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Propellant Management Challenges Related to the Operation of the Depot on Orbit

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Abstract

This paper analyses the comprehensive cryogenic propellant management challenges in low gravity that may be used to model an in-orbit cryogenic propellant depot for space exploration in the future. This research presents a framework that enables analysis of novel propellant in the depot at the preliminary case to understand the problems associated with different subsystems of the space depot, such as the Supply Tank, Transfer Lines, and Receiver Tank, due to various parameters discussed such as gas-free removal of liquid, phase separation, boil-off, heat transfer, chill down, no-vent filling, and so on. Environmental problems resulting from the depot's location are also stated.

In addition to this, mitigation techniques to counter the problems as mentioned earlier are also discussed, which can be considered, such as using active and passive cooling techniques.

1. Introduction

In any manned mission architecture, the propellant mass fraction dominates almost all transportation segments of any mission requiring heavy-lift launch systems, such as Saturn V, Starship, and SLS. To mitigate this problem, the use of orbital propellant depots has been extensively studied.

In-space refueling is a major potential benefit to the in-space transportation system beyond low-Earth orbit, according to the Augustine Committee report. However, perceived complexity and launch costs have hampered the development of propellant depots, and essential technical demonstrations for cryogen handling in microgravity are required before NASA mission planners can embrace these concepts. Many technologies required for long-term cryogenic storage in LEO, such as active and passive temperature management, propellant acquisition and gauging, and cryogenic transfer between storage vessels, are now being tested by NASA on a technological demonstration mission.

To achieve a propellant depot in operation, the study of challenges related to propellant handling and management and its mitigating techniques are vital parts of phase 0/A research work. Therefore, this paper presents a framework that enables the analysis of a novel propellant depot in a preliminary case to understand the problems associated with depot operation. [23]

1.1 Low Gravity

According to Hartwig 2014 [13] , gravity affects many processes in space, such as the separation of the liquid and vapor phases within the propellant tank. Generally, the lowest achievable potential energy state within the tank governs the location of the liquid/vapor interface. In the standard gravity field of Earth, the fluid density dictates this location because the heavier liquid settles to the bottom and the lighter vapor rises to the top. However, in the microgravity conditions of space, surface tension becomes the controlling mechanism for phase separation because the liquid tends to wet the walls, leaving a gaseous core in the center. Tank pressurization is a vital component of cryogenic fluid transfer at low g. This provides the driving force for liquid transfer and promotes liquid thermodynamic subcooling. The development of low-g pressurization technology has the same objectives as the earlier launch vehicle technology programs: to determine (and minimize) the mass of pressurant gas required to pressurize and expelled fluid from the supply tank under various operating conditions to determine the resulting degree of liquid heating .[32] The static liquid orientation in low-g is characterized by the Bond number, which is defined as the ratio of gravity to the surface tension forces:

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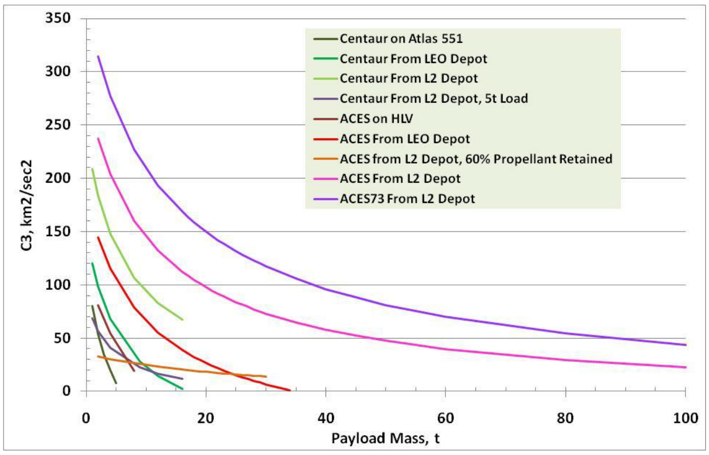

Figure 1: Amplification of Vehicle Capabilities with Depot operations

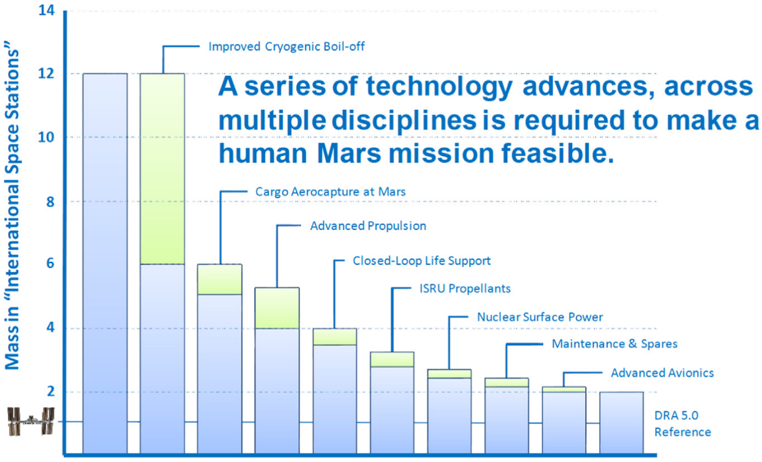

Figure 2: NASA OCT Mars mission mass saving potential due to technology investment.

$$Bo = \frac{\rho g L_c^2}{\gamma_{LV}} \tag{1}$$

where the characteristic liquid-vapor interface length is taken as the ullage region radius. Cryogenic tankage in space is often characterized by small bond numbers. Spherical or highly curved interface configurations are encountered. The dominance of capillary forces, combined with the surface wetting characteristics of cryogens, reduces the amount of direct gas-to-wall contact area and increases the liquid-vapor interfacial area, thus altering the heat and mass transfer during the pressurization and expulsion processes. The interfacial heat and mass transfer may be augmented by the instabilities of the liquid-vapor interface arising from the imposed disturbances. Accelerations in low-g environments vary in magnitude and direction owing to vibrations, excitation of natural frequencies, spacecraft maneuvering, and other causes. Increased fluid motion persistence causes sloshing, and the resulting pressure collapse is a greater concern at low G. Most low-g tankages will be fitted with propellant management devices to control sloshing and ensure liquid delivery at the outlet. Pressurant gas must be injected to prevent the disruption of the successful operation of such devices. For example, warm gas impinging on a screened liquid acquisition device (LAD) can cause dry-out and subsequent breakdown of the capillary screen surface or the formation of vapor within the LAD. Transfer pressure must not exceed bubble point limits for LADs [32] , which is defined as the differential pressure required to overcome the liquid surface tension force at the screen pore and calculated as per the equation given below.

$$\triangle P_{BP} = \frac{4\gamma \cos\theta_C}{D_P} \tag{2}$$

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The capability to diffuse the pressurant results in the maximum stratification of the ullage and minimizes interfacial heat and mass transfer, thus reducing condensation and liquid heating. The lack of stratification due to reduced buoyancy at low g could lead to exorbitant pressurant requirements. In situations with an in-determinant ullage location, the pressurization process can result in the direct injection of gas into the liquid region. This could lead to inefficient pressurization owing to localized superheating of the liquid or the formation of additional vapor pressure in the tank .[32]

2. Challenges

Fluid transfer processes become more difficult to conduct in a low-g environment of space owing to the uncertain separation of the liquid and vapor phases. Propellant management challenges with respect to depot operations should be considered. Consider a supply tank, a feed line, and a receiver tank. Both situations occur for a depot because the depot will be launched empty, become a receiver tank for a tanker spacecraft, and then convert to a supply tank for an exploration mission.

2.1 Supply Tank

The supply tank could be either an ETO resupply tanker or an orbital storage facility. Consider a supply tank in which both situation can be occur in which depot will be launch empty become a receiver tank for tanker spacecraft and than convert to supply tank for exploration missions. For supply tank we consider for determining gas free removal of liquid and phase separation. Also, describing the challenges in low gravity propellant storage(with explaining Boil-off), mass and heat transfer and other effects with respect to supply tank.

