Jacksonville University

The Cryogenic Complex:

Cryogenic Tanks and Storage Systems - On the Moon and Cislunar Orbit

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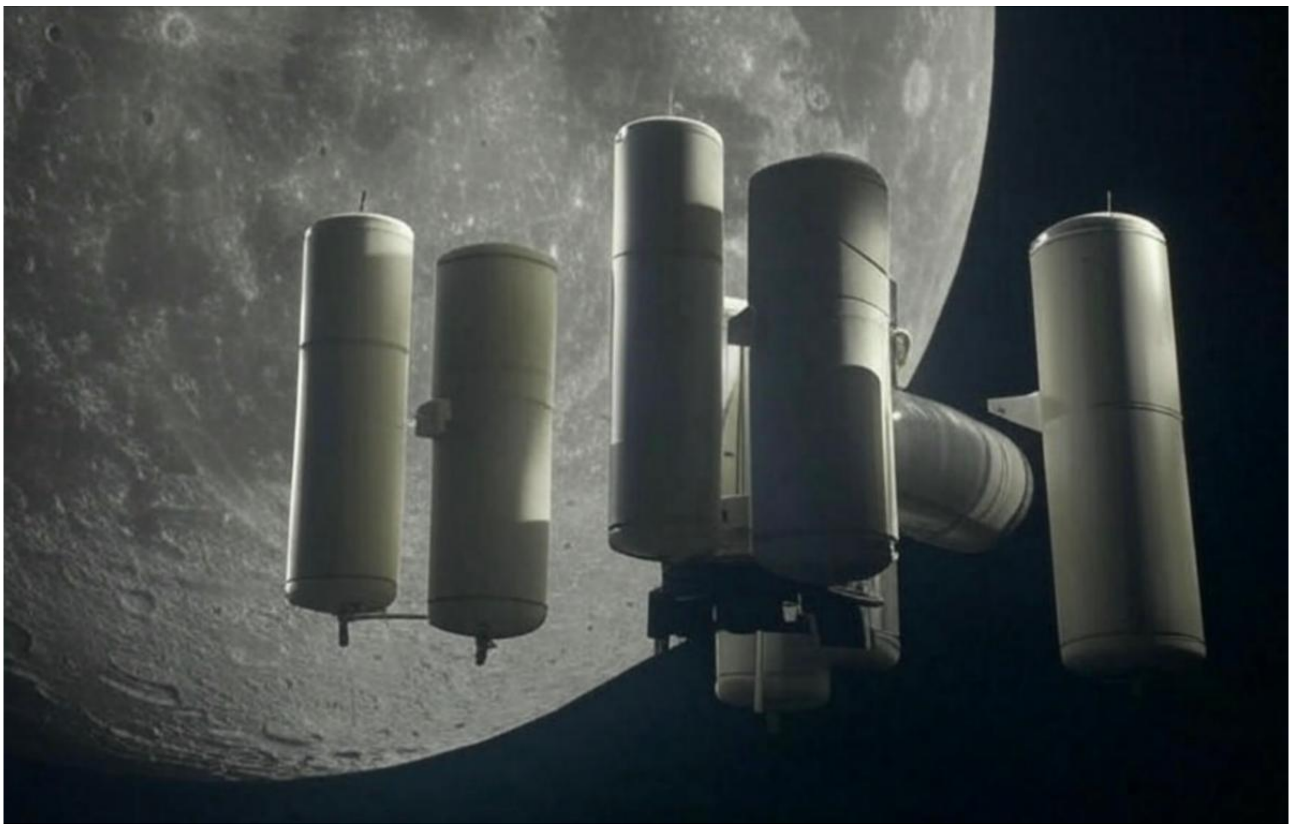


Jacksonville University – Cryogenic Complex: Universal Cryogenic Storage Tank

Theme Category, Major Objectives & Technical Approach

Theme Category

- Low Leakage Cryogenic Components

Major Objectives

- Develop modular cryogenic storage tank system
- Enable sustainable fuel logistics between Earth, Moon and Gateway
- Minimize boil-off and maximize autonomous handling

Technical Approach

- Triple- layer UCST tank design for LH2, LOX
- Electromagnetic docking, telemetry, and robotic compatibility
- Buried lunar tanks and modular orbital depot integration

Image/Graphic:

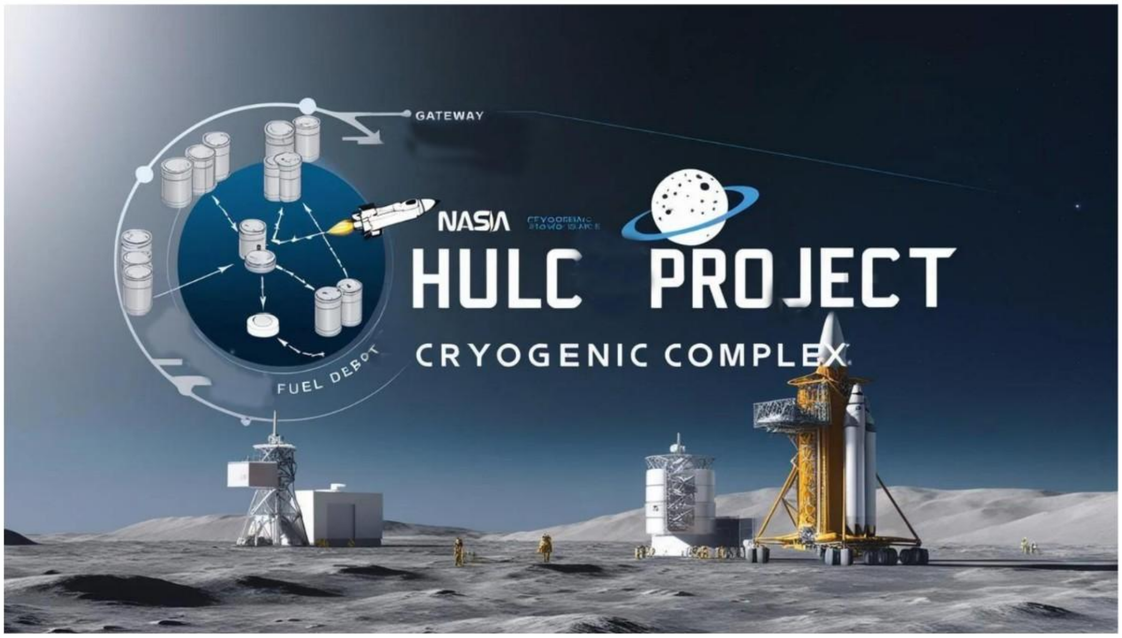
Key Design Details & Innovations of the Concept

