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An Updated Zero Boil-Off Cryogenic Propellant Storage Analysis Applied to Upper Stages or Depots in an LEO Environment

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June 2003

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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AN UPDATED ZERO BOIL-OFF CRYOGENIC PROPELLANT STORAGE ANALYSIS APPLIED TO UPPER STAGES OR DEPOTS IN AN LEO ENVIRONMENT

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Abstract

Previous efforts have shown the analytical benefits of zero boil-off (ZBO) cryogenic propellant storage in launch vehicle upper stages of Mars transfer vehicles for conceptual Mars Missions. However, recent NASA mission investigations have looked at a different and broad array of missions, including a variety of orbit transfer vehicle (OTV) propulsion concepts, some requiring cryogenic storage. For many of the missions, this vehicle will remain for long periods (greater than one week) in low earth orbit (LEO), a relatively warm thermal environment. Under this environment, and with an array of tank sizes and propellants, the performance of a ZBO cryogenic storage system is predicted and compared with a traditional, passive-only storage concept. The results show mass savings over traditional, passive-only cryogenic storage when mission durations are less than one week in LEO for oxygen, two weeks for methane, and roughly 2 months for LH2. Cryogenic xenon saves mass over passive storage almost immediately.

Introduction

NASA has redirected the Integrated In-Space Transportation Program (IISTP) from Code R management to Code S; accordingly, the propulsion elements under development are aligned with science and exploration mission concepts. Several propulsion concepts being studied for these missions could involve cryogenic propellant storage; specifically, advanced chemical, nuclear bi-modal, solar thermal, and perhaps solar electric propulsion, particularly if it is combined with an advanced chemical propulsion assist. In addition to these concepts for IISTP, a propellant depot called the Hybrid Propulsion Module (HPM) led by NASA Langley Research Center, includes cryogenic propellants. These concepts would all involve orbit transfer from LEO, some to higher earth orbits and most to other planets or destinations. The duration of the storage for all of these concepts varies from minutes to years; the purpose of this paper is to estimate the durations where the ZBO storage approach begins to reduce mass of the OTV. This estimation is based on scaling parameters determined from testing as well as analysis and design. The ZBO design work referenced is from a Protoflight ZBO Development Test Article (configuration shown in figure 1), which includes a flight cryocooler integrated with a propellant tank and a radiator, in a LEO simulated thermal environment.

The designs and estimations are guides for propulsion and mission design engineers in their evaluations and trade-studies involving cryogenic propellant usage. Besides helping them, this paper advances several details of the ZBO storage concept from previous studies.[1,2] First, a detailed cryocooler integration design is shown and associated temperature drops are included, as they represent losses that require the cryocooler to operate at a lower temperature. Secondly, a tank mixer has been added to force flow across the heat exchanger coupled to the cryocooler. In addition, a radiator and associated thermal analysis is incorporated to reject the heat from the cryocooler. Finally, a look into the appropriate number of MLI layers for a ZBO tank is described.

Thermal Model

The following discussions on the analysis form the basis of the thermal model used in the analysis. Several parts are repeated from reference 1 for clarity, but the bulk of the work is based on additional research and design.

Cryocooler Model

The cryocooler model used is updated from reference 1. While the hydrogen cryocooler is again modeled using two cryocoolers (for simplicity), in this approach the first cryocooler is used to reduce the temperature of a tank shield to a typical intermediate value of a first stage of a two-stage cooler; the second cryocooler removes the remaining heat that enters the tank through that shield. Reference 1, on the other