2.1.1 Long Term Storage

The use of cryogenic propellants in deep spaces requires the development of long-term storage technology. Passive storage techniques such as multilayer insulation and vapor-cooled shields are reasonably well developed but always involved a certain degree of liquid loss. Active storage techniques such as Zero Boil-off use high-efficiency cryocoolers to remove environmental heating before liquid boiling occurs. These systems are capable of preserving liquid cryogen for the cryocooler lifetime. System trades have shown weight advantages to active storage systems over passive systems in as little as seven days. Ground test data applicability is good for all storage technology issues, except for thermal stratification in a low-gravity environment [5]

2.1.2 Boil-off Storage

Various mission capability elements have dictated the need to develop technology to improve the mass efficiency of the long-duration storage of cryogenic fluids. A driving factor in this efficiency is the high boil-off rates of LH2 and LO2, particularly in a low Earth orbit (LEO) environment owing to the albedo of Earth and solar heating. Low storage temperatures of LH2 and LO2 cause substantial boil-off losses for missions with a duration of greater than several days Minimal or zero loss of cryogenic propellants (i.e.ZBO) during long-term storage for a long duration on an in-space depot is critical for successful exploration missions. Boil-off losses exceeding 3% per month require excess propellant storage margins and translate into a significantly large earth-to-orbit launch capability. Efforts are needed to develop an efficient, low-mass depot concept by upgrading existing thermal analysis tools. Further, development is also needed for a cryogenic analysis tool (CAT) that can quantify system weight comparisons between passive insulation systems and ZBO systems, such as cryo-coolers and radiators, for a defined scenario, including specified cryogenic fluid, environment, and quantity. [16]

In addition, continuing R&D to develop new, more efficient, and longer-lived cryo-coolers is also important; for more details, refer to section 3.3.1. In the area of ZBO and other topics, flight-like components must be developed for use in future system-level technology validation testing.

2.1.3 Propellant thermal stratification

Thermal stratification refers to the non-uniform heat distribution inside the bulk propellant. The non-uniform distribution of heat generates considerable temperature changes in propellant storage vessels and increases the self-pressurization rate of cryogen storage systems, both of which are undesirable [34]

2.1.4 Generation of Foam structures

The vapor bubbles formed at hot spots in the tank walls can generate foam structures, which can be hazardous in operations in orbit. Fluid cavitation, acoustic streaming, and erratic bubble motion are considered to be the causes of boiling heat transfer enhancement in both gravity and microgravity. In microgravity, even at a low heat flux, bubbles nucleate on the wall, coalesce, and form a large primary bubble, which oscillates above the wall. The nucleate boiling regime is fully developed, and the heat transfer is more efficient than under normal gravity.[6]

2.1.5 Tank Pressurization

Tank pressurization involves the introduction of a pressurant gas into the vapor space or ullage of a supply tank to increase the tank pressure. The first step is known as ramp pressurization, ullage compression, or prepressurization. During the next step, liquid expulsion, additional gas is injected into the tank to displace the liquid during outflow and maintain the tank pressure. Either the gaseous phase of the liquid or a non-condensible gas may be used as the pressurant. If a non-condensible pressurant is selected, the gas should have a low solubility limit in the liquid. Otherwise, large quantities of pressurant can dissolve in the liquid. The pressurant may be produced by vaporization of some of the stored liquid (autogenous pressurization), or it may be supplied by an external source, such as high-pressure gas bottles. Generally, external pressurization allows more rapid pressurization and transfer; however, this increases the weight of the pressurization subsystem. In situations employing a cold non-condensible gas, the pressurant may conceivably be employed to provide liquid cooling. Effective tank pressurization provides the necessary liquid subcooling to avoid excessive vapor formation in both the supply tank and the transfer lines. During liquid outflow, the liquid remaining in the tank will boil if the pressure drops below the saturation pressure owing to the expansion of the ullage region. Vapor generation within the fluid transfer path (liquid acquisition device, transfer line, pump, etc.) will adversely affect performance or lead to failure of the supply operation. Therefore, the transfer of cryogens in normal or low-g requires pressurization of the supply tank to prevent flashing or boiling of the cryogenic propellant.[32]

2.1.6 Pressurant Gas

The required amount of pressurant gas is not simply function of the displaced liquid volume, inlet gas temperature, and tank pressure, since the inlet gas transfers heat and is cooled on contact with the colder tank wall and internal hardware. In addition, the initial ullage must be compressed to the higher transfer pressure and evaporation or condensation may occur at the liquid-vapor interface[32]

2.1.7 Estimating Pressurant Requirements

A thermodynamic or lumped-system, analysis may be used to estimate pressurant requirements. Equation 3 was proposed by Gluck and Kline[10] for determining pressurant mass. The three terms on the right hand side account for the volume of liquid displaced, interracial mass transfer, and heat loss from the gas. The dependence on gas specific heat, molecular weight, tank pressure, and inlet temperature (enthalpy) are evident.[32]

$$\triangle m = \frac{(c_p M/R) P \triangle V + c_P T_s m_i + Q}{(h_i - h_s) + c_p T_s} \tag{3}$$

In 1965, Epstein published a correlation to predict pressurant requirements for liquid hydrogen and oxygen in cylindrical tanks. The pressurant can be either autogenous or helium. This correlation was extended in 1968 to include any axisymmetric tank shape and liquid nitrogen and fluorine propellants. The form of the correlation is:

$$\frac{w_p}{w_p^0} = \left[\left(\frac{T_0}{T_s} - 1\right)\left[1 - exp\left(-p_1 C^{p2}\right)\right]\left[1 - exp\left(-p_3 S^{p4}\right)\right] + 1\right] * exp\left[-p_5\left(\frac{1}{1+C}\right)^{p6}\left(\frac{S}{1+S}\right)^{p7} Q^{p8}\right] \tag{4}$$

where

$$w_p^0 = \rho_G^0 \triangle V \tag{5}$$

$$C = \frac{(\rho c_p^0 t)_w}{(\rho c_p)_G^0 D}\left(\frac{T_s}{T_0}\right) \tag{6}$$

$$S = \frac{h_c \theta_T}{(\rho c_p)_G^0 D}\left(\frac{T_s}{T_0}\right) \tag{7}$$

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$$Q = \frac{q \cdot \theta_T}{(\rho c_p)_G^0 D T_0} \tag{8}$$

The dimensionless quantities, C, S, and Q are obtained from Epstein 1965,[98] and represent the ratio of wall-to-gas effective thermal capacity, the modified Stanton Number, and the ratio of total ambient heat input to the effective thermal capacitance of the gas, respectively. Heat transfer coefficients for the gas-to-wall heat transfer are based on free convection. Use of the correlation is not recommended when: outside the range of variables, sloshing occurs, an inefficient diffuser is employed, the initial ullage volume exceeds 20 percent, or ambient wall heat fluxes cause appreciable propellant evaporation.[32]

2.1.8 Self-Pressurization

Tank self-pressurization is a serious issue in cryogenic propellant management. The cryogenic fluid is heated by incident solar radiation, which causes the liquid to evaporate and the tank pressure to increase. The tank would rupture if this self-pressurization was allowed to continue unchecked. Although insulation helps to keep radiation from heating the fluid, the pressure eventually increases. One alternative is to build a stronger tank, although this would necessitate an increase in vehicle mass when a lighter tank design is preferred. Another possibility is tank venting. As the tank venting approach wastes important propellants, it is not recommended. With launch costs of almost $10,000 per pound, any waste propellant represents a huge financial and in-orbit resource loss. Furthermore, the lack of gravity to positively orient the propellant in a predictable manner makes it nearly impossible to find a vent where only vapor may be evacuated. In reality, the influence of surface tension in a microgravity environment may cause the entire tank surface to be wetted even in partially filled tanks. The most common approach is venting; however, venting designs must include thrusters that generate sufficient acceleration to ensure that the fluid is gathered at the end of the tank opposite to the vent. These thrusters, like their propellants, impart mass to spacecraft. Furthermore, the acceleration caused during the reorientation process increases the risk of disruption of onboard activities or alteration of the vehicle's flight path. Therefore, an alternative solution that avoids these issues is desirable.[30]

2.1.9 Heat Input from other sources

The idealized case is defined as a process without heat and mass transfer from the pressurant; this represents the "minimum gas requirement" provided heat input or vapor generation within the tank is insignificant. A "maximum gas requirement" is defined to occur when the pressurant achieves thermal equilibrium with the tank liquid and vapor under saturation conditions at tank pressure. Thermal equilibrium is very undesirable as the liquid is expelled from the tank as a saturated liquid. Any additional heat input to the liquid at this state will likely lead to vapor formation and possibly the subsequent failure of the liquid supply system.[32]

