upper stage mission event sequences deploy the payload(s), then perform contamination and collision avoidance maneuvers (CCAM), including venting of remaining cryogenic fluids into space, as is illustrated in Figure 7.

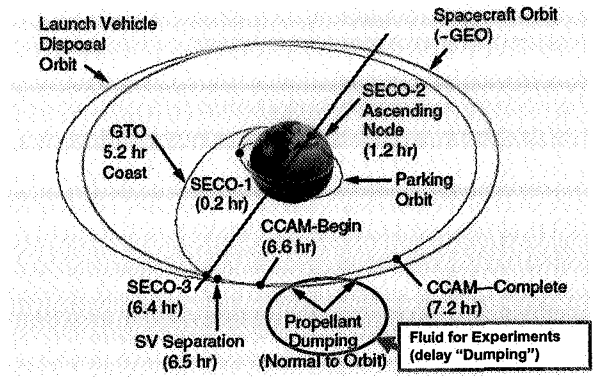


Figure 7. Cryogenic upper stages vent hundreds of pounds of remaining fluids that could be used for secondary flight experiments on virtually every mission.

After the spacecraft deployment occurs and the spacecraft reaches an acceptable distance from the Cryogenic Upper Stage, the stage reorients to a new position. The CCAM moves the stage away from the spacecraft orbit to prevent collision, and expels propellant (in a direction away from the spacecraft) to increase the separation distance and relative velocity, and to prevent subsequent tank rupture. Today's cryogenic upper stages typically complete their primary missions with significant masses of leftover fluids (hundreds of kilograms), including cryogenic liquids (residuals, reserves, trapped fluids, and a hydrogen bias), cold gas (hydrogen ullage gas, oxygen ullage gas, and residual helium), and even some hydrazine RCS propellant.

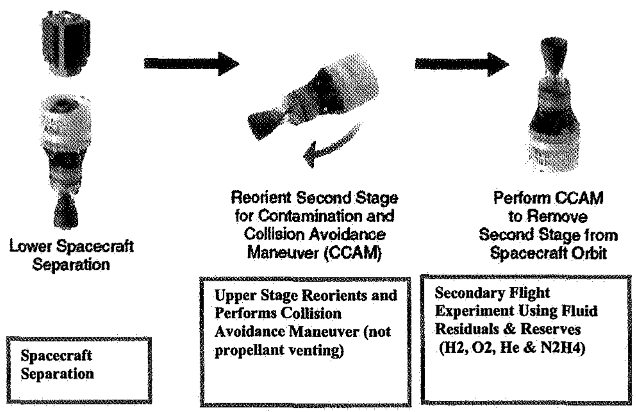


Figure 8. Secondary flight experiments on cryogenic upper stages may use residual propellants to test technology instead of dumping them shortly after payload separation.

As shown in Figure 8, simple flight experiments may test maneuvers or new hardware after the primary mission (e.g., to settle propellant or gauge its mass), and may use boiloff H2 for low-thrust, cold-gas propulsion. More complex flight experiments could use additional batteries or solar power (thermal or photovoltaic) to extend mission duration and could heat H2 boil-off gas to provide more efficient propulsion (specific impulse may reach 800 seconds in a resistojet or solar-thermal thruster, or higher with more advanced thrusters) or use H2 and O2 ullage gas for higher thrust chemical propulsion; either of these propulsion technologies might also be used on future missions before payload release, to significantly increase payload mass (adding hundreds of kilograms to the payload). Flight experiments on upper stages may also add hardware specific to ISCPD technology demonstrations; for example, selected lines on the upper stage may be tapped (with isolation valves closed until payload release) allowing transfer of leftover fluid into well-insulated cryogenic tanks and into high-pressure vessels for warm, super-critical storage (to be used as a pressurant, propellant, or fuel-cell reactant).

CONCLUSIONS

In-Space Cryogenic Propellant Depot systems offer significant advantages for NASA 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. ISCPD sizing is expected to be moderate, allowing deliver of modules to LEO as upper stages without main engines, nearly full of propellant. ISCPD design recommendations include modular construction and features allowing autogenous pressurization (without helium gas). Technology demonstrations may use secondary experiments on cryogenic upper stages as a means for ready access to orbit.

REFERENCES

[1] NASA ESAS Final Report: http://www.nasa.gov/pdf/140637main_ESAS_06.pdf

[2] NASA Administrator's Speech at 52nd AAS Conference, 15 Nov. 2005: http://www.nasa.gov/pdf/138033main_griffin_aas1.pdf, pages 7-10

[3] Griffin B., Thomas B., Vaughan D., Drake, B., Johnson, L., and Woodcock, G., A Comparison of Transportation Systems for Human Missions to Mars, 40th Joint Propulsion Conference,11-14 July 2004, Fort Lauderdale, Florida, AIAA 2004-3834: http://www.inspacepropulsion.com/tech/pubs/AIAA2004_3834AComparisonofTransportationSystemsforHumanMissionstoMars.pdf

[4] Weaver, D. B. and Duke, M. B., Mars Exploration Strategies: A Reference Program and Comparison of Alternative Architectures, AIAA-93-4212,

http://ares.jsc.nasa.gov/HumanExplore/Exploration/EXLibrary/DOCS/EIC043.HTML

[5] Zubrin R. M., Baker, D. A., and Gwynne, O., Mars Direct: A Simple, Robust, and Cost

Effective Architecture for the Space Exploration Initiative, AIAA-91-0328, http://www.cbqc.net/mars/docs/md_reno.pdf

[6]Astronautix, Mars Exploration, http://www.astronautix.com/craftfam/martions.htm

[7] Turner, Andrew E., Low-cost launch and orbital depots: the Aquarius system, in The Space Review, January 30, 2006 http://www.thespacereview.com/article/544/1

[8] Rice, E. E., Development of Lunar Ice/Hydrogen Recovery System Architecture, Final Report, NASA/NIAC Research Grant 07600-021, OTC-G083-FR-2000-1, January 1, 2000; http://www.niac.usra.edu/files/studies/final_report/341Rice.pdf

