# FRACTIONAL CONSUMPTION OF LIQUID HYDROGEN AND LIQUID OXYGEN DURING THE SPACE SHUTTLE PROGRAM

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## 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 350 million liters of liquid hydrogen and over 200 million liters of liquid oxygen during the 30-year Space Shuttle Program. Because of the nature of the cryogenic propellants, approximately 54% of the total purchased liquid hydrogen and 32% 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.

**KEYWORDS:** Hydrogen, Oxygen, Space Shuttle Propellants

## INTRODUCTION

The Space Shuttle uses liquid hydrogen ($LH_2$) and liquid oxygen ($LO_2$) 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 $LH_2$ and $LO_2$, a portion of the total purchased $LH_2$ and $LO_2$ is lost by vaporization prior to combustion in the SSMEs. The losses are divided into three general categories of Storage Tank Fill Loss, Normal Evaporation Loss, and Load Loss as depicted in Figure 1. $LH_2$ and $LO_2$ 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 PRSDS and ECLSS are supplied by a separate system and

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the relatively small quantities, the $LH_2$ and $LO_2$ used in the PRSDS and ECLSS were not considered in this study.

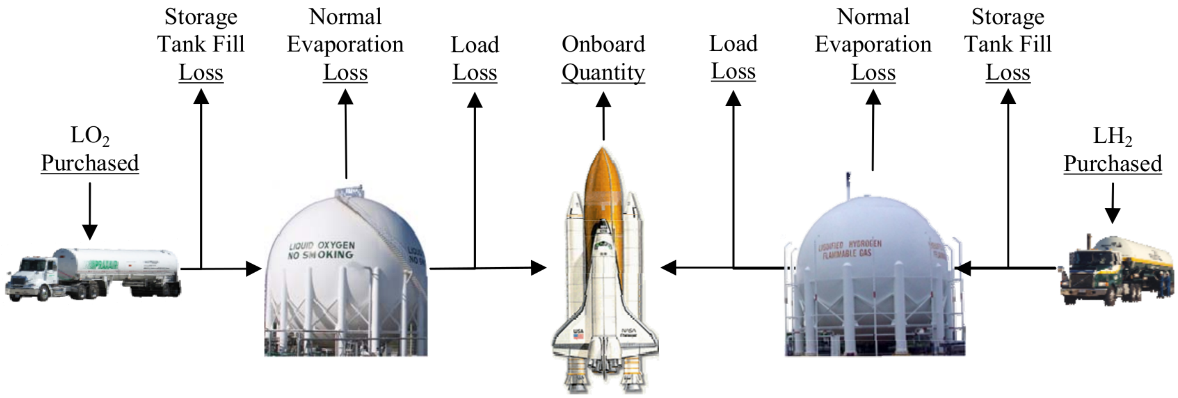

**Figure 1**: LC-39 Cryogenic Propellant Consumption

NOTE: All percentages are taken as a percentage of the total purchased LH2 and LO2 over the entire 30-year program.

## STORAGE TANK FILL LOSS

Throughout the entire Space Shuttle Program (SSP), the propellant grade $LH_2$ and $LO_2$ 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 $LH_2$ and 19,000 liters for $LO_2$. Typically, the vendor delivers $LH_2$ and $LO_2$ to Kennedy Space Center's (KSC) Launch Complex 39 (LC-39) ground storage tanks in waves of five tankers and transfers the propellant by a pressure offload. To accomplish a pressure offload, a portion of the cryogen 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, $LH_2$ and $LO_2$ are discharge from the tanker through a 0.051m nominal diameter vacuum-jacketed flexible hose and an uninsulated 0.076m nominal diameter flexible hose, respectively, into the LC-39 system. The LC-39 systems for both, $LH_2$ and $LO_2$, include piping and components, such as valves and filters. During the offload, the tanker maintains 310 kPag to continue flowing $LH_2$ and $LO_2$ 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 ±130 liters $LH_2$ and ±8 liters $LO_2$, respectively. 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 (although liquid level sensor precision is 4,000L). The overall storage tank fill loss averaged 13% and 6% for the total purchased $LH_2$ and $LO_2$, respectively. Data from six months was used and applied over the entire 30-year SSP.