2.1.10 Gas-free Removal of Liquid

Tank outflow exhibits several interesting phenomena under low-gravity conditions. The first is the drawdown of the free surface. This results in the ingestion of gas into the outlet even when a substantial amount of liquid remains in the tank. The other is the generation of a geyser from liquid momentum when the outflow suddenly stops. Both cause problems for low-gravity tank designers.[5]

From Hartwig 2014,[14] The enabling of all future in-space cryogenic engines and cryogenic propellant depots for future manned and robotic space exploration missions begins with the technology development of LADs upstream in the propellant tank. Depending on the mission requirements, which include the acceleration level, direction, spin, mass flow rate, thermal environment, tank pressure, and desired final liquid fill level, LADs are required to ensure that the tank outlet is sufficiently covered with liquid during all phases of the mission. By design, all in-space cryogenic engines and cryogenic fuel depots require vapor-free liquid delivery. LADs must first be rigorously qualified before they can be routinely used in cryogenic propellant tanks to ensure that both liquid and vapor are favorably positioned within the tank for any mission.

In addition, understanding the underlying fluid mechanics and heat transfer associated with the transfer of cryogenics with LADs has not been well understood in the past because little data exists to characterize the system. Although LADs have been studied for nearly five decades, and they have flight heritage in storable propulsion systems, the combination of low surface tension, complications due to heat leaks at low temperatures, the need for transfer across a wide range of demand flow rates over a range of gravitational conditions, and uncertainty in the liquid-vapor interface within the propellant tank in microgravity makes LAD design in cryogenic propulsion systems quite challenging.

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2.2 Propellant Transfer Line

A propellant transfer system is responsible for delivering propellants from the supply tank to the receiver tank, specifically at the desired mass flow rate and pressure, without any undesirable loss of propellant. The following sections present the challenges pertaining to the transfer line.

2.2.1 Leak-Free Transfer

The "leak-free" transfer of cryogenic propellants during mating and demating procedures is an operational necessity for the in-space depot. It is recommended to take care of leaks and leak rates and their corresponding effects on pressure and temperature during the transfer phase to ensure the reliability of propellant transfer. For example, LH2 has a high tendency to leak being the smallest of all cryogenic propellants. The presence of small cracks in the transfer line can lead to leakage of LH2 through these cracks which results in loss of propellant mass and longer duration for transfer.

2.2.2 Chill-Down Losses

The chill-down of fluid transfer lines is an important part of cryogenic systems, such as those found in both ground- and space-based applications. The chill-down process is a complex combination of both the thermal and fluid transient phenomena. A cryogenic liquid flows through a transfer line that is initially at a much higher temperature than that of the cryogen. Transient heat transfer processes between the liquid and the transfer line cause vaporization of the liquid, and this phase change can cause transient pressure and flow surges in the liquid. As the transfer line was cooled, these effects diminished until the liquid reached a steady flow condition in the chilled transfer line. If these transient phenomena are not properly accounted for in the design process of a cryogenic system, it can lead to damage or failure of the system components during operation.[19]

$$Chill - Down\ Loss = (Pipe\ Internal\ Volume).(Density\ of\ cryogen) \tag{9}$$

Boil-off occurs during the transfer of cryogenic fluid from the supply tank to the receiver tank. Because the heat of the pipe causes the cryogen to boil, the pipe through which the cryogen moves must be chilled to reduce losses. Typically, the transfer pipe is partially filled with cryogen so that it boils and cools the pipe. This action was repeated to achieve complete cooling. Subsequently, the planned fluid transfer can be initiated. The two partial releases into the transfer pipe equate to completely filling the pipe once. Therefore, the chill-down loss is considered to be the volume of the pipe multiplied by the cryogen density. This loss would be incurred for every transfer.[24]

2.2.3 The Vented Chill / No Vent Fill

The on-orbit replenishment of cryogenic liquid propellants in space missions is commonly achieved through tank-to-tank transfers, either from a dedicated tanker or a propellant depot storage tank. The traditional method, known as charge-hold-vent, involves multiple cycles of supplying a small amount of cryogenic liquid to chill the transfer lines and propellant tank, followed by venting to relieve pressure, and repeating the process until the tank is adequately cold and replenished. However, this approach is inefficient and requires precise measurements, valve cycling, and complex operations.

A new alternative method called vented chilled/no-vent fill, was developed to minimize propellant loss and simplify on-orbit operations. In this constant-flow system, the transfer lines and tank were chilled once, whereas the receiver tank was continuously vented. Once the tank was sufficiently cold, the receiver tank valve was closed and the tank was filled without waiting for the receiver components to reach the liquid saturation temperature. However, it is crucial to ensure that sufficient energy is extracted from the system before closing the vent valve to achieve a complete filling. By adopting this approach, propellant loss is reduced, and the overall process is significantly streamlined. The referred paper has described the transfer process and test item, as well as examined the outcomes of the tests.[1]

2.2.4 Transfer Time

When considering the use of pressurized cryogen transfer in space, it is important to keep in mind that the operational settings are often different. The tank-to-tank transfer duration was significantly longer than the fast expulsion of propellants in launch vehicles, emphasizing the impact of heat and mass transfer between the liquid, vapor, and tank walls. Liquid sloshing can also occur during spaceship maneuvers including docking, attitude control, and other normal tasks. Finally, a low-g environment leads to situations in which capillary processes regulate fluid statics and dynamics. The tank pressurization and expulsion procedures are affected by these elements.[32]

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2.2.5 Avoiding triple points of propellants

The temperature and pressure at which a substance can exist in equilibrium in the liquid, solid, and gaseous states is known as Triple Point., eg. LOX(54.361 K, 0.14625 kPa), LH2(13.81 K, 7.042 kPa.)[33] Over-cooling due to the use of active cryo-cooling technologies can lead to the formation of solid particles of the propellants which can choke the flow during the transfer period.[24]

2.2.6 Shielding and Insulation against Heat Loads

Heat loads acting on the depot (discussed in Section 2.4.6) have an influence by providing heat energy to propellants during the transfer phase which vaporizes them and creates wakes inside the propellant feed lines which hinders the transfer operations. In addition to this, maintaining desired mass flow rate of cryogenic propellant during the transfer phase requires notable emphasis.

2.2.7 Latching of valves for efficient transfer of propellant

Before initiating the transfer process, valves must be sensitive to the pressure required to transfer from the supply to the receiver tank so that they open and close as and when required to control the mass flow rate as per requirement.

2.2.8 Handling of the remaining propellant after the transfer process

To ensure that no residual cryogenic propellant vaporizes and causes uneven flow or pressure surges during non-operating mode or in the succeeding transfer phase, residual cryogenic propellant within the transfer line must be appropriately handled, either by venting it off or re-supplying it back to the supply tank or an auxiliary tank.

2.3 Receiver Tank

The receiver tank would be either a propulsive stage or a storage depot tank. The primary concern of the liquid injection method is the assurance of good thermodynamic mixing throughout the filling process. Good mixing must occur throughout the filling procedure to prevent excessive heat transfer to the ullage and the corresponding pressure increases. As the filling process approaches completion, the ability to maintain the pressure within acceptable limits and to verify that the required propellant mass has been transferred (i.e., mass gauging) becomes critical. If the receiver contains a LAD, additional care must be taken to ensure that the vapor is not trapped within the device during the filling process.[15]

2.3.1 No vent Chill and Fill

NASA has been interested in no vent fill transfers for zero-g cryogenic resupply since the 1960s. Performing a no-vent fill in space is advantageous because venting operations cause undesirable disturbances to the spacecraft. Previous work focused on varying the inlet conditions of the cryogen fluid itself, whereas GSFCs approach differs in that venting is prevented by pre-conditioning the receiver tank using a cooling loop as well as providing cooling to condense any vapor developed in the transfer process. This technique requires client dewars. This type of dewar was originally designed to be filled with gas in a no-vent transfer, but gaseous transfers take a very long time to fill and freeze. Minimizing the time required to fill and freeze a client dewar is desirable from an operational standpoint. GSFCs approach using liquid transfers, even for dewars not originally designed to receive liquid cryogen, allows mass to be transferred rapidly as well as less energy and time is required to solidify the cryogen in the client tank.[7]