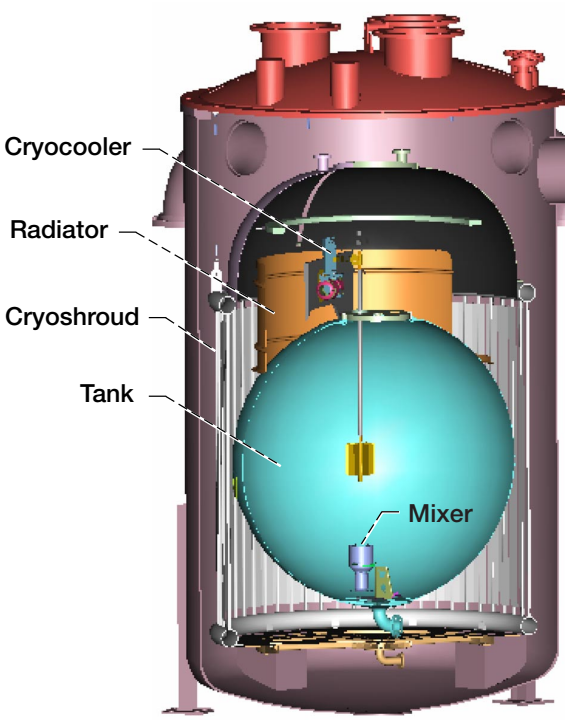

Figure 1.—Three-dimensional drawing of Protoflight Development ZBO Test Article.

hand, incorporated a shield cryocooler in addition to a second cryocooler that removes all the heat entering the tank. The reference 1 advantage is the independence of each stage, while its disadvantage is somewhat heavier second cryocooler and more power. The revised approach disadvantage is that the stages are dependent on one another, and a high thermal load on the first stage could dwindle the performance of the second stage. Accordingly, we are assuming that the cryocooler stages and integration could be designed to match the OTV cryogenic propellant stage performance.

Unchanged from reference 1, the cryocooler sizing relationships are based on Strobridge, with modifications to account for advances in the last 25 years[3] are as follows:

$$\dot{Q}_{ip} = \dot{Q}_c \, (T_h - T_c) \, (T_c \, \eta \, 10^{\Sigma})^{-1} \qquad (1)$$

(1)

where

$$\Sigma = -1.7359 + 0.59998 \log (\dot{Q}_c) - 0.14740 \log (\dot{Q}_c)^2 + 0.021323 \log (\dot{Q}_c)^3 - 0.0012502 \log (\dot{Q}_c)^4 \qquad (2)$$

wherein $\dot{Q}_{ip}$ is the electrical input power, $\dot{Q}_c$ is the cooling power, T_h is the cryocooler heat rejection temperature, T_c is the cryocooler coldhead temperature, and η is the improvement factor. The values used for η were 2.5 for CH_4 and O_2 tanks and 2.0 for H_2 tanks. These factors are estimated based on current and projected near term capabilities.[4,5] Similarly, the mass of cryocooler is based on Strobridge's correlations adjusted by a factor of 0.2 to account for recent advances:

$$m = 0.2 \; \dot{Q}_c^{0.7} \, [(T_h - T_c) / T_c]^{1.45} \qquad (3)$$

Additionally, cryocooler controller mass is included for the first time. It is estimated to be 1.4 times that of the cryocooler itself, based upon existing flight controllers.

Integration Loss and Vapor Cooled Shield Assumption

Another update to the thermal model is the addition of an integration loss, due to physical integration of the cryocooler into the propellant tank. The loss used is based on the integration design of the flight cryocooler in the Protoflight ZBO Development Test Article, which uses liquid nitrogen as the working fluid and transfers 6.8 watts of heat to the cryocooler. The temperature drop was 8.5K (see figure 2 and table 1).