[9] Blair, B.B., Diaz, J., Duke, M. B., Lamassoure, E., Easter, R., Oderman, M., Vaucher, M., Space Resource Economic Analysis Toolkit: The Case for Commercial Lunar Ice Mining , Final Report to the NASA Exploration Team, December 20, 2002, http://www.mines.edu/research/srr/LDEM_Draft4-updated.pdf

[10] Sanders, G. ., In-Situ Resource Utilization (ISRU) Capabilities & Roadmapping Activities, LEAG/SRR Meeting, Oct. 26, 2005, http://www.lpi.usra.edu/meetings/leag2005/presentations/wed_am/01_sanders.pdf

[11] Keaton, Paul W., A Moon Base/Mars Base Transportation Depot, Los Alamos National Laboratory Report LA-10552-MS, UC-34B, September 1985, http://www.physicsware.net/pdf/A_MM_Depot.pdf

[12] Cordell, Bruce M., Transportation Approaches For Manned Mars Missions, AIAA Space Programs and Technologies Conference, September 25-28, 1990 1 Huntsville, AL, AIAA-1990-3892 http://www.aiaa.org/content.cfm?pageid=406&gTable=mtgpaper&gID=86562

[13] Kuck, David L., The Deimos Water Company, Space Manufacturing II, SSI, Princeton 8 May 1997; http://www.spacefuture.com/archive/the_deimos_water_company.shtml

[14] Jones, L. and Bagdigian, D., Space Station Propulsion: Advanced Development Testing of the Water Electrolysis Concept at MSFC, AIAA-89-2615, 25th Joint Propulsion Conference, Monterey, CA I July 10-12, 1989, http://www.aiaa.org/content.cfm?pageid=406&gTable=mtgpaper&gID=60854

[15] Staff writers, NASA To Send New Oxygen Generating System To ISS, Space Daily, Feb 9, 2006 http://www.spacedaily.com/reports/NASA_To_Send_New_Oxygen_Generating_System_To_ISS.html

[16] Bock, E. H. and Fisher, J. G., In-Space Propellant Processing Using Water Delivered as Shuttle Contingency Payload, AIAA-78-941, 14th Joint Propulsion Conference, Las Vegas, NV, 25-27 July, 1978

[17] Smitherman, D., Fikes, J., Roy, S., Henley, M., and Potter, S., Space Resource Requirements for Future In-Space Propellant Production Depots, Space Resources Utilization Roundtable III, October 24–26, 2001, http://www.mines.edu/research/srr/2001%20papers/SRURpaperfinal.pdf

[18] Hill, T., Orbital Supply Depots to Cut the Cost of Travelling to Low Earth Orbit and Beyond, International Space Development Conference, 2005, isdc.xisp.net/~kmiller/isdc_archive/fileDownload.php/?link=fileSelect&file_id=183

[19] Troutman, P., Orbital Aggregation & Space Infrastructure Systems (OASIS)

Executive Summary, 2 October, 2001,http://rasc.larc.nasa.gov/rasc_new/HPM/OASISEXEC_97.pdf

[20] Lo Martin W. and Ross, Shane D., The Lunar L1 Gateway: Portal to the Stars and Beyond, AIAA Space 2001 Conference, Albuquerque, New Mexico August 28-30, 2001, http://www.cds.caltech.edu/~shane/papers/lo_ross_2001.pdf

[21] Keaton, P. ibid (see reference 8)

[22] Garriott, O. and Griffin, M., Extending Human Presence into the Solar System, An Independent Study for The Planetary Society on Strategy for the Proposed U.S. Space Exploration Policy, July 2004, http://www.planetary.org/aimformars/study-report.pdf

[23] Boeing, Space Solar Power and Platform Technologies for In-Space Propellant Depots, Final Report, Report Number RSS00HB656, Contract NAS8-99140, Mod.2, Task 3, November 14, 2000

[24] Marchetta, J., Winter, A., and Hochstein, J., Simulation and Prediction of Realistic Magnetic Positive Positioning for Space Based Fluid Management Systems,42nd AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 5-8, 2004, AIAA-2004-1151, http://www.aiaa.org/content.cfm?pageid=406&gTable=Paper&gID=13176

[25] Martin, J. and Holt, J., Magnetically Actuated Propellant Orientation, Controlling Fluids In A Low-Gravity Environment, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 16-19 July 2000, Huntsville, Alabama, AIAA 2000-3440, http://www.aiaa.org/content.cfm?pageid=406&gTable=mtgpaper&gID=5920

[26] Martin, J. and Holt, J., Magnetically Actuated Propellant Orientation, Controlling Fluids In A Low-Gravity Environment, 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, 16-19 July 2000, Huntsville, Alabama, AIAA 2000-3440, http://www.aiaa.org/content.cfm?pageid=406&gTable=mtgpaper&gID=5920

[27] Chato, D.J., Marchetta, J., Hochstein, J.I. and Kassemi M., Approaches to Validation of Models for Low Gravity Fluid Behavior, NASA/TM—2005-213832, http://gltrs.grc.nasa.gov/reports/2005/TM-2005-213832.pdf

[28] Plachta, D., and Kittel, P., An Updated Zero Boil-Off Cryogenic Propellant Storage Analysis Applied to Upper Stages or Depots in an LEO Environment NASA/TM—2003-211691, June 2003, http://gltrs.grc.nasa.gov/reports/2003/TM-2003-211691.pdf

[29] Chato,D, Low Gravity Issues of Deep Space Refueling, January, 2005, AIAA-2005-25186 http://www.aiaa.org/content.cfm?pageid=406&gTable=Paper&gID=25186

[30] NASA, Evaluation of AS-203 Low Gravity Orbital Experiment - Jan http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19680012073_1968012073.pdf