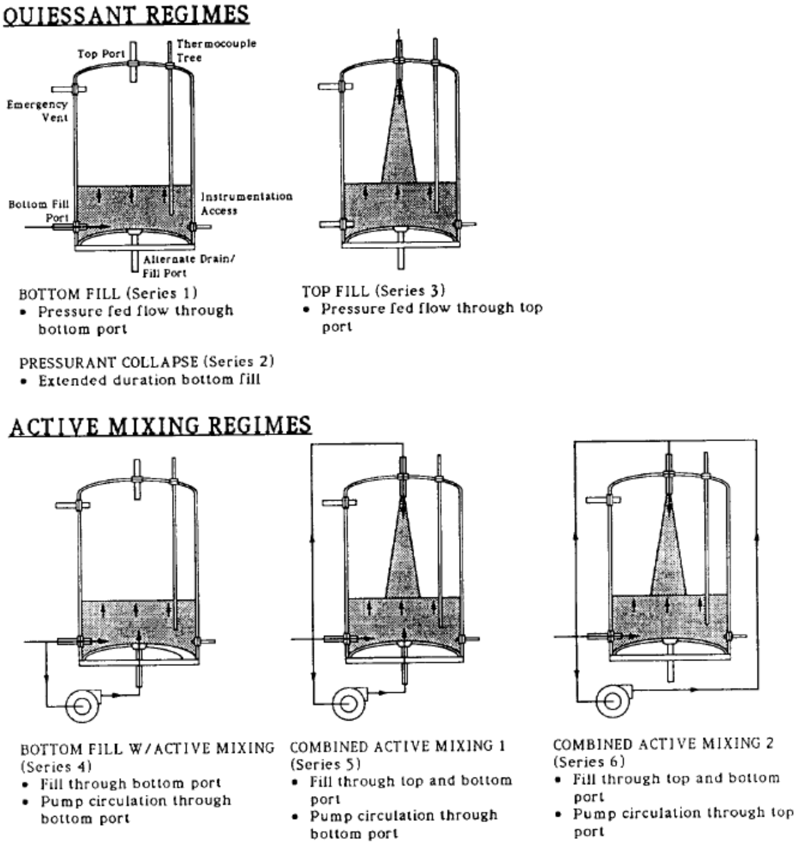
The practice of tank chill down in a microgravity environment is quite different from that of tank chill down in the ground. Under normal gravity, a vent valve on top of the tank could be kept open to vent the vapor generated during the chilling process. The tank pressure can be maintained close to atmospheric pressure while the tank is chilling down. In a microgravity environment, owing to the absence of stratification, such a practice may result in the dumping of large amounts of precious propellant overboard. The intent of the no-vent chill-and-fill method is to minimize the loss of propellant during the chill down of the propellant tank in a microgravity environment. No vent chill and fill method consist of the repeated cyclic process of charge, hold, and vent.[19]

No-vent fill process sensitivity to key parameters, namely fluid inlet temperature, liquid inflow rate, wall temperature, and condensation rate.[27]

2.3.2 Fluid Inlet Velocity

Interestingly, the penetration of the inlet jet as the initial tank pressure is reduced, leading to substantial variations in the ullage flow and temperature fields. Other results show that for reduced initial ullage pressures, significant flow velocities and higher temperatures occur near the interface, which requires consideration of mass transfer and variable heat flux boundary conditions. Measurements of experimental data require include inlet pressure, temperature and mass flow rate history, initial temperature distribution, heat loss history to wall and liquid interface, and interfacial mass transfer rate.[32]

2.3.3 No-vent Fill Regimes



Fill regimes.

Figure 3: Fill Regimes.

Flow routings into the receiver tanks are shown in Figure 3. Series 1,2 and 3 relied solely on the pressure difference between the transfer and receiver tank to affect the liquid transfer and are termed "quiescent" in that there is no externally applied mixing or circulation in the receiver vessel. The simplest of these is series 1, in which liquid from the transfer tank is injected into the receiver through a horizontal jet at the bottom of the tank. This regime best approximates a completely passive fill process and minimizes flow-induced agitation. It is also easy to characterize analytically(because of the determinant geometry and predictable turbulence of the liquid surface) and was used as a reference for comparison with other fill techniques. Test Series 2 employed the same routing as in Series 1 and was performed solely to evaluate the influence of passive destratification on ullage pressure collapse. A significantly lower fill rate was obtained by reducing the pressure difference between the transfer and receiver tanks. The third quiescent regime, that is, Series 3 entailed injection through a line located at the top of the receiver tank. Series 3 entails injection through a line located at the top of the receiver tank. Similar to the previous two, the flow was affected solely by the pressure difference. It assesses the benefits of two condensation-enhancing effects:1. The kinetic energy gained in falling to the bulk liquid surface, which tends to break up and increase the liquid surface area, and 2. Increased surface area caused by exposure of the liquid jet to the ullage. The former effect promotes agitation of the exposed surface

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and thereby enhances condensation, whereas the latter effect is particularly significant if the stream atomizes during descent.

Series 1 and 3 represented extremes of inflow-induced destratification and were useful for assessing the importance of the inlet position. With the bottom fill, the incoming liquid collected around the entrance and suppressed the disruption of the liquid surface. However, with the enhanced method, the liquid enters as an impinging jet that continually agitates the liquid. Series 4,5 and 6 differed from the first three because active liquid mixing was employed within the receiver vessel. The choice of routing for these tests is somewhat arbitrary and almost entirely dictated by the limited number of available ports on the receiver vessel. Series 4 represents the best direct comparison between quiescent and active mixing regimes. Both employ the same inflow routing as in Series 1. The only difference was that the recirculation loop ran through a pump that extracted a small amount of inflow and pumped it into another port at the base of the tank. The remaining two active mixing regimes employed simultaneous filling of the top and bottom inlets. In Series 5, the circulated liquid was injected through the bottom port of the receiver tank, whereas in Series 6, the liquid was injected through the top port. There are a variety of parameters available for evaluating the overall behavior, including the most common filling time, maximum fill level, receiver tank pressure ratio(final pressure/initial pressure), and average fill rate(maximum fill level/fill time). The second type of analysis compares the prediction of transient state variables (i.e. temperature and pressure) but also assesses the filling process sensitivity to key parameters such as fluid inlet temperature, liquid inflow rate, wall temperature, and condensation rate.[27]

2.3.4 Control Cooling of the propellant during storage as well as a transfer

Control Cooling of the propellant during storage as well as a transfer so as to avoid the formation of gas/ solid propellant in the tank as well as at the outlet. It ensures that single-phase delivery of propellant is possible. A new era of space exploration is being planned. Exploration architectures under consideration require the long-term storage of cryogenic propellants in space. This requires the development of active control systems to mitigate the effect of heat leaks.

Since the Supply Tank acts as a Receiver Tank, its Challenges are also applicable here.

2.4 Miscellaneous

2.4.1 Boil-Off Losses

As a precursor to determining propellant losses, the thermal environment of the spacecraft must be characterized. Determination of the temperature of the external surface of the spacecraft, along with the propellant tank size and shape and other factors allows estimation of the boil-off rate. For spacecraft in Earth orbit, the thermal environment consists of three external sources of heat energy from the Sun (solar flux), Earth-reflected heating (albedo times the incident solar flux), and Earth-emitted radiation, also called Earth infrared radiation, or simply Earth-IR. At geostationary orbit (GEO), the values for Earth reflected heating and earth-IR decrease substantially. At Earth-Moon L1, the values for Earth reflected heating and Earth-IR are almost non-existent. Some thermal analysts ignore the effects of Earth reflected heating and Earth-IR at GEO and L1 but they are included here to be consistent. From Thornton 1996,[29] environmental heating rates depend on altitude and orientation of the spacecraft with respect to sources of heat. The solar heat received by the spacecraft surface q_s is given by Eq.10

$$q_s = 1367 a_s cos(\psi) \tag{10}$$

where a_s, is the surface absorptivity and ψ is the angle between the solar flux vector and the surface normal. The radiation emitted by the Earth (Earth-infrared) can be approximated by assuming the Earth to be a black body radiating at T_e = 289 K. The radiation absorbed by the (spacecraft) surface can be expressed as Eq.11

$$q_e = \sigma T_e{}^4 a_e F \tag{11}$$

where σ is Boltzmannâs Constant 5.67051 exp(-8) W m^{-2} K^{-4}, a_e is the surface absorptivity for Earth-infrared radiation, and F is the view factor. The view factor, Eq.12, (also called the shape factor or configuration factor) describes the fraction of the radiant energy that arrives at the surface.