- Advanced MLI & Pyrogel insulation for minimized boil-off; optional active cryocoolers for enhanced thermal control in long-duration missions
- Redundant sealing system using dual-layer metallic and fluorosilicone O-rings to prevent vacuum leaks and ensure compatibility with multiple cryogens
- Modular architecture supports integration with various lander chassis, orbital depot networks, and autonomous robotic handling units
- Integrated telemetry package for real-time tank health monitoring, plus universal cryogenic connectors for plug-and-play compatibility across mission platforms

Summary of Schedule & Costs for the proposed solution's path to adoption

- **Schedule**
  - Year 1: Design finalization & subscale fabrication
  - Year 2: Testing & full- scale build
  - Year 3: Certification & deployment readiness
- **Costs**
  - \$11.7M total & includes design, testing, and maintenance
  - \$146k material & \$11.5M launch

Contents



The Cryogenic Complex: Cryogenic Modular Tanks and Transport System -
The Universal Cryogenic Storage Tank (UCST)

Summary Statement

This project, *The Cryogenic Complex: Cryogenic Modular Tanks and Transport System - The Universal Cryogenic Storage Tank (UCST)*, outlines an innovative, feasible, and cost-effective method for using modular, re-usable cryogenic fuel cannisters called Universal Cryogenic Storage Tanks (UCSTs) as the standard for the Artemis and Human Lander System (HLS) programs. Functioning as both operational tanks and storage units for cryogenic fuels, UCSTs are used for rockets to and within the Cryogenic Complex including the Human Lander System, a Fuel Farm the Moon, an orbiting Fuel Depot, and the Gateway Space Station. These cannisters are equipped with safety-enhanced accessories, are constructed of durable yet lightweight materials, and are designed to endure the rigors of space. UCSTs provide the NASA HLS with an optimal solution for dealing with safe refueling, transporting, and storing multiple types of cryogenic fuels, furthering the mission of settling humans in space.

1. Introduction

Humanity looks to establish a long-term presence in space. NASA's Artemis program seeks to land humans on the Moon, with the goal of establishing a sustainable presence, especially for enabling future missions to Mars. NASA's Space Launch System (SLS) and the

SpaceX Starship will serve as the rockets to carry humans, cargo, and the Orion Spacecraft into lunar orbit. Then, it is a Human Landing System (HLS), SpaceX or Blue Origin, that will operate as the primary vehicle for transporting the astronauts and goods from lunar orbit to the surface of the Moon.

The SpaceX Starship HLS spacecraft, designed for lunar landings, is 52.3 meters tall, 9-meter diameter, and has no heat shield or flaps. It uses landing thrusters, solar panels, and has an elevator system for crew access to the lunar surface.

Artist's concept of the Blue Moon lander.
Blue Origin

Pursuing these goals, we envision a "Cryogenic Complex" as part of NASA's Artemis program, where the transiting HLS, Starship V3 or other spacecraft, and crews can refuel at a Fueling Depot and rest at the Gateway Space Station. The Fueling Depot is supplied by modular fuel cannisters filled and maintained by a Fuel Farm on the Moon. Fuel manufactured and/or stored on the Moon is transported to the orbiting Fuel Depot via the HLS, or a shuttlecraft related to, or derived from, the HLS, while empty cannisters are returned to the Moon for refilling.

Eventually, spacecraft such as the HLS may be designed so that a full fuel cannister can fit as an easy modular replacement for an empty tank. Ideally, a Universal Cryogenic Storage Tank (UCST) would be a one-size-fits all, so that it could be an easy modular unit, but it may, of necessity, evolve into different saleable sizes, much like a favorite fashion offered in multiple but similar sizes.

Using a broad stroke, completing the entire Cryogenic Complex would be a monumental achievement with a timeline for such a project depending on several factors, including the level of technology available, funding, and international cooperation. If we roughly guesstimate, design and planning may take 5-10 years. Infrastructure development could engage another 10-15 years, with final construction consuming another 5-10 years, or, if mimicking highway transportation projects on Earth, construction could continue forever.

Thus, building a completely functional Cryogenic Complex could take 20–35 years or more from concept to completion, depending on resources and technological advancements. As they say, “Rome wasn’t built in a day.” However, each piece of the puzzle designed towards that goal can require much less time, and if several parts are designed, engineered and produced simultaneously, these particulate solutions could be targeted and put to use in the near term, averaging 3 – 5 years. The example we will explore in this paper, within the larger framework of the Cryogenic Complex, is The Universal Cryogenic Storage Tank (UCST).

This proposal outlines an innovative, feasible, and cost-effective method for using modular, re-usable, cryogenic fuel cannisters by first bringing them from Earth to the Cryogenic Complex, either the Fuel Depot or the Moon, and later shuttling them between the Moon and the Fuel Depot using either the HLS or a variant of the HLS vehicle. These cannisters are designed for long-term usage, highest value functionality, and minimal cost.

2. **The Universal Cryogenic Storage Tank (UCST)**

The main element proposed in this project, and the cornerstone of the Cryogenic Complex, is the Universal Cryogenic Storage Tank (UCST). The UCST is a modular, reuseable, cryogenic, cylindrical cannister/vessel designed for LOX (liquid oxygen), LH2 (liquid hydrogen), and/or CH_4 (methane). It is useful in many applications, from underground fuel storage, to transport, to refueling of spacecraft in orbit. The modular design enables the UCST to be latched into the Fuel Depot array of tanks or be easily unlatched and clipped into a spacecraft as a portable, reuseable fuel tank. Likewise, the tank can be off-loaded into a waiting bay at the Fuel Farm on the Moon for refilling or servicing. In this report, we have modified the original proposal in order to refine the scope of the presentation. We aim to create a more coherent and narrow view of the cryogenic technologies to create less confusion and more answers to specific technical questions.

Figure 1: Example of the Universal Cryogenic Storage Tank

2A. Construction

Working with the idea of a standardized, modular tank that can be easily transported within the HLS, we can consider building it to fit within the Starship V3 cargo bay, for example, using a design based on available dimensions and structural constraints.

Starship V3 Cargo Bay Dimensions
Diameter: 9 meters (30 feet)
Height: Estimated ~ 18 meters (59 feet) for cargo space
Volume: Approximately 1,000 cubic meters.

