

Fractional Consumption of Liquid Hydrogen and Liquid Oxygen During the Space Shuttle Program

J.K. Partridge

National Aeronautics and Space Administration
Kennedy Space Center, FL 32899

ABSTRACT

The Space Shuttle uses the propellants, liquid hydrogen and liquid oxygen, to meet part of the propulsion requirements from ground to orbit. The Kennedy Space Center procured over 25 million kilograms of liquid hydrogen and over 250 million kilograms of liquid oxygen during the 30-year Space Shuttle Program. Because of the cryogenic nature of the propellants, approximately 55% of the total purchased liquid hydrogen and 30% of the total purchased liquid oxygen were used in the Space Shuttle Main Engines. The balance of the propellants were vaporized during operations for various purposes. This paper dissects the total consumption of liquid hydrogen and liquid oxygen and determines the fraction attributable to each of the various processing and launch operations that occurred during the entire Space Shuttle Program at the Kennedy Space Center.

INTRODUCTION

The Space Shuttle uses liquid hydrogen (LH₂) and liquid oxygen (LO₂) as a fuel and oxidizer, respectively, for combustion in the Space Shuttle Main Engines (SSMEs) during ascent to orbit. Due to the storage and transfer characteristics of LH₂ and LO₂, a portion of the total purchased LH₂ and LO₂ is lost by vaporization prior to combustion in the SSMEs. The losses are divided into three general categories of Replenish Loss, Normal Evaporation Loss, and Load Loss as depicted in Figure 1. LH₂ and LO₂ are also used for electrical power production, water, and breathing purposes in the Power Reactant Storage and Distribution System (PRSD) and the Environmental Control and Life Support System (ECLSS). However, because of the relatively small quantities, the LH₂ and LO₂ used in the PRSDs and ECLSS were not considered in this study.

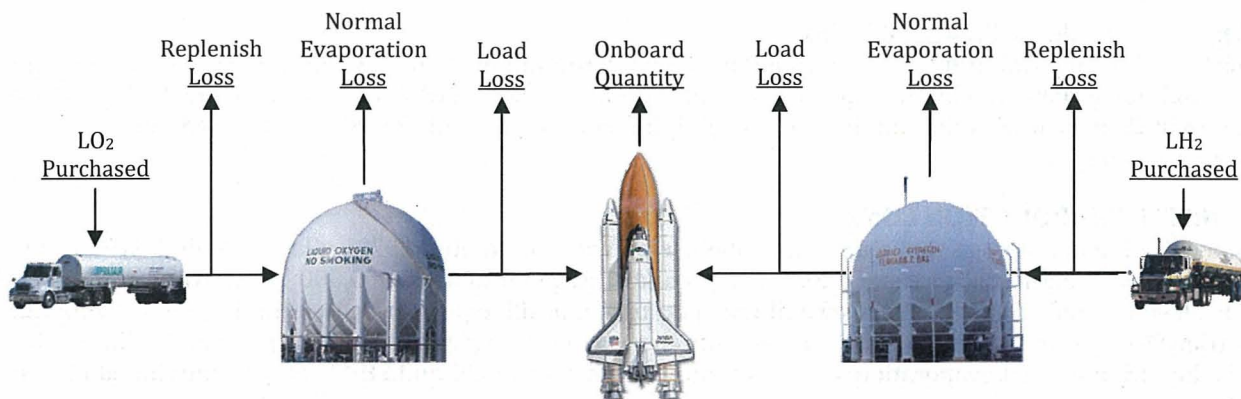


Figure 1: LC-39 Cryogenic Propellant Consumption

REPLENISH LOSS

Throughout the entire Space Shuttle Program (SSP), the propellant grade LH₂ and LO₂ have been produced at a steam methane reformer in New Orleans, LA and an air separation unit in Mims, FL, respectively. The propellant is transported by truck in tankers with a capacity of approximately 50,000 liters for LH₂ and 19,000 liters for LO₂. Typically, the vendor delivers LH₂ and LO₂ to Kennedy Space Center's (KSC) Launch Complex 39 (LC-39) ground storage tanks in waves of five tankers and transfer the propellant by a pressure offload. To accomplish a pressure offload, a portion of liquid oxygen is vaporized in the tanker's vaporizer, or pressure building coil, until the pressure inside the tanker reaches approximately 310 kPag. Once the desired