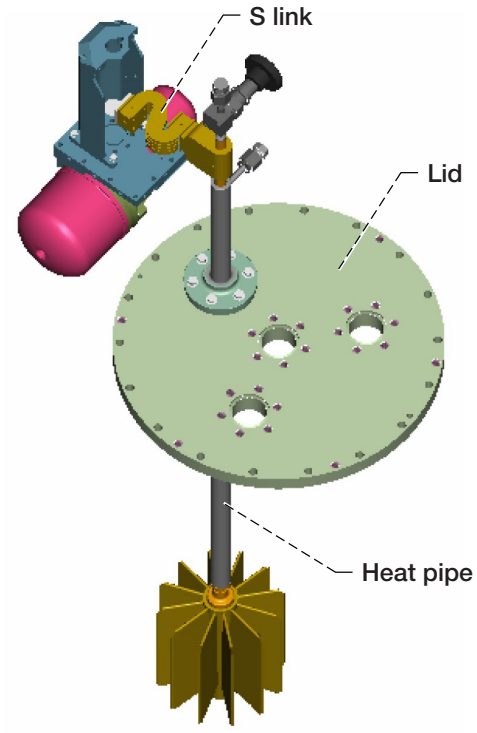

Figure 2.—Integration design connects cryocooler to propellant tank lid.

Integration Element	Temperature Drop, K
Convection drop	0.28
Fin conduction	0
Fin-wall interface	*0.5*
Evaporator wall	0.005
Evaporator	1.3
Condenser	0.98
Condenser wall	0.004
Wall-saddle interface	*0*
Saddle	0.34
Saddle-s-link interface	*0.5*
S-link	4.08
S-link to coldhead interface	*0.5*
Total	**8.5**

Table 1. A listing of the components and interfaces with their calculated or assumed (in italics) temperature drops for integration into a LN2 propellant tank for a protoflight test with an estimated 6.8 watts heating rate.

This drop causes the cryocooler coldhead to operate that much below the propellant bulk liquid temperature, as follows:

$$T_c = T_{bulk} - T_{drop.} \quad (4)$$

This is represented as inefficiency according to the following equation:

$$(1-\eta) = (T_{bulk} - T_c) * (T_h/T_{bulk}) / (T_h - T_{bulk}). \quad (5)$$

For the Protoflight ZBO Development Test Article, $(1-\eta)$ is 12%, which is used in this analysis. While this term would vary slightly with T_{bulk} depending on the fluid, those variations were not included.

The loss for integrating a cryocooler with a liquid hydrogen propellant tank has an additional part because of liquid hydrogen cryocooler's two stages, the intermediate stage (first stage) in addition to the cold head (second stage). The second stage loss is 12%, as discussed above. The first stage loss is more uncertain as it will be integrated differently, perhaps with a heat pipe to cool an oxidizer tank or tank penetrations such as feed lines or tank support struts, or in conjunction with a vapor-cooled shield to reduce the temperature of the insulation. A check on the analysis shows a vapor-cooled shield to be quite heavy, yet it slightly reduces the overall system mass and we have assumed its use around the tank. Because it is much larger and the heat travels further than the heat exchanger attached to the second stage, it will have a greater temperature drop. Correspondingly, a larger loss of 20% was arbitrarily assumed to integrate the shield with the first stage.

The shield mass used is based on a vapor-cooled shield design. Shield valving and controls were not considered.

Mixer Heat Assumption

A mixer, which is integrated into the tank to destratify the propellant and force convective heat transfer across the heat exchanger (as shown in figure 1), is also represented in the analysis and is an upgrade from reference 1. Heat inputs from destratification mixers for existing flight and ground designs and tests were investigated. Analysis for the COLD-SAT[6] flight experiment, and the analysis for our Protoflight ZBO Development Test Article test show that much less jet momentum (and, correspondingly, mixer power) is needed for flight applications. Analyses published by Poth and Van Hook[7] supports this conclusion. They showed that jet momentum for low Bond numbers, which occur in low gravity environments, is a function of jet inertial surface tension forces. For ground tests with the comparatively much higher acceleration force of gravity, large Bond numbers (NBo>10) occur. In this case, jet momentum is a function of jet inertia forces and body forces caused by gravity.