The form suggested is a cylindrical, 9 meters in diameter to match Starship's cargo bay, making them vertically stackable which would allow multiple tanks to be transported in a single launch. The tanks would have reinforced mounting points to secure within Starship's cargo bay during launch and transport. The UCST is not intended for stress profiles on Earth launch and thus avoids the undesirable mass penalty of triple-walled metal tanks. Instead, its structure is optimized for the transit to the moon and Gateway, where structural loads are lower but thermal cycling and micrometeoroid threats persist. A hybrid tank structure featuring an Al-Li 2195 core wrapped in CFRP sacrifices structural integrity for weight reduction. These are materials chosen from studies of NASA's composite cryogenic tanks [16][17], which proved to be strong in lunar vacuum thermal environments (e.g., -230°C to +100°C) without massive multi-shell structures. Ribbing of structural foam between composite skins adds torsional stability with horizontal mounting capability—beneficial when integrating for depots or landers. It is feasible to incorporate a Whipple shield coating for exposed orbit or transit missions, rather than employing triple metal walls in most applications.

Although the exterior of the UCST is common to each type of fuel, the construction of each tank will feature materials optimized for the specific fuel—liquid hydrogen needs extra insulation due to its extreme volatility. LOX, methane, and hydrogen require different pressure management systems to prevent boil-off and leaks.

2B. Three Layers

The first layer: austenitic stainless steel, preferably grade 304. This steel specializes in very good performance at low temperatures. The stainless-steel nature also helps with corrosion resistance. This aerospace-grade stainless steel is recommended for durability and thermal resistance.

The next layer is a Multi-Layer Insulation material, **to** transfer heat and prevent fuel boil-off. This layer is typically made of aluminized Mylar or Kapton, which reflect thermal radiation Next is a spacer layer of thin Dacron mesh or Beta cloth separating the reflective sheets, reducing conductive heat transfer. More layers improve insulation efficiency. Depending on the fuel, this segment of the tank can range from 5 to 30 layers**.**

The third, inner layer, will differ depending on the fuel:

Liquid Oxygen (LOX): Austenitic Stainless Steel (316L, 304), because LOX is highly reactive**,** especially with organic materials, so it requires a liner with high oxidation resistance**.**

Stainless steel is durable, non-reactive, and able to withstand extreme temperatures without brittleness. Anti-corrosion coatings like Teflon or epoxy-based layers can add extra protection

Liquid Hydrogen: Aluminum Alloy (5083, 6061) or Nickel-based alloys (Inconel 625), because hydrogen is the coldest cryogenic fuel, requiring exceptional insulation to minimize boil-off. Aluminum is lightweight, while Inconel 625 can withstand use in extreme environments. Vapor-cooled shields or **a**dvanced polymer linings help prevent embrittlement and permeability issues.

Methane: Stainless Steel (304/316L) or Composite Liners because although Methane is less reactive than LOX, it still needs a strong, corrosion-resistant liner. Stainless steel works well, though carbon-fiber composites are emerging as a lightweight alternative for spacecraft applications. Epoxy-based inner coatings can help resist surface wear over long-duration storage.

Inside the tank there are internal baffles to reduce sloshing and maintain fluid stability in microgravity.

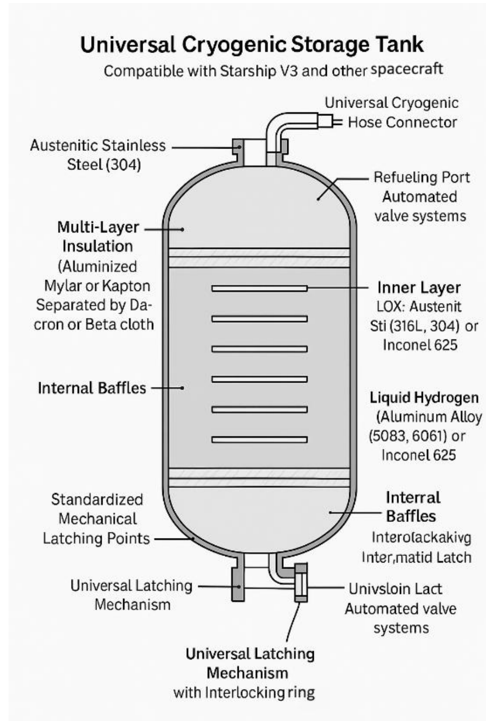


Figure 2: Detailed diagram of the three layers surrounding the tank

The UCSTs use Universal cryogenic hose connectors, compatible with Starship V3 and other spacecraft. A universal connector will be fitted to the tanks to allow them to be fueled and defueled from any system involved in the cryogenic complex. Each tank features standardized mechanical latching points that allow multiple tanks to physically connect into a fuel depot**.** So each tank module would have standardized latching interfaces but separate refueling ports**,** ensuring precise fuel transfer without contamination.

The refueling port**s** consist of automated valve systems for rapid fuel transfer and secure sealing with a pressure-regulated pumping mechanism ensures smooth microgravity fluid flow.

Importantly there are universal latching mechanisms on the tanks, including interlocking docking rings for tank-to-tank connections in orbit, allowing an electromagnetic alignment system to ensure precise locking with structural hardpoints for stability when forming fuel depots.

2C. Sealing and Interface Technology – O-rings and Seals

The sealing and interface technology integrated into UCST is critical to its success in extreme environments. Central to this technology is a dual-layer sealing mechanism that ensures leak-tight performance under vacuum and thermal cycling conditions. The primary seal is a silver-coated nickel alloy that forms a gas-impermeable interface during connection. This material was chosen for its excellent cryogenic tolerance, oxidation resistance, and compatibility with both LH2 and LOX. The backup seal is a high-performance fluorosilicone O-ring, positioned to provide redundancy if the metallic seal is compromised due to micrometeoroid impacts or structural shifts.

To accommodate robotic and autonomous docking, the sealing system includes spring-loaded caps that prevent dust intrusion and maintain cleanliness of the interface. These covers automatically retract during connection and reseal after disconnection, reducing contamination risks from lunar regolith or orbital debris. Leakage testing using helium mass spectrometry has demonstrated performance below 1.0E-9 scc/sec. This surpasses current standards for long-term storage on the ISS and aligns with NASA's low-leakage criteria for next-generation in-space systems.