pressure is reached in the tanker, the LH₂ tanker and the LO₂ tanker discharges through a 0.051m vacuum-jacketed flexible hose and an uninsulated 0.076m flexible hose, respectively, into the LC-39 system. The LC-39 systems for both, LH₂ and LO₂, include piping and components, such as valves and filters. During the offload, the tanker maintains 310 kPag to continue flowing LH₂ and LO₂ into the ground storage tanks.

The total transfer loss was determined by the difference of the change in weight for each tanker and the change in liquid level of the ground storage tank. The tankers are weighed at the source in New Orleans, LA and Mims, FL with a precision of ±0.001 tons. The liquid level change of the ground storage tank is measured by the liquid level indicator with an acceptable accuracy tolerance up to ±100,000 liters depending on liquid level. The overall replenish loss averaged 12.6% and 5.9% for LH₂ and LO₂, respectively. Data from six months was used and applied over the entire 30-year SSP.

The Replenish Loss can be subdivided into three groups, (1) loss due to heat input into the tanker during transit from source to LC-39, (2) loss required to build pressure during the propellant transfer from tanker to the LC-39 ground storage tank, and (3) loss due to LC-39 replenish system chill-down.

Replenish Loss during Transit

The loss due to heat transferred into the tanker during transport is estimated at 2,300 liters for LH₂ and 60 liters for LO₂. The heat input into the LH₂ tanker during transit results in a pressure rise within the tanker since the tanker is not permitted to vent due to U. S. Department of Transportation rules. However, the heat gained during transit is removed from the LH₂ after transfer into the ground storage tank. The estimate was calculated from 49 CFR 178.338 by assuming a 80-hour One-Way Travel Time during a 28 hour transit. The LO₂ tanker is permitted by U. S. Department of Transportation to vent during transit. The estimated loss was calculated assuming a evaporation rate from the tanker of 1%/day (% based on tanker volume) during a total transit time of 8 hours.

Replenish Loss due to Tanker Pressurization

The loss due to tanker pressurization is estimated at 680 liters for LH₂ and 120 liters for LO₂. Just prior to the completion of the tanker offload when the cryogenic propellant tankers are nearly empty of LH₂ and LO₂, the tanker still maintains the pressure at 310 kPag. The loss due to tanker pressurization is estimated by the amount of gas required for the tanker volume at the final pressure.

Replenish Loss due to System Chill-down

Instead of employing a component by component energy balance of the LC-39 replenish system to determine the chill-down requirement, the replenish system chill-down requirement is taken as the difference between the total Replenish Loss and the sum of the replenish loss during transit and replenish loss due to tanker pressurization.

NORMAL EVAPORATION LOSS

Both LH₂ ground storage tanks are 3,220,000 liters (with an additional 7% ullage), double walled tanks insulated with perlite in a vacuum. Both LO₂ ground storage tanks are 3,400,000 liters (with an additional 7% ullage), double walled tanks insulated with perlite in a positive pressure gaseous nitrogen blanket. Heat is transferred from the ambient environment into the ground storage tanks, which vaporizes the LH₂ and LO₂. The loss from normal evaporation accounts for approximately 12.2% and 28.4% of total purchased LH₂ and LO₂, respectively.

Each ground storage tank has its own evaporation profile as a function of the quantity of LH₂ or LO₂ in the tank. For LH₂, the average evaporation rate for the studied period was 1,200 liters/day and 2,700 gallons/day for LC-39A and LC-39B, respectively. For LO₂, the average evaporation rate for the studied period was 3,200 liters/day and 2,600 liters/day for LC-39A and LC-39B, respectively. The studied period was six years.