Applying that analysis to 2.2 meter diameter tanks (additional assumptions include 97% full tank with 0.18 m jet nozzle height), the jet momentum for LO_2 ground applications is 64 times that for flight, and for LH_2 propellants it is 42 times greater. Therefore, the mixer heat added to the tank for flight applications is assumed to be 1/64th (for O_2) and 1/42nd (for H_2) that of our ZBO ground demonstration, which was found to be 16% of the total heat added to the tank. Correspondingly, the submerged mixer heat added for this analysis is assumed to be 0.25% (O_2, CH_4, and Xe) and 0.38% (for H_2) of the heat entering the tank.

Heat Rejection Assumption

The mixer heat (which is almost insignificant) is added to the environmental heat entering the tank and must be removed by the cryocooler and ultimately rejected by its radiator. The lower the rejection temperature is, the higher the Carnot efficiency of the system. The radiator design, cryocooler input power, environmental temperature, vehicle orientation, and the propellant tank heat load directly affect this temperature.

For the Protoflight ZBO Development Test Article, an ANSYS thermal model found the heat rejection temperature to be 50K above the environmental temperature for the radiator design used. Flight radiator designs will be more efficient and, according to the cryocooler manufacturer,[8] this design temperature could be improved for flight to roughly 30K, which was used in this analysis.

MLI Assumption

Another variation from reference 1 is that the number of MLI layers used was eliminated as a variable. This was done to present the results more simply; also, by using a spreadsheet analysis it was possible to narrow in on the appropriate number of layers for each propellant studied. This was found by adding up the predicted passive and ZBO thermal storage mass, that is, the tank, insulation, propellant, and boil-off mass for the passive case and the tank, insulation, propellant, solar array, and radiator mass for the ZBO case for a given number of MLI layers, then vary the quantity of layers and narrow in on the lowest mass results at the point where the passive and ZBO masses were equal. This was done for the average tank diameter used for each propellant. For the LH2 case, the layers were divided up such that 2/3rds (or 30 layers) covered the vapor-cooled shield attached to the 1st stage and the rest blanketed the propellant tank. This proportion was chosen because the MLI layer 2/3rds the way through the thickness is estimated to be close to the temperature of the shield. These results are shown in table 2.

Propellant	MLI Layers Used
LH_2	45
LO_2	30
LCH_4	30
LXe	15

Table 2. The initialization of the number of MLI layers that result in the lowest thermal storage mass for a given propellant.

Passive Analysis Algorithm

The reference 1 algorithm used for tank mass and volume growth estimating was also rewritten, to eliminate a program bug that made it difficult to run. This algorithm determines the necessary tank growth to accommodate boil-off. This solution was iterative, that is, as the tank grew to accommodate boil-off tank volume and surface area increased, causing the boil-off to increase a little more. A small portion (1/100th) of the volume for that boil-off was added to the tank volume and iterated upon as long as it still increased. When it stopped increasing, the tank was at the appropriate size to accommodate boil-off and the iteration stopped.

Variables

The most significant variable in the study was tank diameter (note that all tanks are assumed spherical). The diameters used have been typical propellant tank sizes used in HEDS analysis and in various transportation studies. They are shown in table 3.

Tank Diameters Considered, meters			
LO_2	LCH_4	LXe	LH_2
1.2	1.2	1.2	1.2
2.2	2.2	2.2	2.2
3.3	3.3		3.3
4.4	4.4		4.4
			5.5

Table 3. The tank diameters considered in the trade space, shown for each propellant. Larger tank sizes for higher density fluids were not considered.

Another variable was the power and heat rejection system mass. It is possible and likely for some missions that this mass would be coupled with other much larger vehicle power and heat rejection requirements, thus, results are shown with and without it.

The last variable discussed is tank growth, necessary to accommodate boil-off. For passive solutions, larger tanks mean more tank and insulation mass. This effect is shown in bar graph form. A literature search found no previous analysis that included this very significant mass.