Beyond the sealing itself, the connector interface also supports electrical and data transfer. This allows UCST to relay real-time telemetry—pressure, temperature, and fluid levels—to remote mission control systems, as noted in the Jacksonville University submission, *Cryogenic Fuel and Transfer: The Human Interface – Monitoring and Mitigating Risks.* The integration of a passive alignment collar and active locking mechanism ensures high tolerance for docking misalignment, with robotic arms able to secure the UCST from within ±5 mm of the designated target zone. These features are modeled on NASA's Refueling Interface Specification (RIS) and adapted to meet the broader range of applications foreseen in Artemis-related missions.

The reliability of the sealing system was verified through a combination of computational modeling and physical prototyping. Simulations examined stress concentrations during docking, pressure differentials across seals, and thermal expansion mismatches. Physical tests included 100+ thermal cycles from -230°C to +80°C, along with vibration tests replicating launch and landing shock profiles. The result is an interface system that can reliably perform over multiple connection cycles with minimal degradation, making UCST suitable for long-term infrastructure projects like Gateway or lunar habitats.

Thermal control is enhanced with optional active cryocoolers, included to minimize boil off losses. These can be integrated with VCS (vapor-cooled shields) that siphon off minimal amounts of cryogen vapor to cool critical areas. For buried deployments, regolith offers natural thermal buffering, and simulations using COMSOL Multiphysics indicate boil-off rates can be kept below 0.05% per day when properly shielded. These performance characteristics allow UCST to remain passive for months, enabling highly autonomous refueling networks.

2D. Accessory parts

The UCST will be fitted with standardized and easily replaceable component parts, such as main fueling valves, flow regulators, a calibrated fuel leak retrieval system, and electrical leak monitors, as explained in other Jacksonville University student HuLC proposals.

Universal cryogenic hose connectors compatible with Starship V3 and other spacecraft. Automated valve systems for rapid fuel transfer and secure sealing.

Pressure-regulated pumping mechanisms ensures smooth microgravity fluid flow.
The Latching mechanism consists of interlocking docking rings for tank-to-tank connections in orbit; using electromagnetic alignment system to ensure precise locking, with structural hardpoints for stability when forming fuel depots.

Blow-Out Ports (Emergency Venting): using a burst disc mechanism to safely vent excess pressure in case of failure with controlled venting ducts for gradual pressure regulation and automated fail-safe triggers integrated into onboard monitoring systems.

Boil-Off Return Lines: considers the Gas return manifold for capturing boil-off vapors using a compressed gas recycling system that feeds boil-off back into storage or auxiliary fuel use and thermal isolation valves to minimize fuel loss during storage.

Autonomous Fluid Transfer System – Utilizing microgravity-compatible cryogenic pumps for controlled refueling.

Smart Telemetry Package – Monitors pressure, temperature, fuel levels**,** and sends updates to the spacecraft. To allow independent operation without introducing mass, structural health monitoring systems—incorporating fiber optic strain gauges and embedded RTDs—are only incorporated in units that will experience repetitive thermal/mechanical cycling (e.g., shuttle transit or depot mounts). This avoids over-engineering of single-use or buried UCSTs, a mistake of some heritage tank systems. Pressure relief systems founded on Boeing's burst-disc mechanisms [3][17] are power-free and compact, suitable for buried or passive deployment. See more on this in the Jacksonville University Presentation on *Cryogenic Fuel Storageand Transfer: The Human Interface - Monitoring and Mitigating Risk...*

3. Useability and Versatility

Operationally, UCST is engineered for both flexibility and autonomy. The modular, reuseable, cryogenic canisters support various mission architectures, designed for both cryogenic storage and durable transport between the Earth, the Fuel Depot, the Gateway, and the lunar surface Fuel Farm. The canisters will be insulated to maintain the cryogenic state of LOX and LH2 in the extreme lunar environment. This includes protection from the vast temperature swings on the Moon's surface, where temperatures can vary between -173°C during the night and +127°C during the day. UCSTs can be robotically deployed and retrieved, connected to ISRU units for on-site fuel generation, or transferred between spacecraft as consumable modules.

Modular and interconnectable, the cannisters are planned to work like energy "batteries" – easily replaceable where needed, into cargo bays, storage complexes, and ultimately "snap on" to appropriately designed spacecraft, such as Orion or Starship. The canisters will be lightweight and durable, constructed using advanced composite materials to minimize mass while ensuring they can withstand the stresses of launch, space transit, and docking operations. Refillable and reusable, after each mission, the canisters will be returned to the lunar surface where they can be refilled with LOX, and LH2 extracted from lunar mining operations. The canisters will be designed for quick refueling cycles, optimizing the use of lunar resources, and reducing the need for costly Earth-based supplies.

Utilizing toroidal or multi-compartment tank designs is anticipated to reduce slosh-induced instability, with internal baffles and diaphragms to further control fluid motion. Toroidal tanks can reduce slosh instability during burns and maneuvers, but come with complexity in insulation. For modularity and simplicity, cylindrical shapes remain preferred for static depot storage, while shuttle variants may adopt hybrid geometry. This focused use-case distinction allows optimized structural layouts without imposing mass or complexity penalties across all tank types. Structural reinforcement can be achieved by employing composite materials with high thermal resistance and structural integrity to withstand launch loads. Thermal insulation can be enhanced utilizing multi-layer insulation (MLI) blankets and aerogel-based coatings to reduce heat transfer. Incorporated cryocoolers can actively manage tank temperatures and prevent boil-off, as well as additional solutions advanced by our classmates in their proposals. Also, phasechange materials can be employed within the insulation to counteract temperature fluctuations. Other considerations include an internal bladder system consisting of a flexible membrane inside the tank that expands and contracts to keep the fuel contained in a stable configuration, reducing sloshing during transport and orbital fluctuations.

4. **Placement**

4A. General tank placement

Keeping cryogenic propellant tanks out of the Sun, or at least minimizing exposure, is pivotal to reducing boil-off. Practically every serious proposal for orbital propellant depots or deep-space stages incorporates this principle: either by orienting the vehicle in a sun-favorable attitude, by adding passive sunshields, by gentle rotation, or most often a combination of these.

Permanent shadowing of the tank provides the best insulation short of active refrigeration it drastically cuts radiant heat transfer, allowing missions like lunar landers, depots, or Mars transfer vehicles to preserve their precious cryogens for longer. As design papers and mission studies from NASA, ESA, and industry have shown, the optimal thermal strategy is usually to point the heat away to cold space, for example, a depot in LEO maintained at north orders of magnitude fares better than an unprotected tank. Where shadowing isn't 100% achievable, engineers rely on reflective insulation, specialized coatings, and rotation to mitigate solar input.