This report assumes that the LC-39 ground storage tanks were full the entire life of the Space Shuttle Program, which is not true. For instance, the LC-39A LO₂ ground storage tank was drained in 1993 for a couple of months for a valve repair. Also, the ground storage tanks had an elevated evaporation rate during

refurbishment, when the ground storage tanks were painted with a gray primer. Nevertheless these variations are considered very minor influences over the large time interval of 30 years.

LOAD LOSS

Cryogenic propellant loading of the Space Shuttle typically begins at T-6, which is about 10 hours prior to launch. The Space Shuttle External Tank (ET) is fully loaded in three hours and spends the remaining seven hours in a stable replenishment mode. In the event of a scrubbed launch attempt (scrub), the LH₂ and LO₂ is drained from the ET and returns to the ground storage tank, which takes about 1-2 hours to complete. The load loss accounted for 20.7% and 33.7% for LH₂ and LO₂, respectively.

A load loss occurred each time the Space Shuttle was loaded with cryogenic propellant. However, a scrub can be declared during any phase of loading and the subsequent load losses are not incurred.

Since no flow meters exist within the ground system, the losses incurred during each loading phase are estimated using the ground storage tank liquid level indicator. The time periods for each phase are known and recorded due to valve positioning showing the transition from one loading phase to the next loading phase. The liquid level was noted for each transition to determine the change in ground storage tank liquid level. The change in ground storage tank liquid level during the System Chilledown phase and the Stable Replenishment phase was the loss for each phase. However, the cryogen aboard the ET was subtracted from the change in ground storage tank liquid level during the Filling phase and Drainback phase to determine the loss during that phase.

System Chill-down Loss

The cryogenic propellant loading process begins with ground storage tank pressurization by flowing the cryogen to a vaporizer and subsequently to the ullage of the ground storage tanks. LH₂ loading uses the pressure transfer method, while LO₂ loading uses the pump transfer method. Thus, hydrogen pressurization phase lasts until LH₂ ground storage tank reaches sufficient pressure to transfer the LH₂ to the ET, while the oxygen pressurization phase of the LO₂ ground storage tank lasts until sufficient pressure is achieved to provide the net positive suction head required by the LO₂ pump. After the pressurization phase, LH₂ begins to flow toward the launch pad and cools the cross-country transfer line to the Mobile Launch Platform and the Space Shuttle Orbiter Main Propulsion System to LH₂ temperatures. Likewise, after the oxygen pressurization phase, LO₂ flows into the LO₂ pump until it is cooled to LO₂ temperatures; thereafter the LO₂ is pumped toward the launch pad and cools the cross-country transfer line to the Mobile Launch Platform and the Space Shuttle Orbiter Main Propulsion System to LO₂ temperatures. The total loss during system chill-down is approximately 45,000 liters and 95,000 liters for LH₂ and LO₂, respectively.

Loss During Filling

After system chill-down is completed, LH₂ and LO₂ are loaded into the ET during three general phases of filling termed slow fill, fast fill, and topping. The slow fill phase loads the ET to 5% and 2% for LH₂ and LO₂, respectively, followed by the fast fill phase, which loads the ET to 98% for both, LH₂ and LO₂, and finally the topping phase completes the loading to 100% of flight level. Slow fill, fast fill, and topping occur in about 150 minutes and 135 minutes for LH₂ and LO₂, respectively. Approximately 65,000 liters of LH₂ and 95,000 liters of LO₂ are lost during the filling of the ET.

Stable Replenishment Loss

After the ET is full, the cryogenic loading systems transitions into stable replenishment. The cryogen loss during stable replenishment is due to the heat transfer through the ET insulating foam, heat transfer into the cryogenic propellant transfer system, and continual SSME conditioning. Approximately 380 liters of LH₂ and 475 liters of LO₂ flow from the ground storage tanks every minute during stable replenishment. The length of stable replenishment has varied over the SSP, and depends on the amount of work required to be performed such as loading astronaut crew and tank inspections as well as the launch window. Ultimately, stable replenishment occurs until a scrub is declared or until about five minutes before launch. The average total stable replenishment is approximately 185,000 liters and 190,000 liters for LH₂ and LO₂, respectively.