$$F = cos(\lambda)/H^2 \tag{12}$$

where λ = the angle between the surface normal and the heat flux H = r/R, where R is radius of the Earth, and r is the distance from the center of the Earth to the spacecraft

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Earth reflected heating, Eq.13, depends on the albedo factor (AF), and is defined as the fraction of the solar radiation striking the Earth that is reflected back into space. Earth reflected heating is described by

$$q_{\mathrm{a}} = 1367 AFa_{\mathrm{s}}Fcos(\theta) \tag{13}$$

where θ is the reflection angle from the Earth to the spacecraft. Using an average Earth albedo (AF) of 0.367. The values calculated for all sources are summarized in Table 1. Given the thermal environment and the illuminated area of the tank, the surface temperature can be estimated using eq. 14

Table 1: Thermal Environment at LEO, GEO, and L1 Source, Refer Pg-15 of [24]

Heat (Watts/m^2)	**LEO**	**GEO**	**L1**
Solar constant	1,367	1,367	1,367
Earth emitted infrared.	350.3	9.1	0.16
Earth reflected heating	444.2	11.5	0.2
Total	2,161.50	1,387.60	1,367.36

$$\sigma T^4 = [(\alpha/\epsilon)S + (\alpha/\epsilon)(RH) + E](A_p/A) \tag{14}$$

where
T = outside temperature of the spacecraft (K)
σ = Stefan-Boltzmann's constant = 5.67051exp(-8) W/m^2-K^4
α = absorptivity (= 0.14 for outer layer of MLI)
ϵ = emissivity (= 0.60 for outer layer of MLI)
S = solar flux (1,367 W/m^2)
RH = Earth reflected heating
E = Earth infrared
A_p = projected area of the propellant tank
A = total surface area of the propellant tank

Measures for boil-off: It is the amount of vapors per unit of time, boil-off rate. It can be an absolute measure kg/h, kg/day, or a relative measure % vaporized from the total amount per unit of time. The boil-off rates comparison for LH2 and LO2 at different locations is provided in Table

Table 2: Estimated Range Boil-Off Rates, Refer Pg-16 of Source: [24]

	Boil-Off rate at Location (Kg/hr)		
Cryogenic	LEO (400 Km)	GEO	L1
LH2	0.0164-0.2044	0.0097-0.1268	0.0095-0.1245
LO2	0.0296-0.1437	0.0157-0.1002	0.0153-0.0977

- Based on modified Lockheed Model.
- Assumed 60 layers of MLI
- Solar constant, earth reflected heating, and earth- infrared radiation included for each orbit

Currently, most ground-based liquid hydrogen storage tanks have perlite plus vacuum insulation without active shielding, resulting in boil-off rates of **1-5%/day** Boil-off could be reduced to **0.01-0.05%**/day by using storage tanks based on LHE technology (MLI insulation and active shielding).[12] For a laboratory vessel holding liquid nitrogen, the boil-off rate may be **0.01 kg/h**.[31] The evaporation rate as a percentage of LNG volume in the tank decreases with the increase ethane molar fraction in the mixture. In mass terms, there is an slow increase of boil-off rate as a function of ethane molar fraction (from **645.3 kg/h** for pure methane to **648.1 kg/h** for 10% content of ethane).[35]

2.4.2 In Space Servicing and Maintenance

One of the most significant obstacles to more ambitious - yet still affordable -space missions in Earth's vicinity is our inability to affordably preposition consumables and other technologies (including spares for in-space servicing and

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maintenance). This is especially important when it comes to propellants, such as those used in vehicles that transport Crews or payloads must be delivered on time. As long as high-value (and high-cost) space equipment cannot be repaired and refueled locally outside a low earth orbit (LEO). This problem affects mission planning for a wide range of future missions, but it's especially important for (a) major, high-value missions like human exploration beyond LEO; (b) large-scale defense and/or security-focused mission systems; or (c) future space industries (like larger, multipayload geostationary Earth orbit (GEO) platforms, space solar power systems, and related concepts).[16] Also, Robotics in space servicing and maintenance are currently in great research,[17] and robotics refueling has also been discussed.[3]

2.4.3 Parameters influencing pressurizing gas requirements

The most important elements influencing pressurant requirements are the temperature and pressure of the inlet gas. To produce the lowest residual gas mass, the input gas temperature needs to be maximized, the pressure minimized, and a pressurant with low molecular weight and high heat capacity is chosen. Heat transfer with the tank wall is predominant in most tanks, while interfacial heat transfer with the liquid is minor. The interface liquid will be at the saturation temperature, which corresponds to the total gas pressure, resulting in a heated liquid layer near the contact. Any damage to this layer results in rapid gas condensation and a loss of gas pressure.[32] If the pressurization lines have already been chilled, the lowest pressurant gas mass is necessary for the maximum pressurant gas temperature.[18]

2.4.4 Thermal Management

According to NASA's Office of the Chief Technologist, cryogenic thermal management is the greatest game-changing technological innovation for lowering the mass required in orbit, as shown in Fig.2. Long-term cryogenic thermal management innovations can significantly reduce the cost of the exploration design. An orbiting propellant depot will benefit from the development of long-term thermal management, and studies have shown that an exploration design that includes an orbital fuel store can lower the cost and complexity while boosting reliability, extensibility, and adaptability. The first step in developing a propellant storage architecture is to determine the type of heat management that is required. A comprehensive system-level analysis and trade study of the thermal needs of orbital propellant storage are required to accomplish so.[4]

2.4.5 Space Thermal Environment

The space environment is the most important component in determining on-orbit heat loads. The Sun's direct radiation, albedo reflected off the Earth's surface, and infrared energy emitted from the surface all contribute to the heat loads in the LEO. In all orbiting spacecraft, direct solar radiation is the primary source of environmental heat. The average solar irradiation at Earth's mean distance from the sun (1AU) is 1367 W/m^2. Because of Earth's light elliptical orbit around the Sun(eccentricity 0.017), the intensity varies by approximately plus or minus 3.5%, from 1322 W/m^2 to 1414 W/m^2. Sunlight reflected off other celestial bodies is known as albedo. The Earth's albedo experienced by an orbiting spacecraft is highly dependent on both orbit inclination and altitude. Reflectivity is generally greater over land than over the ocean. The thermal energy that is not reflected by the Earth is absorbed and eventually emitted as infrared(IR)energy. The amount of IR energy experienced by an orbiting spacecraft is also dependent on its orbit and location, as the local temperature of the Earth's surface changes the amount of energy emitted.[4]

2.4.6 Heat Loads

Some of the heat transfer phenomena to be examined are conduction, free and forced convection, aerodynamic heating, radiation, and chemical reactions. Different values for the gas-to-wall convective heat transfer coefficient are expected, depending on the pressure, flow velocity, and geometrical features. Interfacial mass transfer can occur in two forms: evaporation and condensation. Evaporation or boiling of the cryogen owing to the ambient heat input is also possible, as is the condensation of the pressurant on the exposed cold wall during liquid expulsion.[32]

The specific orbit and orientation of the spacecraft must be considered to estimate the amount of energy that a spacecraft experiences in orbit. With the energy conservation equation and the Stefan Boltzmann Law, the equilibrium external temperature of the spacecraft is computed by the Energy Conservation Equation for a body in Space,

$$\sigma_B T_0^4 = \left[\frac{(Q_{Sun} + Q_{er})\beta + Q_i}{\epsilon} + Q_{IR} \right] \frac{1}{A_0} \tag{15}$$

where σ_B is the Stefan-Boltzmann constant 5.670 exp(-8) W/m^2-K^4, Q_{Sun} is the direct thermal radiation from the Sun, Q_{ER} is the Earth reflected albedo, Q_{IR} is the radiant infrared power emitted from the Earth, Q_i is the heat produced by the spacecraft's internal instruments, β is the surface absorptivity, ϵ is the surface emissivity, and A_o is the total