Looking ahead to lunar bases and Mars voyages, these passive thermal control methods – sometimes augmented by active cooling – will be the cornerstone of managing cryogenic fluids in space. The consensus is clear: when it comes to preserving propellant, a cryogenic tank that "hides" from the Sun will outperform one that basks in it. Sources that support this conclusion include thermal control design reports by NASA and ULA, Apollo mission thermal operations; ESA zero-boil-off studies, and modern analyses of proposed orbital cryogenic depots.

4B. The Fuel Farm - tanks on the Moon

An important and truly innovative aspect of the UCST cannisters is that they will be buried 5-10 meters underground, underneath the Moon's surface which will help regulate temperature and provide a degree of radiative insulation. In lunar surface operations, UCSTs are designed to be partially buried, exposing only their top interface. The lunar regolith will help protect the tanks by regulating temperature, reducing exposure to thermal cycling, cosmic radiation, and micrometeoroid impacts. Their robust outer CFRP layer, combined with structural foam ribs, provide added resistance against pressure gradients when buried or exposed.

Underground tanks will significantly reduce the amount of cooling needed as well as help with retention of cryogenic fuels. The tanks will have helium pressurization to allow fuel flow to fueling stations above ground that will fuel transport shuttles as well as other lunar lander modules. Surface robots equipped with standard grappling tools can access, relocate, or refill UCSTs without the need for human intervention.

4C. The tanks at the Fuel Depot – orbiting tanks

Several UCSTs linked together will form a modular tank system developed for easy and convenient storage of cryogenic fuels in space. The tanks can be easily inter-locked to provide an easy orbiting system of tanks for enroute refueling. An accessory attachment to the UCST is the linking interlock that connects multiple UCSTs into re-designable grids, and permits the building of customizable bays or docks for spacecraft refueling and servicing. Depending on the refueling methodology, the spacecraft and tanks can be relinked to enable alternate processes such as motor-pump refueling, differential pressure refueling, or moveable craft placement for motion-aided refueling maneuvers. For orbital use, UCSTs may be mounted on trusses or housed in refueling depots like the envisioned LOX/LH2 Gateway Node. Their modularity enables strategic placement based on mission demands. RFID chips, QR-coded fiducials, and thermal beacons support robotic alignment and health diagnostics. Each UCST also logs its operational history to assist in mission planning and lifecycle assessment.

4D. Onboard spacecraft tanks

UCSTs are intended to be used as primary fuel tanks on HLS type-system spacecraft. UCST variants are mission optimized. Shuttle-compatible units have thinner walls, using passive pressure-regulated expulsion rather than internal pumps. This is based on NASA's RIS guidelines and modeled after CryoDock robotic systems [4][10]. Connector design includes fault-tolerant collars for robotic misalignment and a standard keg-style interface with Blue Moon, Starship 3, and Gateway fueling ports. By standardizing the docking interface but not over-constraining the physical form factor, UCSTs can be swapped between vehicles without a "one-size-fits-all" compromise. USCT can be seamlessly integrated into any component of the HLS program as fuel tanks or storage. Their modular design allows a quick-latch mechanism for replacement while their robust design ensures endurance under the harshest cryogenic and space conditions. Transporting tanks to locations as cargo, UCSTs can be mounted to lander exteriors or stored within payload bays. Their pressurization system uses helium backfill to drive cryogens out via differential pressure. This passive transfer mechanism eliminates the complexity of onboard pumps, simplifying integration with fuel depots and transfer vehicles. The keg-style connector ensures compatibility across vehicle generations, including Starship 3 and derivatives, Blue Moon landers, and Gateway service modules.

5. The Fuel Depot

Currently there are no publicly known, fully operational orbital cryogenic depots that might be widely available for general space missions, however there are companies such Eta Space , with their CryoDock single use refueling, and MT Aerospace, asserting that they are actively developing and testing technologies for orbital cryogenic depots.

Our unique and innovative Fuel Depot is envisioned as a tethered collection of orbiting UCST (Universal Cryogenic Storage Tanks), equipped with docking stations and service bays configured for efficient handling of various spacecraft. Here transiting craft can park and refuel, leave their main heavy ship for servicing, and shuttle to either the Moon or the Gateway via HLS links.

The Fuel Depot will offer standardized cryogenic hose connectors supporting quick fuel transfer to visiting spacecraft. The Fuel Depot will acknowledge the issues concerned with microgravity handling and is capable of zero-g fluid transfer using capillary channels and active pumping. A major improvement of the Fuel Depot over existing discussions of refueling methods is that it does not require a separate cargo-transport fueling spacecraft such as a “refueler” and relieves the difficult operation of coupling/decoupling with another transiting spacecraft for the purpose of fueling. A big advantage of the Fuel Depot is that several tanks will be ready with fuel, and multiple, hasty launches for refueling will not be needed. Another huge advantage of the Fuel Depot is that shuttle-craft can keep lower minimum onboard fuel requirements and reserves, saving money on unnecessary hauling of fuel and increasing safety for crews by lowering fire hazards caused by overloading fuel for transport or exigency use.

6. **Earth to Cryogenic Complex – Cargo Rocket**

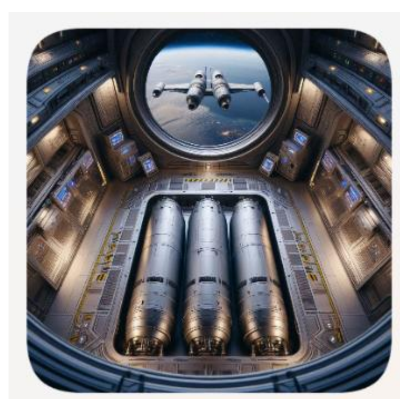
The first step for using the modular fuel cannisters is to first get them from Earth to the Cryogenic Complex, either the orbiting Fuel Depot or the Moon. This part of the proposal outlines a system for stabilizing cryogenic fuel tanks during flights aboard the SpaceX Falcon Heavy, ensuring safe transport to the Moon. The focus is on structural reinforcement, thermal management, and dynamic stabilization to prevent excessive sloshing and movement that could compromise mission success.