[31] Google, AS-203, http://www.infothis.com/find/AS-203/

[32] R.F. Lacovic. Centaur Zero Gravity Coast and Engine Restart Demonstration on the Titan/Centaur (TC-2) Extended Mission, NASA TM X–71821, Oct. 1975, http://adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=1975STIN...7613155L&db_key=PHY&data_type=HTML&format

[33] Henley, M. W., Secondary Applications of Expended Orbital Transfer Systems, October, 1989, IAF Congress-http://adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=1989mala.iafcS....H&db_key=PHY&data_type=HTML&format=

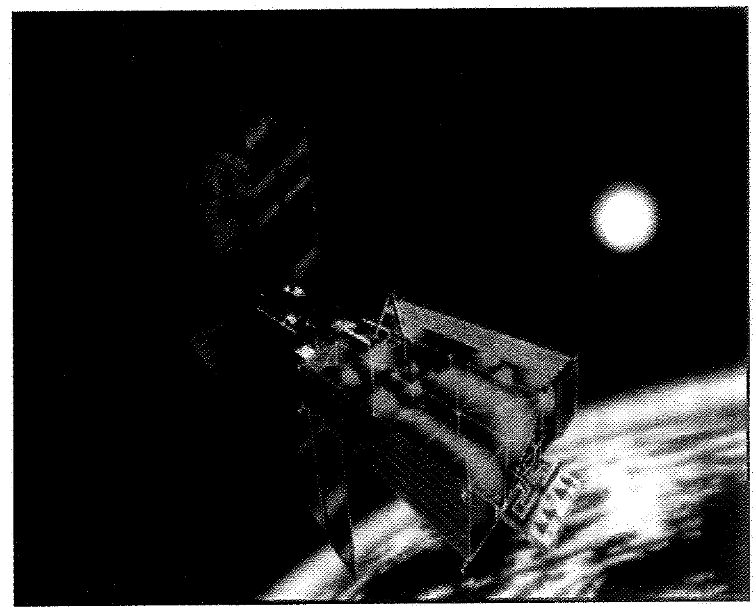
In-Space Cryogenic Propellant Depot (ISCPD) Architecture Definitions and Systems Studies

57^{th} International Astronautical Congress
Valencia, Spain
2^{nd} – 6^{th} October 2006

John Fikes
Joe Howell
Marshall Space Flight Center
National Aeronautics and Space Administration

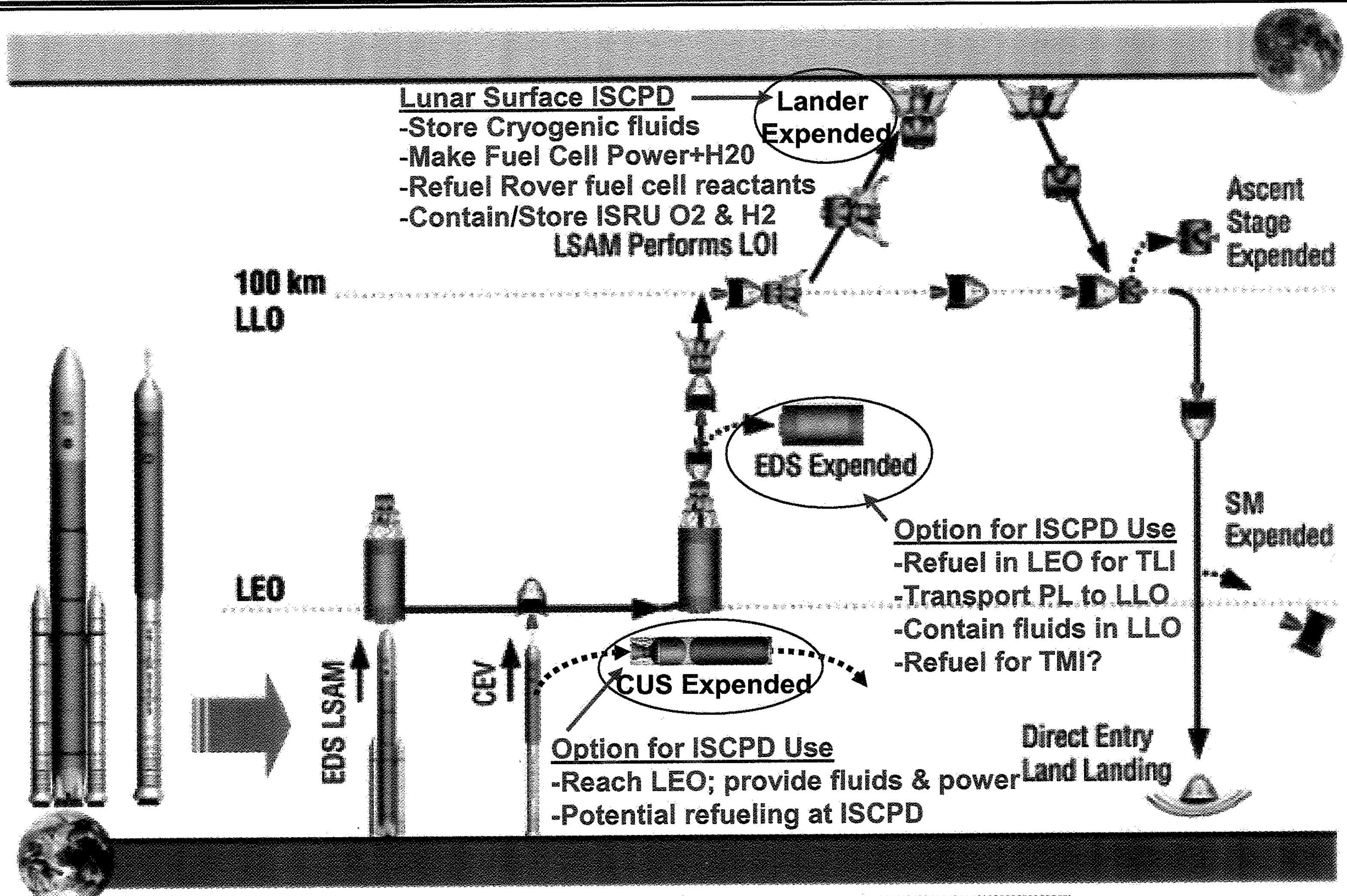
Objectives of an In-space Cryogenic Propellant Depot