Summary of Assumptions

Because of the many parameters used and the significant changes from reference 1, table 4 is included to summarize the analysis approach.

Parameter	Assumed Value	Basis	Variation from Ref. 1
Tank Mass per Surface Area	5.4 kg/m^2 for H_2, O_2, CH_4, 20 kg/m^2 for Xe	Analysis by MSFC mission analyst. Reflects a 25% mass reduction in present tank designs.	Xe not previously analyzed. Its high tank density was assumed because of Xe's high density.
Insulation Mass per Surface Area	0.02 kg/m^2/layer	Based on actual design for flight at MSFC[9]	Includes mass for purge bag for LH2 and LO2
Tank Ullage	3%	Prevent tank rupture	None
Tank Residual	2%	Inaccessible propellant	None
Fluid Properties		Sat. liquid at 0.2 MPa	None
Environmental LEO Temperature	243K	Avg. temp. of Earth and Sun oriented orbits. From radiation analysis of a representative vehicle.	250K
Margin	5%	Cryocooler sized to remove 5% more heat than enters tank.	0%
Heat Rejection Temperature	273K	See text.	250K
Insulation Heating Rate	Lockheed Equation (include equation) times 1.8	1.8 is a compensating factor, which correlates with reference 3 testing results.	Thicker MLI blankets not considered
Penetration Heating	$\dot{Q} = 1.28\times10^{-4}\,(f/35)^2\,(T/250)^{2.3}$ m for O_2, CH_4, and Xe tanks, $\dot{Q} = 2.70\times10^{-4}\,(f/35)^2\,(T/250)^{1.6}$ m for H_2 tanks f = frequency T = heat rejection temp.	S glass epoxy struts[10]	None
Mixer Heat	0.25% of tank heating for LO_2, LCH_4, LXe; 0.38% for LH_2	See text	Not included
Integration Loss	12% or 20%	See text	Not included
Cryocooler controller	1.4 times cryocooler mass	Existing flight controllers	Not included

Table 4. A summary of assumptions used in analysis.

Results

All results shown use the thermal storage mass, which is defined as follows:

Passive: Tank, insulation, propellant, boil-off, and tank/insulation growth.

ZBO: Tank, insulation, propellant, cryocooler, solar array, radiator.

The first graph (figure 3) includes passive and ZBO thermal storage mass predictions for oxygen as a function of storage duration, or the days in LEO with cryogens, regardless of the number of engine burns. That graph is repeated twice more, for methane (fig. 4) and hydrogen (fig. 5). From those graphs and additional runs with xenon, the equal mass lines were constructed and are shown (fig. 6). These are the storage duration's where the passive and ZBO masses are equal; durations longer than these are predicted to reduce mass for ZBO; durations shorter would benefit if passive storage was used.

The bar graph in figure 7 shows the effect if power systems were available to power the cryocooler. Eliminating that mass from the trade reduces the

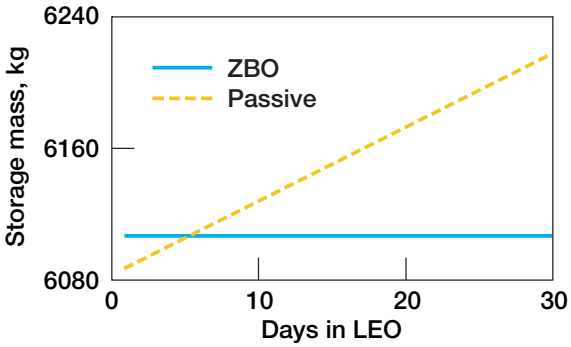

Figure 3.—Passive and ZBO cryogenic thermal storage mass versus duration for LO2 storage in 2.2-m-diam tank.

