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Helium Conservation by Diffusion Limited Purging of Liquid Hydrogen Tanks

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June 2024

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Nomenclature

CS	Core Stage
ET	External Tank
FOM	Figure of Merit
GHe	Gaseous Helium
GMT	Greenwich Mean Time
GN_2	Gaseous Nitrogen
He	Helium
KSC	Kennedy Space Center
LH_2	Liquid Hydrogen
ppm	Parts Per Million
psia	Pounds per square inch absolute
psig	Pounds per square inch gauge
scf	Standard Cubic Feet
scfm	Standard Cubic Feet Per Minute
scmm	Standard Cubic Meters Per Minute
SLS	Space Launch System
SSP	Space Shuttle Program
STP	Standard Temperature and Pressure
VAB	Vehicle Assembly Building

Abstract

Recently, the new 1.2-million-gallon liquid hydrogen (LH_2) storage tank at the Kennedy Space Center Launch Complex 39 was purged, replacing nitrogen with helium, using a piston purge process. This purging approach had been used on Space Shuttle External Tanks (ET) in the past, but not on one of the large LH_2 tanks. The result was a huge success, potentially saving more than 1 million cubic feet of helium and significant labor. To better understand this result, a diffusion-based purge model was developed. The model predictions accurately match the helium concentration data, providing understanding of the helium savings and suggesting how to better optimize the purging of this large tank for future operations. The model was then applied to the piston purging of the Space Shuttle ETs, showing that these purges were not optimal, but that the amount of wasted helium was not excessive and that additional helium might have been saved by small changes to the process. The Space Shuttle Program (SSP) has ended, but these results are applicable to the purging of future large cylindrical LH_2 tanks. Finally, data have been obtained on inerting the Space Launch System (SLS) Core Stage (CS) LH_2 tank, replacing hydrogen with helium after an aborted launch. This is a more complicated case, but the model predicts that substantial helium might be saved by modifying the current purging process.

1.0 Introduction

Large amounts of helium are used to purge and pressurize aerospace LH_2 tanks and transfer lines. Practically all the helium used for this purpose is discarded into the atmosphere, where it eventually ends up escaping into space. This wasteful process is exacerbated not only by the finite supply of helium [1, 2], but also the recent sale of the Federal Helium Reserve [3]. Government purchases of helium through the Federal In-Kind Program ended in 2022 [4], likely raising the price of this commodity to support future NASA spaceflight programs. In 2022, the official US estimated price for Grade A helium was $310 per thousand standard cubic feet (scf), but the price in the private market was $500 per thousand scf. Helium recovery is, at present, an unlikely option, in part because during the Apollo Program, Air Products evaluated a possible helium recovery system [5] and showed that the cost exceeded the savings. There was a large-scale helium recovery system studied under a small business innovative research project using membrane electrode assemblies [15], but this ended in 2015 with no apparent follow-on effort. More promising is an operational helium recovery system developed by Airgas [16] in support of the SLS, but this was a custom system and few details have been published. So, a more immediate route to saving helium is to examine the purging processes and attempt to optimize them [6, 7].

When new LH_2 tanks are turned over by the manufacturer, they are often slightly pressurized with dry nitrogen to minimize water vapor and other atmospheric intrusion. This nitrogen must be replaced with helium before introducing LH_2 to prevent the creation of frozen nitrogen. The two primary cases presented in this report fall into this category, where helium is used to purge nitrogen, are the new LH_2 storage tank at the Kennedy Space Center's (KSC) Launch Complex 39 [8] and the ETs [13] used by the SSP. When these tanks were purged with helium, consideration was given to saving helium by introducing the helium at the top of the tank and extracting the nitrogen from the bottom. Both purging operations were successful in saving helium, as will be quantified by comparing them to an idealized, diffusion limited, purging process.