- Servicing of propellants and consumables in space
- Manage the economics of cryogens 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 In Space Cryogenic Propellant Depot Uses with NASA's ESAS-Recommended Architecture

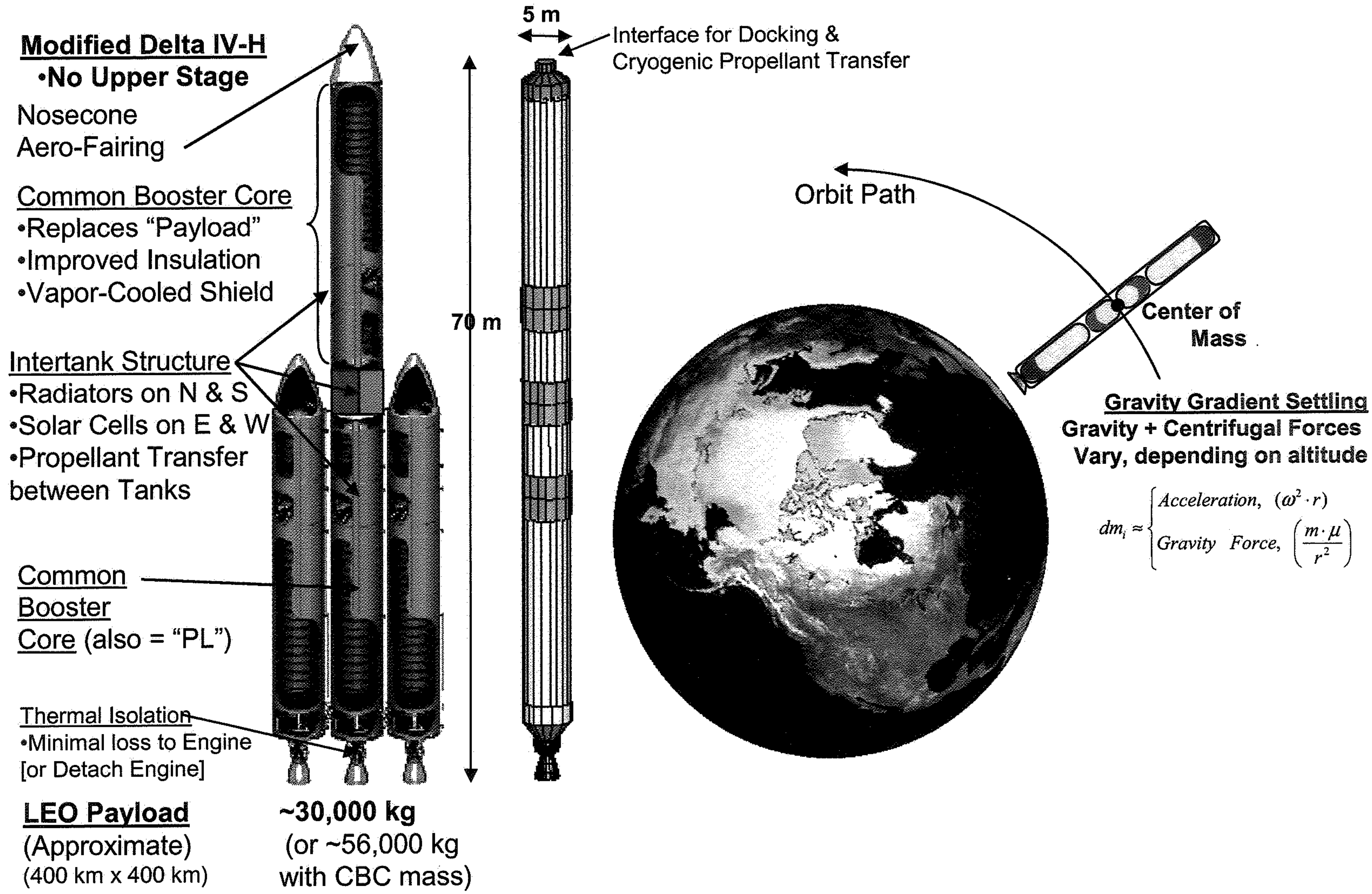


(estimates)	Earth Departure Stage		CEV Upper Stage		Lunar Lander	
Dry Mass (kg, *lbm*)	19,345	*42,645*	17,467	*38,507*	6,137	*13,529*
Propellant (kg, *lbm*)	207,704	*457,884*	163,538	*360,519*	25,105	*55,344*
Residual (kg, *lbm*)	2,719	*5,995*	2,955	*6,515*	486	*1,071*

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-Meteroids & 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