Cryogenic fuels such as liquid hydrogen (LH2), liquid oxygen (LOX), and liquid methane (CH_4) are essential for deep-space missions but present significant challenges in transportation due to their extreme temperatures and sensitivity to movement. The Falcon Heavy cargo bay is located at the top of the rocket, within the payload fairing (which sits on top of the second stage of the rocket, at the very top of the vehicle) provides a viable platform for lunar-bound payloads, but proper fuel tank stabilization is crucial to maintaining integrity and performance.

One objective of this proposal is to ensure that an advanced stabilization system is used to secure cryogenic fuel tanks within the Falcon Heavy cargo bay, thereby minimizing sloshing and shifting of cryogenic fluids during launch, spaceflight, and lunar approach.

Other objectives are to ensure optimal thermal insulation and additional measures to prevent excessive boil-off. Our classmates address these topics in related proposals. We also recognize the importance of enhancing safety measures to mitigate risks associated with rapid acceleration, vibrations, and microgravity effects.

We address design considerations for the modular tanks here in Part IV below, but regarding transport of the tanks, we need to consider tank geometry and placement, such as positioning tanks at the center of mass of the cargo bay for optimal weight distribution. One option is to integrate a modular mounting framework with vibration-damping materials to absorb launch-induced stress and implement active securing mechanisms, such as retractable clamps or adaptive braces, to accommodate pressure fluctuations. An active stabilization system can include a damping system using gyroscopic stabilizers or fluid motion controllers.



It might be useful to implement real-time monitoring via accelerometers and gyroscopes to adjust stabilization parameters dynamically. Larger unwanted vector moments could be counter-acted using thruster-based corrections or reaction wheels. More simply, a gimbal suspension structure would allow multi-axis movement to counteract launch vibrations and gravitational shifts.

7: Fuel Depot to the Moon and back – The HLS and Shuttles

The ability to efficiently transport essential resources like liquid oxygen (LOX), liquid hydrogen (LH2), and methane (CH_4) from the Moon to the Fuel Depot (refueling station) of the Cryogenic Complex, becomes the next critical goal. Here we investigate the design of a specialized Shuttle rocket system that will transport LOX and LH2 canisters from the Moon's surface to the Fuel Depot, leveraging reusable canisters refilled from lunar mines. The design focuses on sustainability, efficiency, reliability, and cost-effectiveness, ensuring that the rocket can handle the unique requirements of lunar launch conditions and long-duration space travel.

Reaching a cislunar orbit around the moon from the lunar surface would typically take a few days depending on the chosen trajectory and spacecraft capabilities, with a direct transfer method taking the shortest amount of time, usually between 3-4 days. Key considerations include propulsion systems, vehicle architecture, tank design, the refueling process, and a cost analysis. There are positive economic implications of using such a rocket for future lunar infrastructure development, emphasizing the role of reusable canisters in minimizing costs over time.

The Gateway is an essential component of NASA's Artemis program, serving as a staging point for lunar exploration and long-term lunar infrastructure. Located in a highly elliptical orbit around the Moon, Gateway will also act as a hub for spacecraft traveling to and from the lunar surface. To ensure the viability of Gateway, the transport of liquid oxygen (LOX) and liquid hydrogen (LH2) from the Moon's surface to the fueling station is a critical requirement, as these propellants will be used for lunar landers, space exploration vehicles, and spacecraft refueling for missions to Mars and beyond.

We are recommending here the design of a HLS Shuttle rocket system capable of transporting LOX, LH2, and methane canisters refilled from lunar mines to the Gateway and Fuel Depot. By incorporating reusable canisters, this system aims to minimize launch costs while ensuring the availability of essential propellants for space operations.

The rocket system must achieve several objectives to facilitate the transport of LOX, LH2, and methane canisters from the Moon's surface to the Gateway and Fuel Depot. These objectives include reusable canisters, designed for multiple cycles, including refilling from lunar mines. This capability significantly reduces the cost of propellant transport by reusing the same canisters.

Design considerations include *payload capacity* as the rocket must carry large, heavy tanks of LOX and LH2, essential for refueling spacecraft. The rocket design must maximize *fuel efficiency* to minimize the amount of fuel required for lunar ascent and the transit. Instead of building a whole logistics chain, this entry is concentrated on the HLS Shuttle-UCST interface. UCST tanks are actually optimized for lunar ascent to NRHO with the need for ~2.5 km/s delta-v. This lower need (in comparison with Earth orbit) allows for lighter structural loads and less support hardware for tanks. Separation of the fuel delivery system from launch architectures benefits the UCST to obtain lunar-specific structural tuning lighter skins, lower number of layers, and active cooling only for transit as an option. The tanks are pre-pressurized with helium and have passive differential pressure-driven flow without mechanical complication. Their design limits were set according to NASA's Cryogenic Disconnect Challenge [10] and DSNE load profiles [20], aiming at shuttle compatibility without excess overdesign. The system must be *reliable* enough for repeated missions, with *safety features* that ensure safe operations for both crew and cargo.

Considering cost-effectiveness and ensuring long-term sustainability, the Shuttle rocket should reduce overall operational costs, particularly through reusability and integration with lunar mining operations.

The Shuttle rocket must be optimized for the Moon's low gravity, lack of atmosphere, and the need for efficient ascent from the surface. The current propellant choice is liquid oxygen (LOX) and liquid hydrogen (LH2) as propellants, given their high energy efficiency and suitability for deep space travel. These propellants offer the highest specific impulse (Isp) available from chemical propulsion, making them ideal for long-range missions and efficient transport to lunar orbit.

8: The Lunar Fuel Farm - Lunar Mining and Refueling Operations

Lunar regolith contains essential materials such as oxygen, hydrogen, and water ice, which can be processed into LOX and LH2 through mining and extraction methods. The rocket system will leverage in-situ resource utilization (ISRU) to harvest these materials and convert them into usable propellants. Lunar mining and extraction operations will involve using automated systems or robotic mining equipment to extract water ice from permanently shadowed craters or other suitable lunar sites. The extracted water will be electrolyzed to produce oxygen and hydrogen, which will then be stored in the refueling stations on the Moon's surface. Localized refueling stations will be equipped with the necessary infrastructure to store and pump LOX and LH2 into the reusable canisters. They will need to be highly automated, operating with minimal human intervention, to ensure rapid and efficient refueling.

Figure 3: Example of Fuel Farm to be used with all the tanks

For the rocket system to operate effectively, a robust set of surface operations will be required, including one or more lunar launch pads: The system will require specialized launch infrastructure to accommodate the rocket's lifting capacity and ensure safe launch conditions. Automated rovers or cranes will be used to load the refueled canisters onto the rocket, facilitating the transport of LOX and LH2 to the launch vehicle.