A very different purge process occurs when a LH_2 flight-weight tank is in use and must be drained and then purged with helium to inert the tank. Recent examples of this occurred when the SLS experienced two launch aborts, one on August 29, 2022, and one on September 3, 2022, before achieving a successful launch on November 16, 2022 [14]. After each launch abort, the LH_2 in the CS of the vehicle was removed using pressurized helium, leaving behind a mixture of gaseous helium and hydrogen. Later, this mixture was purged using helium to achieve safe, non-flammable levels of hydrogen. This inerting process was not designed to save helium, but in this report, the potential helium savings achievable with an optimal diffusion limited purge are shown.

2.0 The New LH_2 Storage Tank

In the 1960s two 850,000-gallon[1] LH_2 tanks were constructed, one at each pad at the KSC Launch Complex 39, to support the Apollo Program. Figure 1 shows one of the tanks. These tanks consist of an inner sphere that holds the LH_2 and an outer sphere, providing a gap filled with insulation and evacuated to minimize boil-off. These Apollo era tanks were designed with a large connection port to enable the evacuation of the inner sphere by attaching a large vacuum pump. Figure 2 shows the Pad A tank during construction in 1965 with the inner sphere and the lower half of the outer sphere completed. These tanks supported the SSP and are now being used to support other launch programs, such as SLS.

Figure 1. Image of one of the 850,000-gallon LH_2 tanks used to support the Apollo and Space Shuttle Programs.

[1] English units are used in most of this report to be consistent with the data and the needs of operational personnel; metric units are used in the modeling sections.

Figure 2. Construction photo of the Pad A LH_2 tank (1965) showing the completed inner sphere and the lower half of the outer sphere.

There have been two relatively recent nitrogen purges of 850,000-gallon LH_2 storage tanks, one in 1985 and one in 2015. In each of these cases the inner sphere was pumped down to remove the nitrogen and then helium was used to backfill the volume and increase the pressure to 20 pounds per square inch absolute (psia). This evacuation/backfill method is the optimum method for converting a tank to a 99.9+% gaseous helium (GHe) requiring just one volume of GHe to accomplish the task *if the system is designed properly to accommodate the vacuum pumping.* However, due to very stringent residual gas criteria, these purges required multiple cycles of evacuation and refilling the tanks, using more than 1 million scf (almost 9 times the tank volume at standard temperature and pressure (STP)) and 14 days for the 1985 case and 45 days for the 2015 case. If the nitrogen purge levels used in the new LH_2 tank had been applied to the previous purges, then only one cycle would have been needed. Single-wall tanks like the Shuttle ET or SLS/Artemis CS are not designed for negative atmospheric pressures so other means of converting to a GHe background are required.

A new, 1.2-million-gallon, vacuum insulated, LH_2 storage tank has been constructed at KSC's Launch Complex 39 to support the SLS vehicle. Unfortunately, this new tank was not designed with a vacuum connection port to the inner sphere, so in September of 2023, the nitrogen left in the inner sphere by the manufacturer was purged with helium using a different process. The original plan was to convert the tank to GHe by the pulse purge process, pressurizing the volume to 30 psia, venting back to atmospheric pressure and repeating until the gaseous nitrogen (GN_2) concentration was less than 0.1% (1000 ppm). This would have taken roughly 10 volume exchanges to achieve so the use of 2 million cubic feet of helium was planned. The engineers at KSC decided to try a different approach to conserve as much helium as possible based on helium conservation testing performed near the end of the SSP (that testing is described in Section 3.0 of this TM). This alternative purging approach, called flow-through purging or piston purging, introduces helium at the top of the vessel and pushes the heavier nitrogen and other gases out of the bottom. Because of the large size difference between the Shuttle ET and this sphere and the large difference in purge flow rates involved, there was concern that this new storage tank purging process would not happen quickly enough, and that significant diffusive mixing of the helium and nitrogen would occur. However, the piston purge process proved very effective, with the nitrogen and residual humidity being removed in 44 hours and only using 409,000 scf of helium (roughly 2.2 times the dry tank volume), a huge savings in helium and manpower.

In addition, this purge used a speed-of-sound binary gas sensor, capable of monitoring the nitrogen-to-helium ratio in the tank drain line, instead of drawing gas samples and waiting for lab tests to determine the purge state. Having real-time data not only allowed the support personnel to schedule their activities, but it also provided data that can lead to a better understanding of the purge process. A mass spectrometer was used to confirm the maximal allowable nitrogen level had been reached, but unfortunately, the temperature of the exhaust gas was not measured.