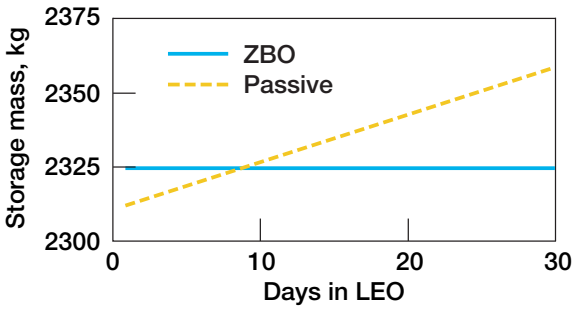

Figure 4.—Passive and ZBO cryogenic thermal storage mass versus duration for LCH_4 storage in 2.2-m-diam tank.

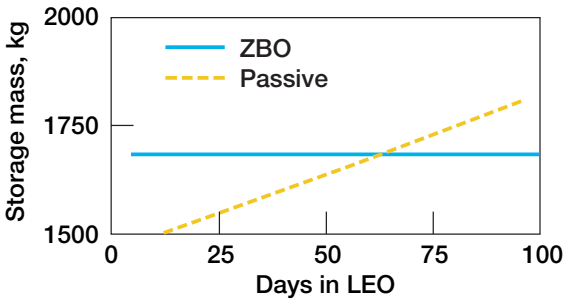

Figure 5.—Passive and ZBO cryogenic thermal storage mass versus duration for LH_2 storage in 3.3-m-diam tank.

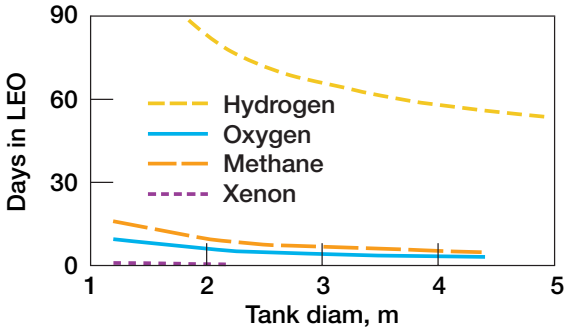

Figure 6.—Graphical composite that shows duration at which ZBO and passive storage mass is equal for a given tank size. Durations longer than these are predicted to save mass if ZBO is incorporated.

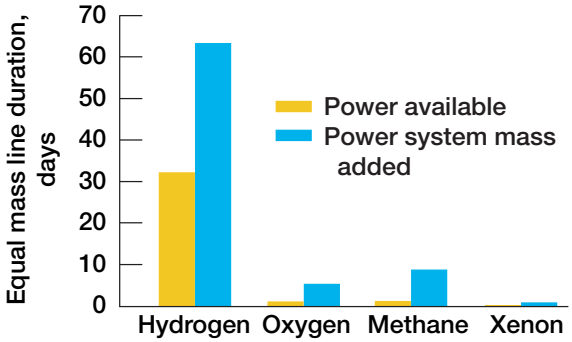

Figure 7.—Equal mass variation if power system is available and mass not included. If so, ZBO applicable for much shorter durations.

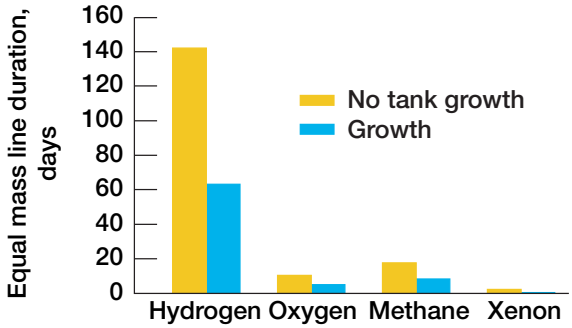

Figure 8.—Equal mass variation if tank growth to accommodate boil-off is not considered. If not, passive thermal control mistakenly appears to reduce mass to much longer storage duration than it should.

equal mass line's days in LEO substantially. Next, figure 8 shows the effect if tank growth was not considered. If not, then ZBO would not nearly be so beneficial.