9. Verification Tools and Facilities

UCST testing would plan on using established NASA and university-affiliated test facilities. The primary testbed for subscale work could be the local UCF Cryogenics Laboratory, with its 2.5-meter cryostat, thermal instrumentation systems, and LN2 and LOX handling capabilities. Full-scale testing utilizes NASA Marshall's environmental simulation chambers and KSC's Swamp Works regolith testbed.

Thermal simulations can be conducted using COMSOL Multiphysics and ANSYS Fluent. Mechanical integrity assessments use ABAQUS and SolidWorks Simulation. Leak propagation and failure mode analysis can be carried out with MATLAB scripts integrated with thermal sensor logs. Each UCST will be embedded with fiber optic strain gauges, RTDs, and capacitance-based liquid level sensors.
Interface docking evaluations can use robotic test rigs based on ISS-standard and RIS-aligned specifications. Assessments would include connector repeatability, pressure lock integrity, and seal degradation over 200+ cycles. Other anticipated additional tools would include leak detectors, infrared imaging for thermal mapping, and 3D photogrammetry scanners for post-test dimensional verification.

Testing would culminate with a validation report correlated with to Technology Readiness Levels (TRL) milestones, NASA, and HLS flight certification requirements. Appropriate documentation would help ensure UCST advances to orbital demonstration or lunar payload integration within the 3–5 year HuLC timeline, with operational prototypes potentially available sooner.

10. Time-Line

UCST development is structured over a 36-month plan, broken into six major phases.

Phase 1 (Months 0–6) involves design finalization, CAD modeling, and initial material procurement. The subscale test apparatus would probably be constructed at UCF CryoLab.

Phase 2 (Months 6–12) would allow the fabrication of the first 25–50 L units for LN2 testing, boil-off analysis, and thermal vacuum exposure.

Phase 3 (Months 12–18), full-scale (300–500 L) units could be built and undergo complete thermal, structural, and robotic compatibility tests. This includes radiation shielding verification, regolith abrasion trials, and interface qualification.

Phase 4 (Months 18–24) would emphasize automated operations and lifecycle stress testing (thermal cycling, vibration, and fatigue analysis). Units would be exposed to realistic mission conditions including dust and radiation simulation.

Phase 5 (Months 24–30) focuses on software integration, with data systems interfacing with NASA telemetry protocols and AI-based health diagnostics implemented. Robotic deployment trials would occur during this window, validating the autonomous logistics workflows.

Phase 6 (Months 30–36) is planned to be dedicated to final documentation, NASA HLS certification, and delivery readiness. A flight-ready UCST prototype will be submitted for orbital or lunar depot integration.

Built-in schedule reserves are placed between Phases 3 and 4, allowing up to 3 months of unexpected technical rework. Milestone reviews at M6, M12, M24, and M36 ensure progress is assessed and adjusted in coordination with stakeholders and mission partners.

11. Cost Analysis

The development of this rocket system will require substantial investment, particularly in the areas of design, propulsion technology, and infrastructure. Key cost factors include engineering and design: Developing a reusable system for transporting cryogenic propellants from the lunar surface to the Fuel Depot and Gateway will involve significant R&D and testing, particularly for the canister refilling system and lunar mining operations. Infrastructure development such as the construction of lunar mining facilities, refueling stations, and launch pads will be a critical part of the overall investment.

Lunar mining operations that establish the technology for mining and processing lunar resources into LOX and LH2 will be a significant upfront cost, but it will ultimately lower the cost per mission by reducing dependency on Earth-based supplies. Once developed, the operational costs will be lower due to the reusability of the canisters. Key factors influencing the operational cost include the fact that the use of lunar resources will reduce the cost of refueling, as it eliminates the need to transport LOX and LH2 from Earth. The ability to reuse the same canisters multiple times will significantly reduce the cost per mission, as the infrastructure for refilling and re-launching becomes more streamlined.

The initial launch costs per mission will vary depending on the scale of the rocket and the degree of reusability achieved. However, as reusable canisters and lunar mining operations become more refined, the price per launch could decrease significantly, making lunar transport more affordable and sustainable in the long term.

If we were to shuttle fuel from Earth rather than the Moon, the Falcon Heavy provides a useful cost baseline. A Falcon Heavy launch has a payload capacity of approximately 63,800 kg to Low Earth Orbit (LEO) and 16,800 kg to lunar orbit, at a cost of around $150 million per launch. This results in: $2,350 per kg to LEO vs. $8,900 per kg to lunar orbit.

By comparison, transporting fuel from the lunar surface to the Gateway, even at a high-end estimate of $5,000 per kg, is still more cost-effective than launching directly from Earth. Furthermore, if ISRU (In-Situ Resource Utilization) technology advances, lunar refueling could be done at a fraction of current projections. ISRU is a space exploration technique that uses local resources to support human missions, rather than relying on supplies from Earth.

Budget Breakdown

UCST's development costs reflect its use of advanced materials, robust testing protocols, and orbital qualification standards. The total cost is estimated at $11.745 million, broken down as follows:

Phase	**Cost (USD)**	**Description**
Materials	$146,000	Raw materials: Teflon, Al-Li 2195, Mylar, Pyrogel, CFRP (~1000 kg total)
Manufacturing	$39,000	Labor, cutting, assembly, and tooling ($39/kg avg)
Testing	$35,000	Cryo performance, structural integrity, radiation resistance
Maintenance (5y)	$25,000	Routine inspection, sealing replacement, upgrades

Launch to LEO	$11,500,000		Based on 1150 kg @ $10,000/kg via Falcon 9, Vulcan, or Starship
Total		**$11,745,000**	

These costs incorporate both government and commercial standards for reliability and space safety. Support from partner institutions such as academic contributions and NASA centers may reduce long-term cost. Future iterations would see reductions through economies of scale and additive manufacturing.

12. Conclusion

The design of a reusable UCST system for storing and transporting LOX, LH2, and methane throughout the Cryogenic Complex, from the Earth to the Moon's surface, to Gateway, to a Fuel Depot, represents a significant leap toward sustainable lunar exploration in the HLS program.