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radiating surface area. Using this relationship, the temperature output from STK can be converted to the total heat rates experienced by the spacecraft in the designed orbit.Using this technique, the thermal heat load can be computed for spacecraft in different orbit altitudes and inclinations. Instead of a single estimate of the heat load from the literature, one can simulate the actual orbit and obtain values for the heat load during the time of interest.[4]

The structural(Q_s), penetration(Q_p), mixer(Q_m), and parasitic(Q_{para}) heat loads are taken from Plachta 2006.[25] Plachta gives a brief description of the formula's origin and how it is adjusted for their particular study. The study uses the formula to compute heat loads on a small cryogenic tank in orbit(on the order of $10m^3$). All the equations are functions of the size and/or mass of the tanks or the amount of propellant in the system, which helps us to scale the heat load. For conservatism, a multiplier can be applied to these heat load equations, and the impact of such a multiplier can be evaluated. In this study, no multipliers were applied. The heat load formulas given by Plachta are

$$Q_s(LO_2) = \frac{(M_{\text{tank}} + M_{\text{prop}})(T_H - T_C)}{1,154,364} \tag{16}$$

$$Q_s(LH_2) = \frac{(M_{\text{tank}} + M_{\text{prop}})(T_H - T_C)}{1,200,000} \tag{17}$$

$$Q_m(LO_2) = \frac{V_{\text{tank}}}{25.6}C_2 \tag{18}$$

$$Q_m(LH_2) = \frac{V_{\text{tank}}}{16.8}C_2 \tag{19}$$

$$Q_p = 0.0025(T_H - T_C)\sqrt{V_{\text{tank}}} \tag{20}$$

$$Q_{\text{para}} = 1.3636 * 10^{-6} f_{\text{eclipse}} {P_{\text{in}}}^{1/3}({T_H}^2 - {T_C}^2) \tag{21}$$

M_{tank} is the mass of the propellant tank, M_{prop} is the mass of the propellant stored in the tank, and V_{tank} is the volume of the propellant tank. C_2 is the duty cycle of the mixer, where the typical value ranges between 0 and 1 to represent the precedence of time the mixer is in operation. For this study, C_2 is held constant at a value of 1 to represent a conservative estimate of the heat load. $f_{eclipse}$ is the eclipse factor for the cryocooler, i.e. the percentage of time the spacecraft is in eclipse and the cryocooler is not in operation. Notice that only the structural heat load is dependent on the propellant level in the tank, and it scales linearly with the decreasing propellant load. The majority of the heat load into the system is through multi-layer insulation materials. The contribution of these secondary heat loads is minimal until a large number of layers of insulation is used.[4]

2.4.7 Propellant Geysering

Geysering is defined as the quick expulsion of a boiling liquid and its vapor from a vertical tube. Because many rocket vehicles use cryogenic fluids as propellants, geysers are of primary interest to engineers in the missile business. Geyser problems occur when propellant feed systems are designed, which normally require long lines to link the propellant tank to the engine. Because the propellants are cryogenic, the environment heats the propellant in the feed line during the interval between missile fuelling and launch. If a geyser occurs during this time and the line is emptied of liquid, the liquid may generate large impact loads at the bottom of the line, causing serious damage to the vehicle. If sufficient knowledge about the factors that cause geysering is available during the initial design of the propellant feed system, the geyser problem can potentially be eliminated.[22]

2.4.8 Storage Duration

One of the biggest technological hurdles of a propellant depot based mission is the long-term storage of cryogenic fluids in orbit. A thorough model of the thermal characteristics of a propellant store must be constructed to comprehend the impact of various technologies on the overall feasibility of the propellant depot architecture. The model will examine the balance between heat that enters cryogenic fluids from outside sources and heat that are removed from the fluid via radiators and/or cryogenic refrigeration devices. The boil-off of cryogenic fluids when there is excess heat, as well as the system mass of the cryogenic thermal management system, are major figures of merit for system-level studies.[4]

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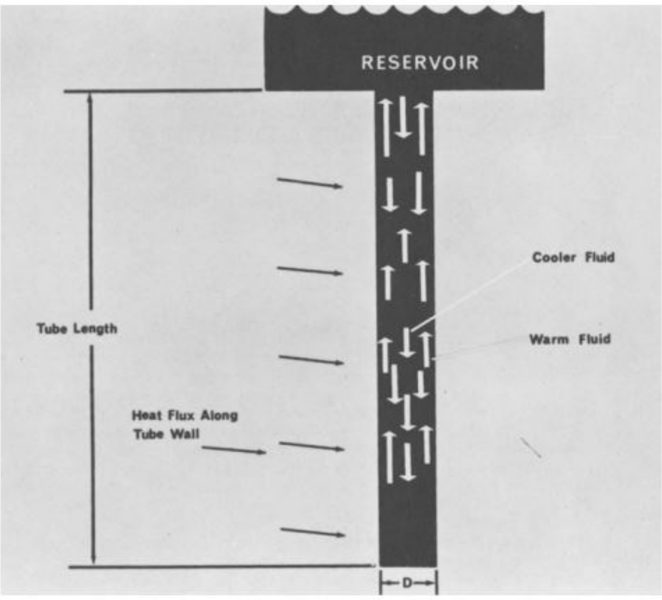

Figure 4: Fluid circulation in a geyser tube.

2.4.9 Conditioning of Propellants

Another option for high-vapor-pressure propellants is to condition the propellants to saturation conditions, which is known as the VaPak strategy. This type of system has a number of flaws that make it unsuitable for the applications in question. Sub-optimal propellant packing (owing to elevated temperature and hence reduced liquid density, resulting in larger tanks), hard propellant thermal control (to maintain the system at the correct operating pressure), and two-phase flows in the feed system are among these disadvantages.[2]

2.4.10 Liquid Propellant Reorientation

Liquid rebounding or geysering can occur during liquid reorientation using low-level acceleration. A criterion consisting of a dimensionless Weber number grouping based on liquid flow conditions at the tank bottom delineated the regions of geysering and no geysering. The dimensionless Weber number grouping represents the ratio of inertial flow forces to surface tension forces. The Weber number, which delineates the regions of geysering and no geysering, was empirically determined to be 4 in both concave- and convex-bottomed models. The quantitative results of liquid accumulation rates, which would allow time estimates for complete liquid reorientation, were heavily dependent on the overall geyser dynamics.[20]

3. Mitigation Techniques

Cryogenic propellant management is a critical aspect of in-orbit propellant depots, which are designed to store and distribute cryogenic propellants such as liquid hydrogen (LH2) and liquid oxygen (LOX). Efficient and effective management of cryogenic propellants is essential to ensure their stability, prevent excessive boil-off, and optimize their use in various space missions. Mitigation techniques for cryogenic propellant management in in-orbit propellant depots involve a combination of passive and active strategies aimed at minimizing propellant losses, controlling temperature, and maximizing storage capacity.

3.1 Propellant Management Devices

From Hartwig [13] , the purpose of a PMD (Propellant Management Device) is to separate liquid and gas phases within a propellant tank and to transfer vapor-free propellant from a storage tank to a transfer line en route to either an engine or a receiver depot tank, in any gravitational or thermal environment. The aims of PMDs and LADs are

- to keep the propellant port covered with propellant as long as feeding is required

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- to control the center of gravity
- to suppress or damp liquid sloshing
- to guarantee the venting of the tank (or components) without liquid removal (loss).

Figure 5 illustrates why liquid acquisition devices (LADs) are required for successful receiver depot tank operation. On the ground or during launch, LADs are generally not required because vehicle thrust and high-g levels can maintain phase separation within the propellant tank. In micro-gravity however, in the absence of settling thrusting maneuvers to favorably position the liquid, there is no way to guarantee vapor-free propellant flow out of the tank without using a LAD. After sufficient time, in an unsettled environment, liquid and gas phases will combine such that a two-phase mixture may cover the outlet. At a bare minimum, a mixture of gas and liquid sent to the engine will cause combustion instabilities, and at worst cause complete engine failure.