Launch Options: Large Monolithic Depot Concept



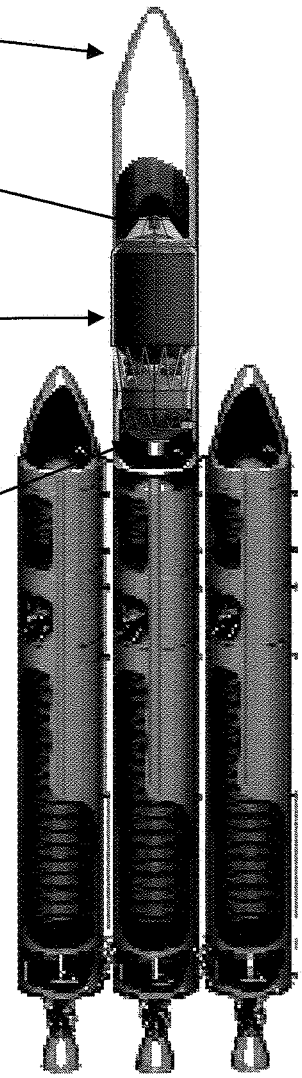
Example Depot Launch as Upper Stage

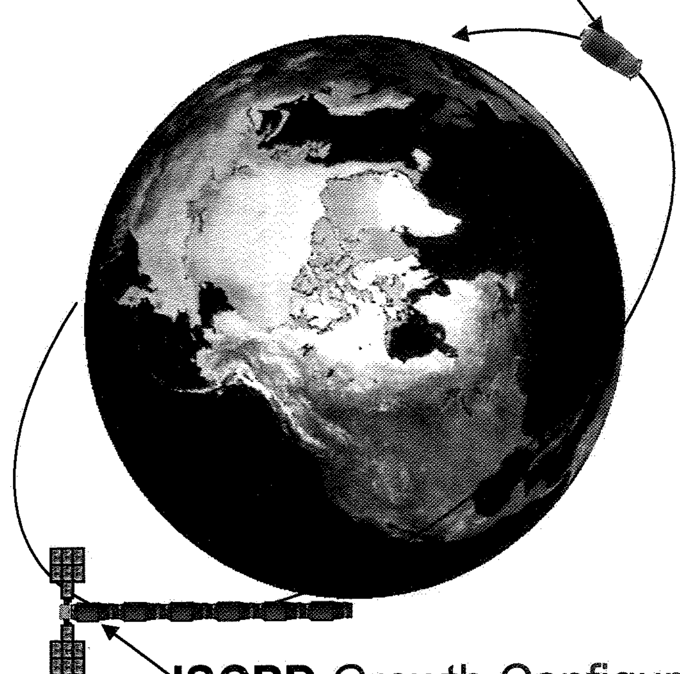
Payload Fairing
- May be shorter

Payload/Docking I/F

Cryo Upper Stage is **ISCPD Module**
- Reach Orbit nearly Full of Cryogenic Propellant

RCS Circularization
- Main Engine deleted
- Low Thrust adequate





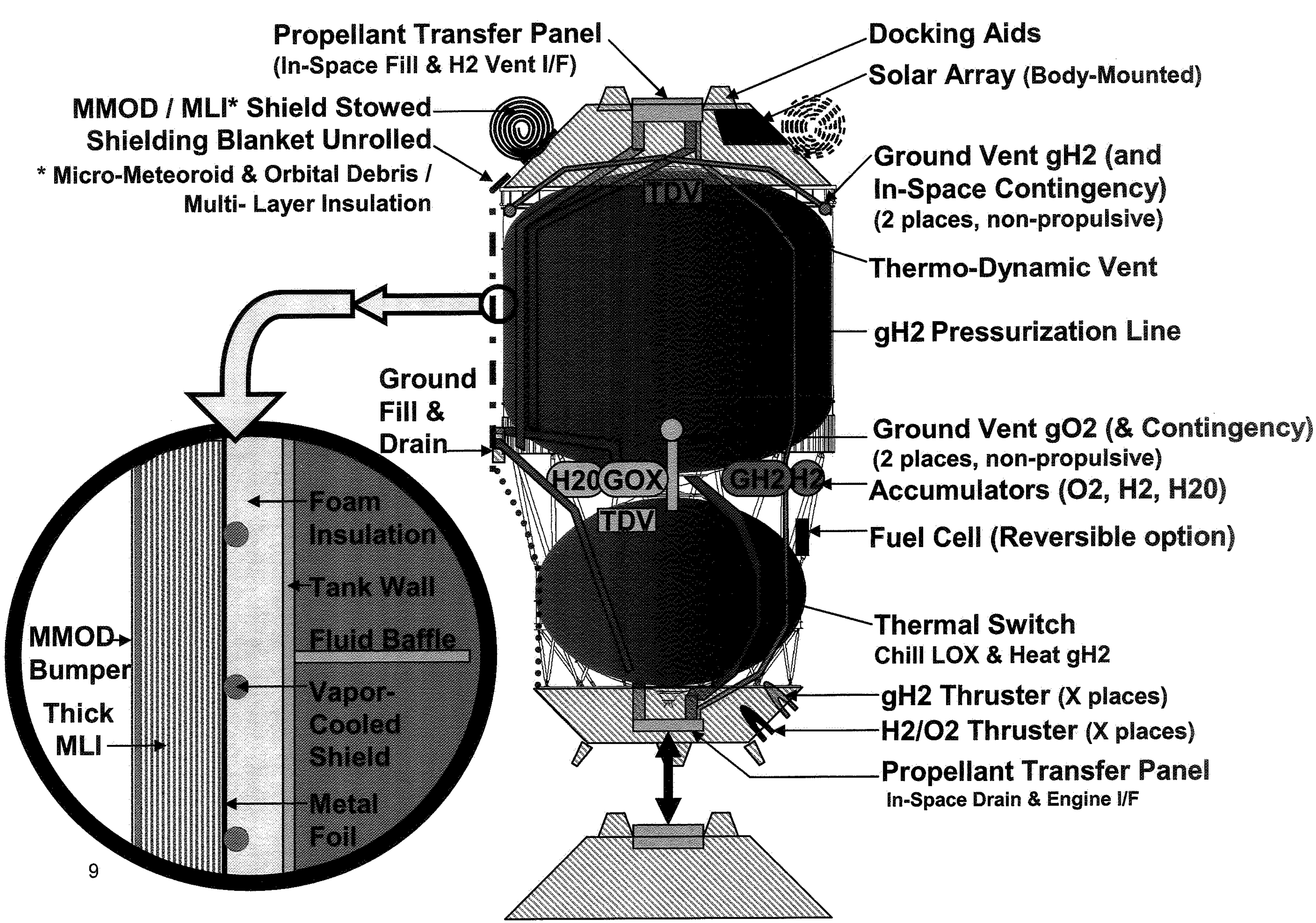
ISCPD Functional Requirements (through Launch)