Drainback Loss

In the event of a scrub, LH₂ and LO₂ are drained from the ET. The ground storage tanks are vented to ambient pressure to allow the LH₂ and LO₂ to drain from the ET to the ground storage tanks. During the drainback, the ET continues to receive ambient heat that vaporizes the LH₂ and LO₂ throughout the drainback period. Thus, most of the ET volume of LH₂ and LO₂ are recovered with the exception of approximately 42,000 liters and 30,000 liters, respectively. The Drainback Loss is only incurred after a scrub, tanking test, or flight readiness firing. A first-attempt launch occurred on about 56% of the Space Shuttle missions, however, a scrub to launch ratio was about 75% due to multiple scrubs for some Space Shuttle missions and including tanking tests and Flight Readiness Firings.

QUANTITY ONBOARD

The quantity of LH₂ and LO₂ in the ET at launch is 1,450,000 liters and 534,000 liters, respectively. The Quantity Onboard is per launch and to date, there have been 134 flights of the Space Shuttle.

CONCLUSION

The previous discussion presents the various losses over a 30-year flight program, as well as outlining a method to estimate the cryogenic propellant losses for future programs. If this data is used to estimate future program consumption, it is imperative that the modeler understands the dependency of each loss. Figure 2 shows the summary of the fraction of each loss and the onboard quantity with respect to the total cryogenic propellant purchase.

The ground storage tank liquid level indicator was used to measure the amount of cryogen consumed during various operations at KSC. As stated above the allowed tolerance of the liquid level indicator can provide uncertainty within these numbers depending on the liquid level in the sphere. Nevertheless, the analysis within this paper provides a reasonable estimated consumption over the entire program.

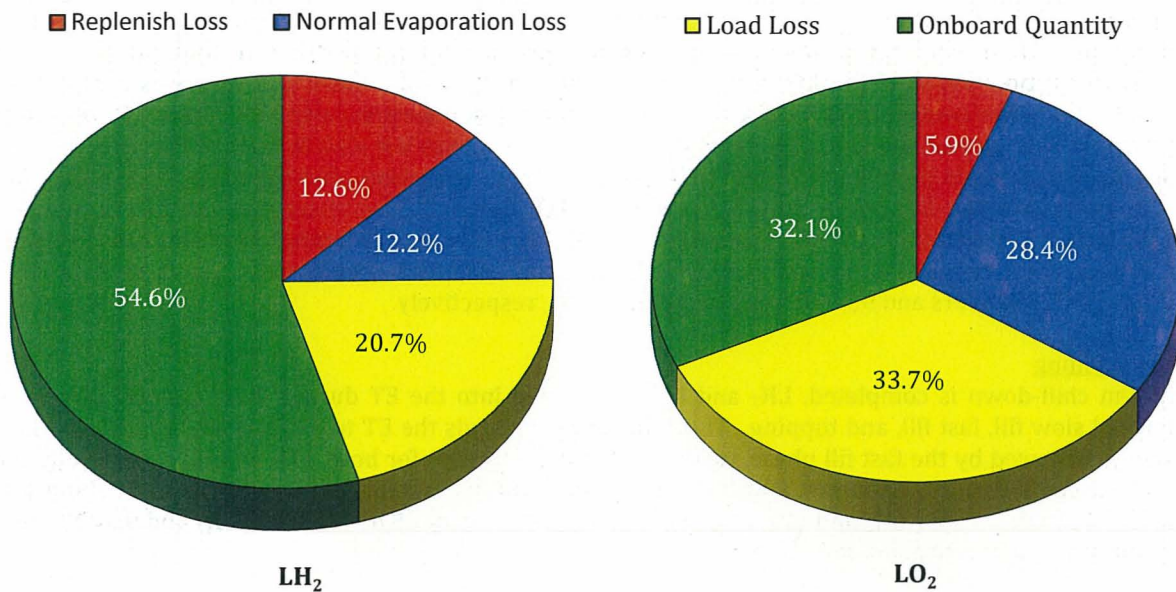


Figure 2: Fraction of Total Cryogenic Propellant Purchased Over 30-Year Space Shuttle Program

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