Discussion

The results are surprising. The durations in LEO where ZBO starts to reduce mass are surprisingly low, which could lead to more applications for cryogenic propellants.

The first chart developed, figure 3, is for 2.2m diameter LO_2 tanks. This shows that ZBO storage durations as low as 5 days in LEO save mass when compared to the traditional passive storage approach. The results for methane storage (figure 4) are a little different in that more days are required before ZBO storage reduces mass, 8.5 days, compared to the 5 days for oxygen storage. At first glance, this is not obvious as methane's boiling point is higher than oxygen's, reducing its cooling requirements. However, boil-off mass is also dependent on the inverse of the heat of vaporization; methane's is 2.4 times that of oxygen.

Hydrogen storage takes quite a bit more days in LEO before ZBO is beneficial and also presents a challenge to cryocooler technology and the integration of two-stage cryocoolers. Still, if missions require storage times in excess of 64 days in LEO, ZBO is predicted to save mass (see figure 5).

Liquid xenon storage begins to save mass almost immediately over gaseous xenon storage. Even so, the relatively high density of xenon gas and low quantities needed for electric propulsion complicate the storage design decision.

Figure 6 compiles the results of all propellants considered and shows the effect of size--the larger the tank, the fewer days in LEO when ZBO has reduced mass. While that is the prediction, beware that this analysis uses floating point cryocooler designs and fewer large cryocoolers exist.

One cryocooler issue that could improve the ZBO results is its design. Existing flight cryocooler designs (one of which was incorporated in this analysis) include a small coldhead that cools a plate that mounts to an instrument. As shown herein, the temperature difference between coldhead and the bulk liquid is substantial, causing larger cryocoolers to be used. A design made specifically for cooling-fluid in a propellant tank could reduce this integration loss. It could involve submersion of the cold portion of the working fluid tube directly into the propellant, eliminating the coldhead and associated loss. Another variation could be the use of the propellant itself as the cryocooler working fluid. Such designs were not considered here but were explored in reference 11.

Summary

NASA is investigating an array of exploration missions and propulsion technologies for our future. Many of those concepts include cryogenic propellants, possibly involving long storage durations. This analysis addresses the storage duration effect on cryogenic thermal storage system performance, with the purpose of possibly minimizing the storage issue. One method worthy of consideration is zero boil-off storage, which has become more interesting because of the tremendous advances in cryocooler technology. This was applied to oxygen, methane, hydrogen, and xenon propellants in tank sizes of 1.2, 2.2, 3.3, 4.4, and 5.5m in diameter. This technology provides mass savings over traditional, passive- only cryogenic storage when mission durations are as short as one week in LEO for oxygen, two weeks for methane, and roughly 2 months for LH2. Cryogenic xenon saves mass over passive storage almost immediately.

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13. ABSTRACT ***(Maximum 200 words)***

Previous efforts have shown the analytical benefits of zero boil-off (ZBO) cryogenic propellant storage in launch vehicle upper stages of Mars transfer vehicles for conceptual Mars Missions. However, recent NASA mission investigations have looked at a different and broad array of missions, including a variety of orbit transfer vehicle (OTV) propulsion concepts, some requiring cryogenic storage. For many of the missions, this vehicle will remain for long periods (greater than one week) in low earth orbit (LEO), a relatively warm thermal environment. Under this environment, and with an array of tank sizes and propellants, the performance of a ZBO cryogenic storage system is predicted and compared with a traditional, passive-only storage concept. The results show mass savings over traditional, passive-only cryogenic storage when mission durations are less than one week in LEO for oxygen, two weeks for methane, and roughly 2 months for LH_2. Cryogenic xenon saves mass over passive storage almost immediately.

14. SUBJECT TERMS

Cryogenics; Cryocoolers; Thermosyphons; Zero boil-off; Low-earth orbit; Orbit transfer vehicles; Propellent depots; Long-term propellant storage

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