Safety Constraints	General - Pressurized Structures, Safe-Life, etc
Launch Vehicle	Constraints of Launch Mass, Center of Mass Height, Moments of Inertia, Fundamental Modes of Vibration, Propellant slosh issues
Launch Environments	EMC/EMI, Acoustics, Vibration, Shock, Thermal, Pressure Loads, Design Load Conditions, Aerodynamics
Launch Functions	Basic Functions (Required): Venting, Monitor States and Modes, Perform Sequencing, Perform Navigation, Perform Guidance, Control Pressure in-Flight, Receive Range Safety Commands, Distribute Range Safety Commands, Collect Telemetry Data, Transfer Telemetry Data, Transmit Telemetry Data, Store and Distribute Power, Vent Internal Volume, Store Oxidizer (LO2), Store Fuel (LH2), Store Pressurant, Detect Automatic Destruct Criteria, Perform Destruct (if needed) Propulsion Functions (e.g., for self-transportation to final orbit): Prepare Engine for Operation, Prepare for Engine Burn, Ignite Engine, Perform Engine Burn, Terminate Engine Burn, Provide Attitude Control During Coast, Provide Attitude Control in Burn
Launch Interfaces	Interface with the Range, Ground Control, and Launch Vehicle, Internal Interface Requirements: Computer Resources, Reliability, Maintainability, Avionics Architecture, Command & Control, Range Safety, Telemetry, Power System, Propulsion, Materials, Processes & Parts

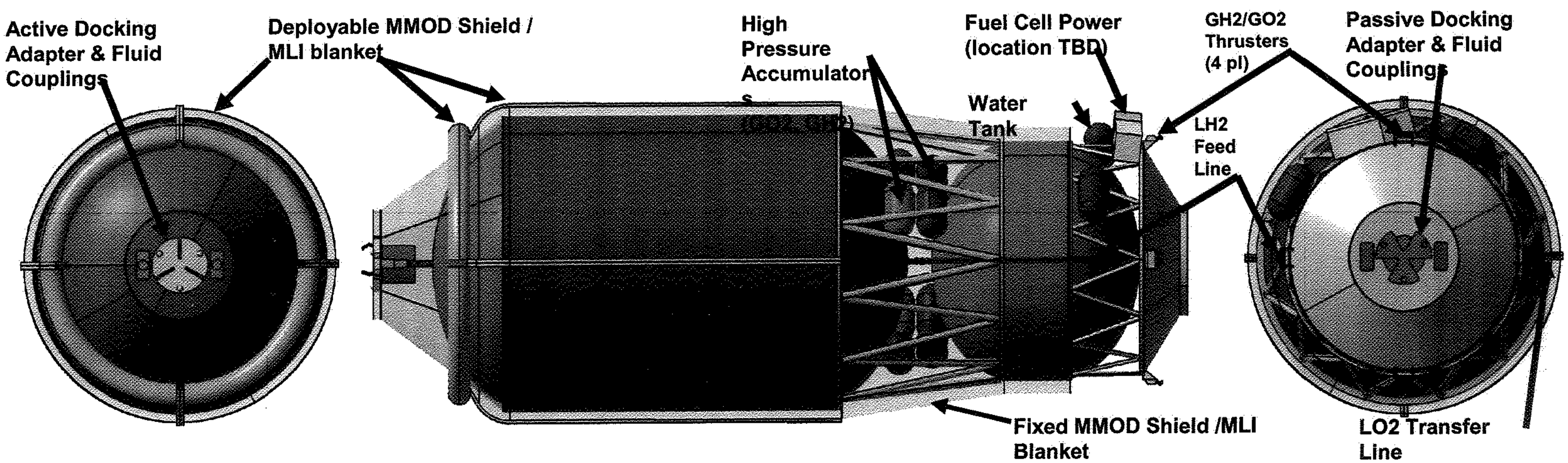
ISCPD Functional Requirements In Space

Deploy Subsystems	Solar arrays, Radiator, Antenna, Insulation, Shadow Shield, …
Ensure Safety	Orient to minimize heat, Contingency venting of ullage, etc.
Insulation	Limit heat in transfer & orbit, Allow heat increase ("thermal switch")
Impact Shielding	Protect against Micro-Meteoroid and Orbital Debris hazards
Boil-Off	Minimize (passively): Thermodynamic vent systems, Para-to-ortho H_2 conversion, Vapor-cooled shield, heat exchange; non-propulsive vent Integrate boiloff with propulsion, fuel cell power & ECLSS; gH_2 vent
Low Thrust (gH_2)	Fluid settling, Delta V & attitude control (cold/warm gas, resisto-/arc-jet)
Moderate Thrust	Re-orient & stabilize docking operations (gH_2 or gH_2-gO_2)
Control Attitude	Maximize solar power, Minimize heat flux (sun & Earth), drag & MMOD
Electrical Power	Support spacecraft functions; Growth to allow refrigeration
Refrigeration	Provide Cooling (H_2 alone or staged (warms O_2)), Radiate waste heat
Fluid Acquisition in Full Range of Acceleration	Zero-g (use settling, surface tension/ magnetic force) Micro-g (gravity gradient, drag/ low thrust) High-g (moderate to high thrust, rotation, or gravity of moon or Mars)
Docking	Station-keep, control attitude, Mate, Connect (electricity, & fluids)
Tank Venting	Vent or pre-chill before fill; growth option to exchange ullage gas
Fluid Transfer	Receive & transfer to other vehicles, Provide pressurization for flow
Pressurization	Helium gas or Autogenous (using Hydrogen and Oxygen gas)
Health Monitor	Assess Propellant Condition & Quantity
Other Functions	"Service Station" uses, C3I, Human Interfaces, End-of-Life Disposal