The storage tank fill 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 system chill-down.

### Storage Tank Fill Loss during Transit

The loss due to heat transferred into each tanker during transport is estimated at 2,300 liters/tanker for $LH_2$ and 60 liters/tanker for $LO_2$. The heat input into the $LH_2$ 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 $LH_2$ after transfer into the ground storage tank. The estimate was calculated from 49 CFR 178.338 by assuming an average tanker during a 28 hour transit. The $LO_2$ tanker is permitted by U. S, Department of Transportation to vent during transit. The estimated loss was calculated assuming an evaporation rate from the tanker of 1%/day (% based on tanker volume) during a total transit time of 8 hours.

### Storage Tank Fill Loss due to Tanker Pressurization

The loss due to tanker pressurization is estimated at 680 liters/tanker for $LH_2$ and 120 liters/tanker for $LO_2$. Just prior to the completion of the tanker offload when the cryogenic propellant tankers are nearly empty of $LH_2$ and $LO_2$, 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.

### Storage Tank Fill Loss due to System Chill-down

Instead of employing a component by component energy balance of the LC-39 storage tank fill system to determine the chill-down requirement, the storage tank fill system chill-down requirement is taken as the difference between the total Storage Tank Fill Loss and the sum of the storage tank fill loss during transit and storage tank fill loss due to tanker pressurization. Thus, the loss due to system chill-down is deduced to be 3,500 liters/tanker and 950 liters/tanker.

## NORMAL EVAPORATION LOSS

Each pad (LC-39A and LC-39B) has a $LH_2$ and $LO_2$ ground storage tank. Both $LH_2$ ground storage tanks are 3,220,000 liters (with an additional 230,00 liters ullage), double walled tanks insulated with perlite in a vacuum. Both $LO_2$ ground storage tanks are 3,400,000 liters (with an additional 240,000 liters 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 $LH_2$ and $LO_2$. The loss from normal evaporation accounts for approximately 12% and 28% of total purchased $LH_2$ and $LO_2$, respectively.

Each ground storage tank has its own evaporation profile as a function of the quantity of $LH_2$ or $LO_2$ in the tank. For $LH_2$, the average evaporation rate for the studied period was 1,200 liters/day and 2,700 liters/day for LC-39A and LC-39B, respectively. For $LO_2$, 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 $LO_2$ 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 exterior of the ground storage tanks were painted with a gray primer. Other maintenance requirements include analytical sampling and ground storage tank pressurization tests on at least an annual cycle. 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 hours, 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 $LH_2$ and $LO_2$ are drained from the ET and returns to the ground storage tank, which takes about 1-2 hours to complete. The load loss accounted for 21% and 34% of the total purchased $LH_2$ and $LO_2$, 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 portion of the 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 Chilldown 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.

### Load Loss due to Ground System Equipment Chill-down

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. $LH_2$ loading uses the pressure transfer method, while $LO_2$ loading uses the pump transfer method. Thus, hydrogen pressurization phase lasts until $LH_2$ ground storage tank reaches sufficient pressure to transfer the $LH_2$ to the ET, while the oxygen pressurization phase of the $LO_2$ ground storage tank lasts until sufficient pressure is achieved to provide the net positive suction head required by the $LO_2$ pump. After the pressurization phase, $LH_2$ 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 $LH_2$ temperatures. Likewise, after the oxygen pressurization phase, $LO_2$ flows into the $LO_2$ pump until it is cooled to $LO_2$ temperatures; thereafter the $LO_2$ 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 $LO_2$ temperatures. The total loss during system chill-down is approximately 45,000 liters and 95,000 liters for $LH_2$ and $LO_2$, respectively.

### Load Loss During Filling External Tank

After system chill-down is completed, $LH_2$ and $LO_2$ 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 73,000 liter level and 11,000 liter level for $LH_2$ and $LO_2$, respectively, followed by the fast fill phase, which loads the ET to 1,420,000 liter level and 525,000 liter level for $LH_2$ and $LO_2$, respectively. Finally the topping phase completes the loading flight level. Slow fill, fast fill, and topping occur in about 150 minutes and 135 minutes for $LH_2$ and $LO_2$, respectively. Approximately 65,000 liters of $LH_2$ and 95,000 liters of $LO_2$ are lost during the filling of the ET.