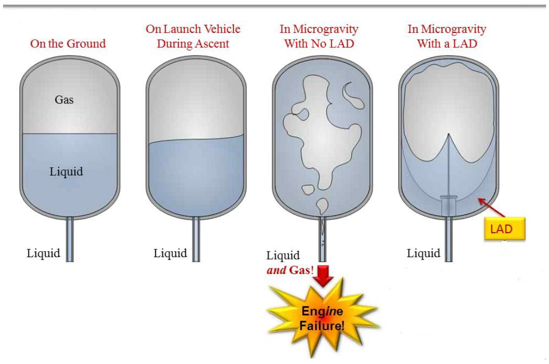

Figure 5: Illustration of Why Liquid Acquisition Devices are Required.

Complete propellant transfer from a storage tank to the customer is divided among the following four stages:

1. Vapor-free liquid extraction from the storage tank.
2. Chill-down of the transfer line
3. Chill-down of the receiver system
4. Fill of the receiver system

PMDs, therefore, represent the first step in the propellant transfer process. PMDs must be designed and implemented to ensure that there is always communication between the PMD and liquid anywhere within the tank and to ensure that the tank outlet is sufficiently covered with liquid during any phase of the mission.The three primary total communication capillary-driven PMDs include vanes, sponges, and screen channel LADs.

3.1.1 Vanes

Of the three, the simplest and most reliable PMD is the vane. Relative to screen channel LADs, vanes are open acquisition PMDs that allow for a much simpler design at the cost of not being able to sustain or supply higher flow rates. Vanes have rich flight heritage in storable propulsion systems but none in cryogenic systems

3.1.2 Sponge

The second total communication capillary-driven PMD is the sponge. A sponge is defined as an open structure PMD that has the ability to maintain and refill propellant at the tank outlet. Of the three, the sponges by far have the most flight heritage in storable propulsion liquid acquisition systems. Relative to vanes, the sponge is heavier and slightly more expensive; relative to screen channel LADs it is a much simpler design. Like vanes, sponges have no flight heritage in cryogenic propulsion systems.

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3.1.3 Screen channel

The third total communication capillary-driven PMD is the screen channel liquid acquisition device or gallery arm. A screen LAD is defined as a closed channel with three solid walls and one porous wall. Screen channel LADs use the same basic capillary pumping force as vanes and sponges, but offer a much more robust solution to liquid acquisition over a wider range of thermal and gravitational conditions. The primary difference between screen channels and vanes and sponges is that the channel creates an internal and closed flow path for liquid to flow from the bulk propellant in the tank to the outlet of the tank. The presence of the screen allows for relatively higher flow rates under more adverse accelerations and promotes higher resistance to gas ingestion, at the cost of a more complex and expensive design. Screen channel LADs have flight heritage in storable propulsion systems, and are the only PMD type to ever be used in a flight cryogenic system. Total communication devices, such as channels, distributors, and tank liners, are used in systems that experience small acceleration changes and demand lower flow rates over longer time scales. During either quiescent or transient flow environments, the screen serves three purposes.

1. To maintain communication between the tank outlet and propellant during all phases of the mission. When liquid approaches the porous screen, the screen admits liquid into the channel.
2. To separate and control phases. When pressurant gas or vapor approaches the screen, liquid surface tension forces within the screen pores block vapor admittance.
3. To rewet portions of the screen that dry out due to exposure to warm pressurant gas; the screen can wick liquid along the screen.

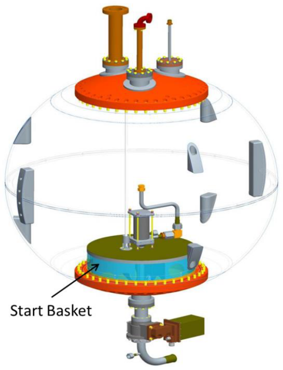

Figure 6: Example of a Screen Channel Start Basket/Sump.

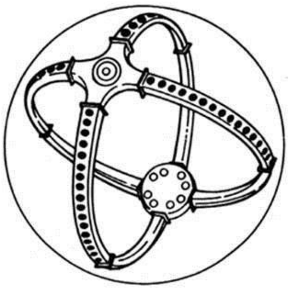

Figure 7: Example of a Total Communication Screen Channel Liquid Acquisition Device.

The channels all converge to a common location at the tank outlet in order to ensure that there is communication between the propellant and the tank outlet during the mission. As liquid is withdrawn from the tank and vapor approaches the screen, surface tension forces block vapor entrance into the channel, but allow the liquid to flow freely. Screen channel LADs succeed in preventing gas ingestion so long as the pressure differential across the screen does not exceed the bubble point pressure.

Two kinds of thermal management techniques are discussed to handle the aforementioned challenges i.e. active and passive.

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3.2 Passive Control Management

Passive thermal management refers to cooling technologies that rely solely on the thermo-dynamics of conduction, convection and radiation to complete the heat transfer process. These technologies are the most commonly used, the least expensive and the easiest to implement.

3.2.1 Insulations

Spray on foam insulation

Thermal insulation systems manage pre-launch tanking, pad hold, and ascent environments that mitigate liquid air condensation on tank walls (Limited layer multilayer insulation).[21]

Multi Layer Insulation

1. Standard cover for satellite isolation
2. Blankets with many layers Lagen (up to 25) of foils (thickness: 6 μm) made of FEP Teflon, Mylar, or Al Kapton etc. with small α.
3. N Layer reduce the thermal radiation by a factor of 1/(N + 1)
4. Coatings can improve reflectivity on the warm side
5. Spacers with small heat capacity between the single layers
6. Metalic blankets needs to be grounded in order to avoid charging.

Vacuum jacket

Vacuum jacket shell provides useful insulation during pre launch filling. VJs represent a mass penalty to any space system once on-orbit.[21]

MMOD protection

MMOD protection micrometeoroid protection - spacing in layer, Micro- Meteoroid Orbital Debris (MMOD) barrier protection.

3.2.2 Radiators

The radiator is a region with a precisely designed calculated size ratio a/e that radiates the satellite's internal heat into space. It's mostly made of polished or lacquered metals. During the orbital phase, it was always open. Closed loop systems have been used to convey the fluid cooling agent to the radiators.

In short: Radiators should have (or be)

1. emissivity $e > 0.8$ and absorptivity $a < 0.2$
2. high emission
3. small size
4. Insusceptible against solar irradiation
5. light coloured (white) surfaces
6. space proven coatings

For design, the aging behaviour of radiators must be taken into account. a can increase up to 10% per year due to surface degradation mostly by solar UV light.

3.3 Active Control Management

Active thermal management refers to cooling technologies that must introduce energy typically from an external device to augment the heat transfer process. Their drawbacks include the need to use electricity in order to operate.

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3.3.1 Active Cryocoolers

The use of thermal insulation materials can reduce the heat load experienced by cryogenic fluids on orbits significantly, however they cannot fully eliminate it. For long term storage of these cryogenic fluids and to eliminate boil-off losses, active thermal management is required. The most common form of active thermal management is the use of an electrical refrigeration system or cryocoolers. Cryocoolers transfer energy from the cryogenic fluids to a working fluid through the use of heat exchangers. Almost all the space-qualified cryocoolers developed till date use on small satellites or probes to cool instruments. Most of these coolers operate with a cold head temperature ranging from 4 to 120 K and have cooling capabilities ranging from several milliwatts to tens of watts. A survey of space-qualified cryocoolers is compiled from a variety of sources; these cryocoolers are shown in Figure 8 For LO2 storage, the solution is straightforward, as it is possible to integrate existing high capacity 90 K flight coolers, or derivations of them, directly with an LO2 tank. This is not a viable option for LH2 because the required 20 K coolers of the required thermal power do not yet exist. However, analysis performed under ISCPD predicted that a large percentage of the heat leak into an LH2 tank could be intercepted at 90 K, thus circumventing the need for a high capacity 20 K flight cryocooler. Spitzer (superfluid helium dewars) and Wide Field Infrared(solid hydrogen cryostat dewars). Spitzer demonstrated an equivalent average cryogen boil-off rate of 0.05% per day achieving an operational mission duration total of over 5 years (66 months on-orbit).[21]

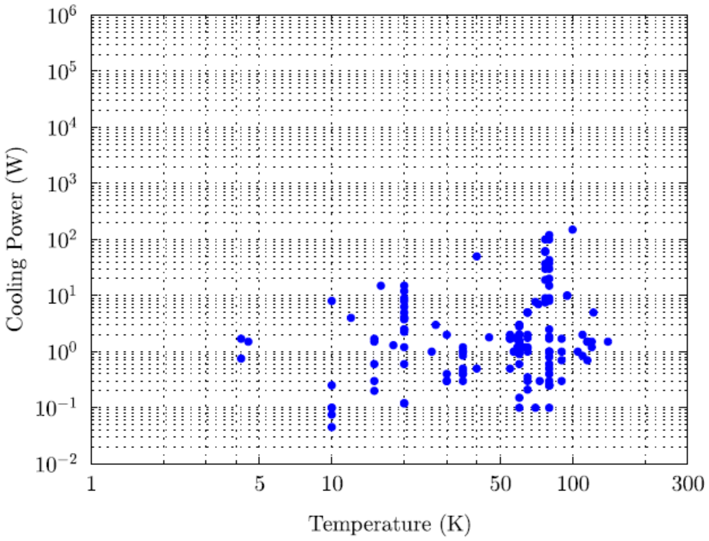

Figure 8: Survey of performance of cryocoolers.