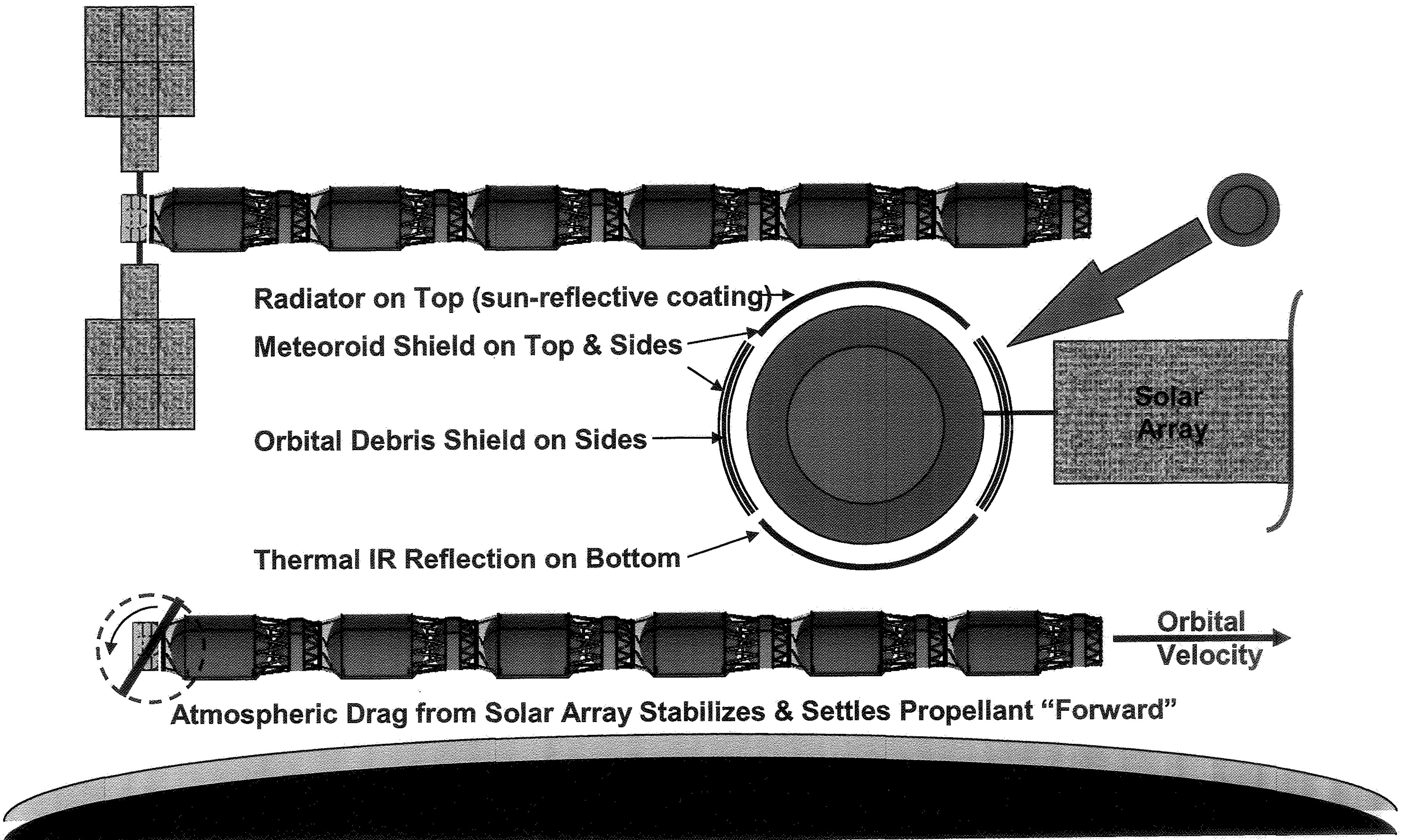
Reference ISCPD Module Concept



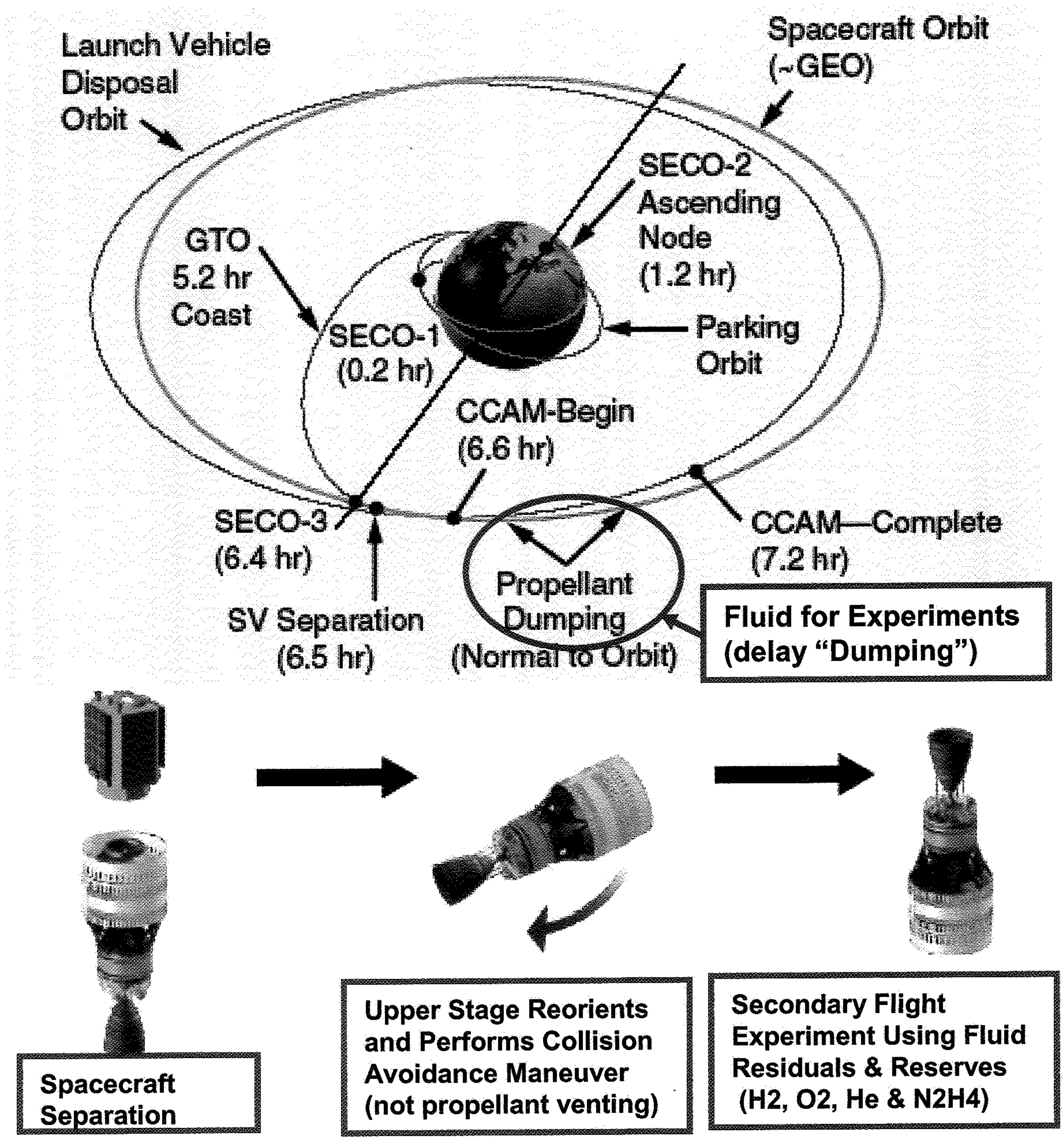
Reference ISCPD Module Design



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



Secondary Flight Experiment Opportunities

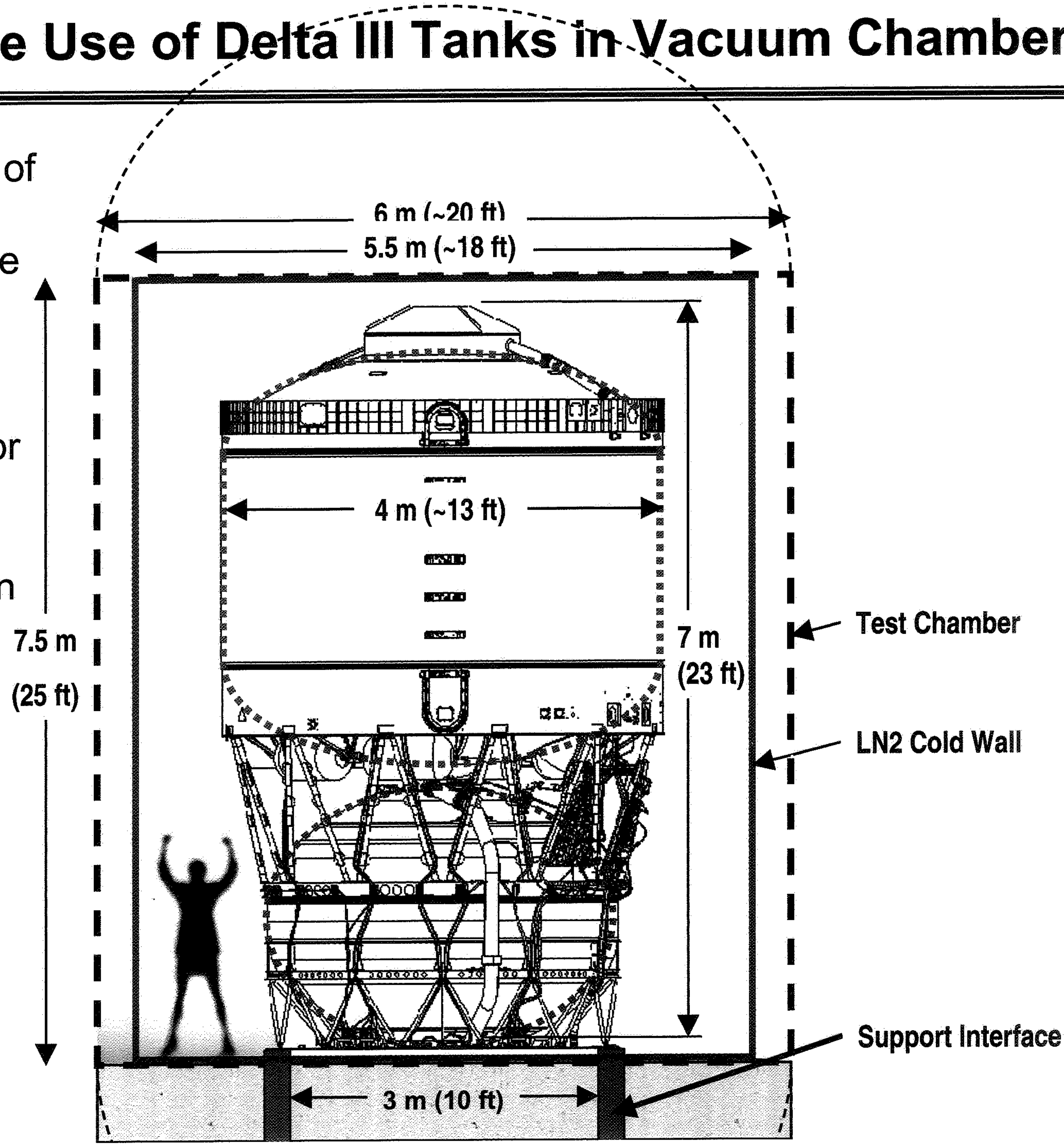


<u>Cryogenic Fluid Flight Experiment Objectives</u>

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

Example Use of Delta III Tanks in Vacuum Chamber

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



Summary

- In-Space Cryogenic Propellant Depots 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
- ISCPD modules are expected to be moderately-sized
  - Allowing deliver of modules to LEO nearly full of propellant (as upper stages without main engines)
- ISCPD design recommendations include modular construction and autgenous pressurization (no He gas)
- Technology demonstration may use secondary experiments on cryogenic upper stages for ready access to orbit