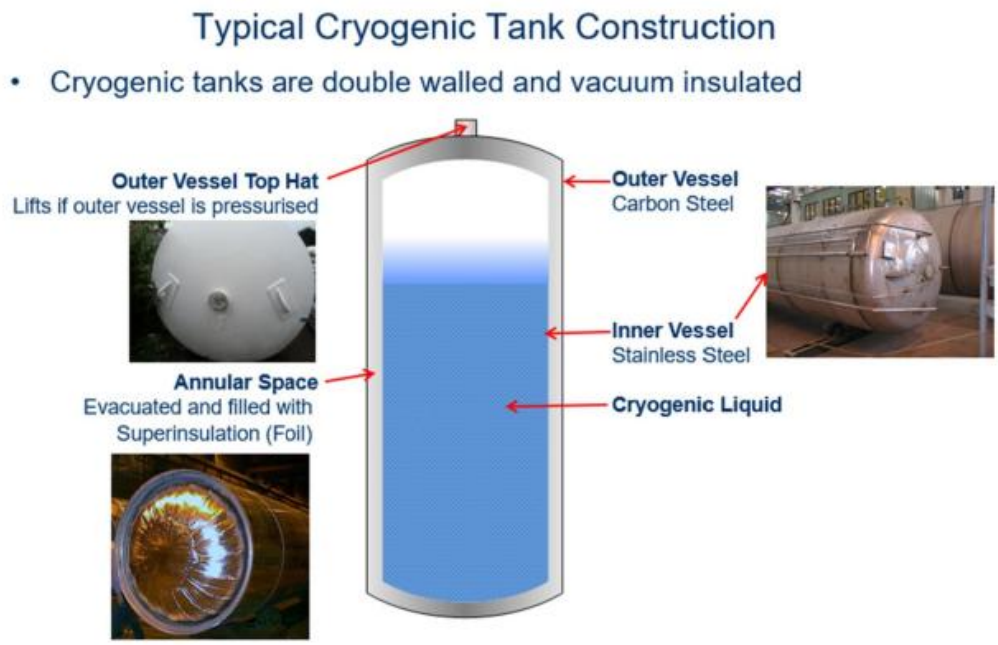
Incorporating reusable canisters refilled from lunar mining operations, this system reduces dependency on Earth-based resources and minimizes the long-term cost of transporting essential propellants. As technological advancements in mining, refueling, and rocket reusability continue, this system could become a cornerstone of lunar infrastructure, enabling not only Gateway operations, and refueling operations at the Fuel Depot, but also further exploration of the solar system.

UCST offers a groundbreaking approach, addressing critical challenges in storage, mobility, and autonomy through a comprehensive system design that emphasizes low leakage, high adaptability, and environmental durability. Its modular architecture, advanced sealing interface, and robust material stack ensure functional performance across varied mission profiles—including ISRU support, orbital transfer, and long-duration lunar deployment.

Rigorous testing procedures, technical foresight, and environmental modeling validate UCST's readiness for complete integration NASA's Human Landing System. This project bridges critical infrastructure gaps for sustainable exploration and supports long-term fuel strategies vital to Artemis, Gateway, and beyond. As a scalable and field-replaceable cryogenic solution, UCST sets a foundation for a new generation of propellant management systems.

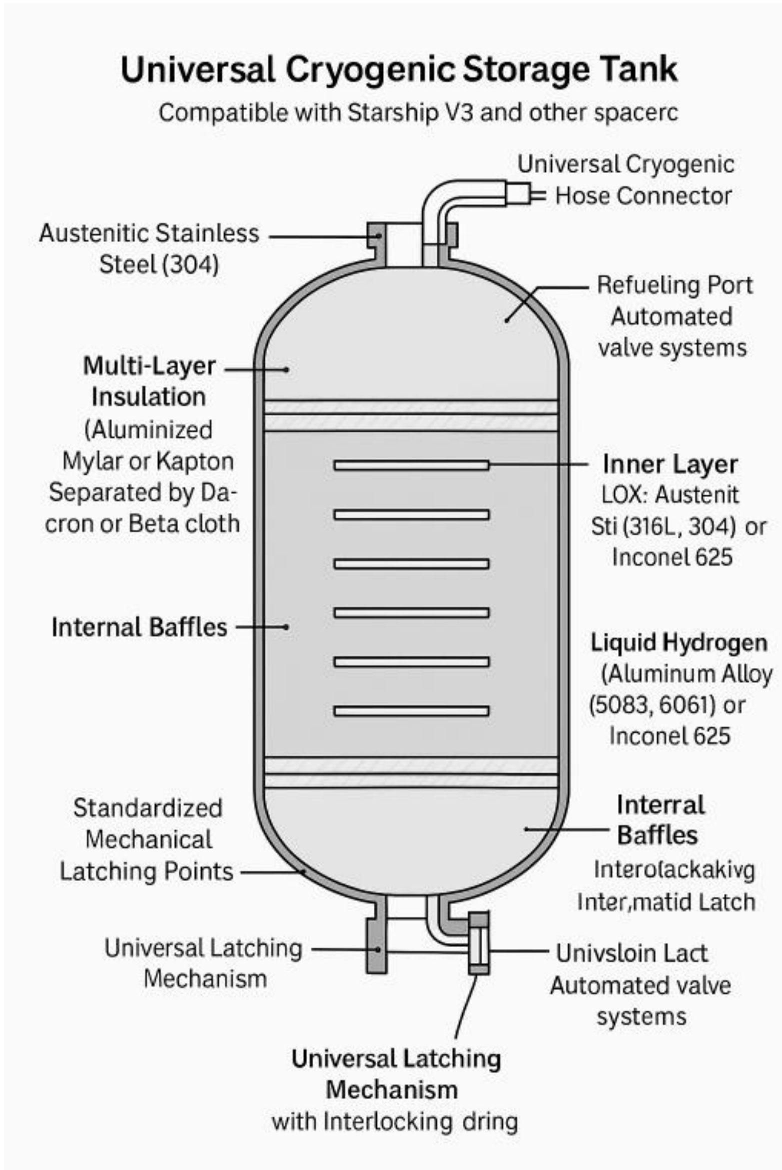
In summary, although the entire Cryogenic Complex may be a large and sophisticated mission, the use of UCSTs - Universal Cryogenic Storage Tanks (UCSTs), which are reuseable, modular, cryogenic cannisters, recognizes a new utility which is innovative, technically feasible, and an appropriate solution with a high likelihood of success, for application and operation in deep space and lunar environments, designed to integrate particularly and significantly with the Human Landing System (HLS) program.

Appendix I



Cryogenic Tanks – typical current construction

Appendix II



Cryogenic Tank UCST – New Construction

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