3.3.2 Zero-boil off and cryogenic fluid conditioning techniques

Zero-boil-off and cryogenic condition techniques that can extend the hold time of liquid cryogens in space are of interest for a cryogen servicing spacecraft. A cryocooler on the servicing spacecraft's liquid cryogen source tanks could allow for long-duration storage of the cryogen until a client spacecraft was ready to be serviced. In addition, a cryocooler would allow the cryogen to be sub-cooled prior to the servicing operation which would further decrease the boil-off experienced due to heat leak in the transfer process as well as reduce the energy required to freeze the cryogen once it had been transferred to the client spacecraft[7]

3.4 Vortex Suppressor

The vortex suppressor is included to prevent vortices from forming at the outlet tube's entry, allowing the propulsion system thruster to maintain the required flow rate. The vortex suppressor is made to handle the fluid loads that come with spin and de-spin motions on a spaceship.[28]

3.5 Propellant Settling

From Goff 2009,[11] A few propellant settling options with corresponding pros and cons are discussed in this section.

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3.5.1 Zero-G Handling

Pros:

- Does not require reaction mass for propellant settling
- Integration with big stations easier
- Configuration and orientation independent of operations
- Loading/offloading operations identical

Cons:

- Zero-G thermal control, transfer, and liquid acquisition are low TRL

3.5.2 Propulsive Settling

Pros:

- Settled cryo handling is high TRL, and simplifies all other depot functions
- Settling and re boost functions can be combined

Cons:

- Uses reaction mass for settling
- Hard to integrate with existing space stations
- Constrains tank arrangement to get correct settling effects

3.5.3 Centrifugal Settling

Pros:

- Does not require reaction mass for propellant settling
- Settled cryo handling is high TRL, and simplifies all other depot functions

Cons:

- May require despinning for docking
- May need to be combined with another process for transfer ops
- Constrains tank arrangement to get correct settling effects

3.5.4 ED Tether Settling

Pros:

- Provides reboost and propellant settling without using reaction mass
- Can use zero boil-off systems

Cons:

- Requires moderately large station with significant solar power capability
- Low TRL for ED tethers
- Challenges docking
- Constrains tank arrangement to get correct settling effects

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3.5.5 Gravity Gradient Settling

Pros:

- Does not require reaction mass for propellant settling

Cons:

- Requires very long tether and large overall system
- Complex system dynamics
- Constrains tank arrangement to get settling effects correctly

3.5.6 Electromagnetic Settling

Pros:

- Does not require reaction mass for propellant settling
- Provides more control over propellant positioning
- More flexibility on tank arrangements and depot layout

Cons:

- Electromagnetic settling is low TRL
- Superconducting electromagnets may add significant weight
- Uncertainty if existing electromagnets sufficient for large LH2 tank settling

3.6 Acoustic effects on heat transfer in microgravity conditions

From Buil and Cinca 2021,[26] The use of acoustic fields for the control and elimination of vapour bubbles in propellant tanks is a potential technology for managing boiling in propellant tanks. The piezoelectric transducers are placed close to the hot regions where bubbles occur in the acoustic approach. The acoustic (Bjerknes) force exerted on the bubbles by the acoustic wave created by the transducer may cause the bubbles to travel away from the hot regions and into the subcooled liquid, where they may collapse.

The acoustic actuation applied in the experiments in microgravity conditions increased the heat flux an 8.6% with respect to the scenario on the ground without actuation, and an 8.4% with respect to the scenario in microgravity without actuation. The heat flux enhancement could reach much higher values with an accurate selection of the acoustic parameters. The time evolution of the heater surface temperature and heat flux showed a ripple when acoustic actuation was applied and the heater was on a PMMA substrate. This behavior can be associated to the fluctuating acoustic amplitude near the PMMA substrate. In fact, the acoustic field near the heater depends on the acoustic impedance of the substrate material. When an Aluminum substrate was employed, no such amplitude fluctuations were observed. Therefore, in the case of propellant tanks made of Aluminum, a behavior of temperature and heat flux smoother than in the experiments presented here could be expected. The temperature decrease and heat flux increase when acoustic actuation is applied in microgravity can be used to mitigate bubble generation and, therefore, to control boil-off in propellant tanks. The different boiling characteristics in the cryogenic propellants with respect to HFE-7100 would imply different acoustic requirements. However, the physics involved does not substantially differ since the acoustic actuation capabilities for heat enhancement are expected to remain, despite its performance could change. Therefore, the acoustic approach is a good candidate for the thermal management of cryogenic propellants and, also, electronics cooling in space.

3.7 Sub-Cooling

Chill-down time decreases with the increase in the driving pressure and thereby reduces the liquid consumption.This is to be expected since the higher driving pressure produces higher mass flux that, in turn, yields higher heat transfer coefficients. Sub-cooling the propellant in the tank reduces the chill down time in general for all the cases studied.

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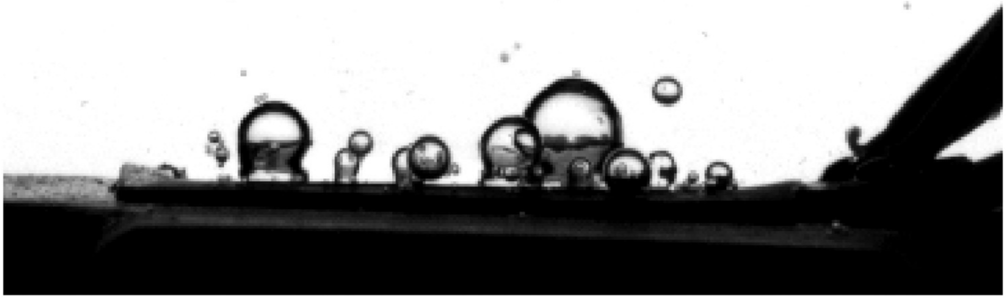

Figure 9: Bubbles generated by boiling in microgravity.

4. Conclusion

This study focuses on the specific challenges associated with propellant management in low-gravity environments during in-orbit operation. These challenges include boil-off, gas removal prior to transfer, phase separation, and heat load management from various sources, all of which are crucial for developing an effective thermal management system. Additionally, the research highlights the difficulties related to transfer lines and receiver tanks, such as chill-down losses, transfer time, no-vent filling operations, and handling of residual propellant. This study also identified the common challenges encountered throughout the depot.

This study investigated the implementation of mitigation techniques for efficient propellant management in low-gravity environments. It specifically explores the impact of acoustic effects on heat transfer and analyzes the benefits associated with various insulation types, including multilayer insulation (MLI), Vacuum Jackets (VJs), and Spray-on Foam Insulation (SOFI). This research also focuses on the significance of micrometeoroid and orbital debris (MMOD) protection measures. Additionally, this study examines the deployment of leak-free sensor technology and cryogenic fluid conditioning techniques to minimize boil-off, vortex suppressors, and radiators. This investigation also encompasses the evaluation of propellant management devices, pressurant requirements, active cryocoolers, and subcooling methods. The findings suggest that incorporating these techniques can enhance the overall efficiency and performance of cryogenic propellant depots over the long term.

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