### Load Loss During Stable Replenishment

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 450 liters of $LH_2$ and 475 liters of $LO_2$ 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 is terminated when a scrub is declared or within the final five minutes for a launch. The average total stable replenishment is approximately 185,000 liters and 190,000 liters for $LH_2$ and $LO_2$, respectively.

### Drainback Loss

In the event of a scrub, $LH_2$ and $LO_2$ are drained from the ET. The ground storage tanks are vented to ambient pressure to allow the $LH_2$ and $LO_2$ to drain from the ET to the ground storage tanks. During the drainback, the ET continues to receive ambient heat that vaporizes the $LH_2$ and $LO_2$ throughout the drainback period. Thus, most of the ET volume of $LH_2$ and $LO_2$ 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 76 of the 135 Space Shuttle missions, however, there were 236 loadings due to tanking tests, Flight Readiness Firings, and multiple scrubs for some Space Shuttle missions.

## QUANTITY ONBOARD

The quantity of $LH_2$ and $LO_2$ in the ET at launch is 1,450,000 liters and 534,000 liters, respectively. The Quantity Onboard is per launch with a total of 135 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.

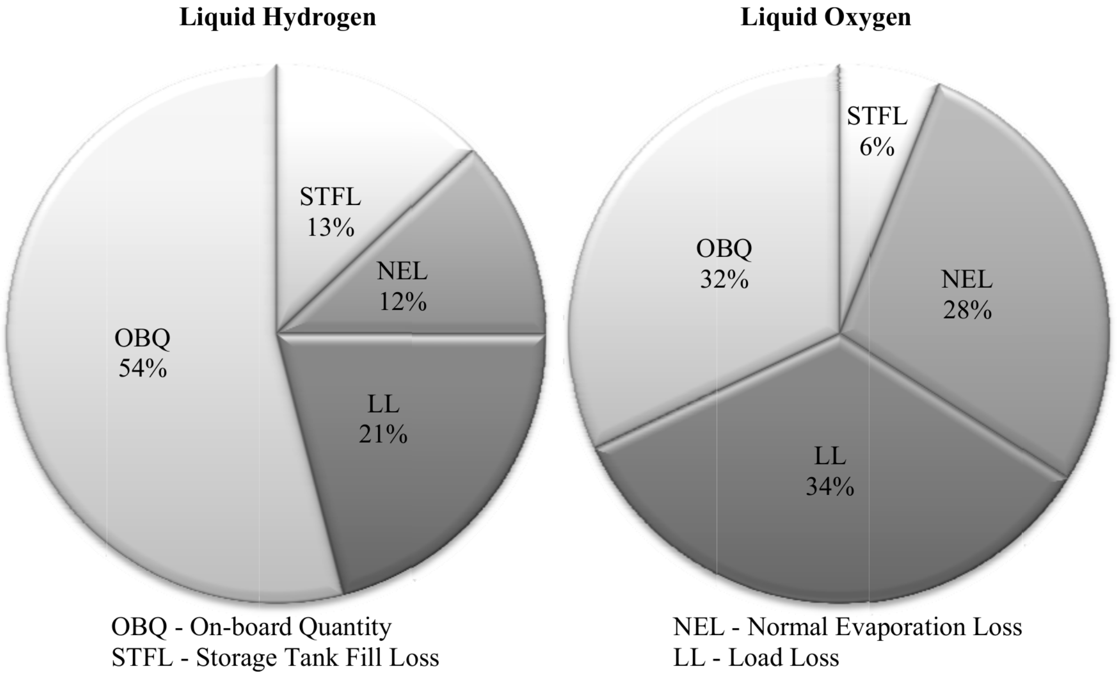

**Figure 2**: Fraction of Total Cryogenic Propellant Purchased Over 30-Year Space Shuttle Program

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