The measured helium concentration being discharged from the bottom of the tank during purging is shown in Figure 3. Using a piston purging process saved as much as 1.6 million scf of helium when compared to the prior pulse purging approach. But can this be improved upon further? To what degree is turbulent mixing affecting the purge? If the helium flow rate were changed, would it substantially reduce the amount of helium required? Would changing the temperature of the gases save helium? In the next section a diffusion-limited model of the tank purge is developed, allowing insight into the answers to these questions.

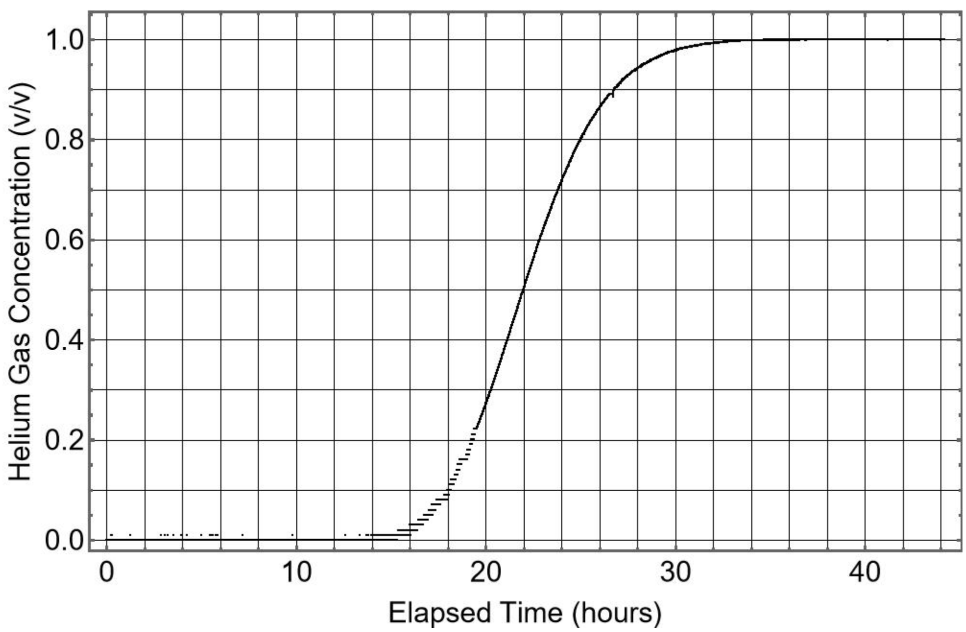

Figure 3. Helium concentration in the LH_2 tank during the new purging process.

2.1 Diffusion Limited Model of the LH_2 Tank Purge

This subsection describes the tank details and assumptions that were made to develop the diffusion-limited purge model. In the next two subsections metric units are occasionally used to allow comparison to the diffusion literature.

2.1.1 Configuration and Assumptions

In setting up this model, the following assumptions are made:

1. LH_2 pad operations personnel estimated the tank pressure at 0.75 pounds per square inch gauge (psig). So, assume that the helium and nitrogen are at an absolute pressure of 1.05 atmospheres.

2. The inner tank is spherical with an inner radius, *R*, of 35.5 feet (10.82 meters) yielding a total volume of 187,000 cubic feet (1,400,000 gallons). This is larger than the advertised storage capacity of 1.25 million gallons, which includes ullage space and accounts for contraction of the tank.

3. The helium is loaded into the tank through a long pipe that travels through the insulation gap between the inner and outer tank, as sketched in Figure 4. This pipe ends on an 8-foot-radius diffusing ring (also called the helium injection ring), containing 77 2-inch-diameter upward-facing holes, located at the top of the tank. The holes are located approximately 2.5 feet vertically below the very top of the tank. When helium first enters the tank, it will mix with the nitrogen in the volume above the holes, but this mixing will not be complete. Streamlines of rising helium will contact the nitrogen only along their edges, allowing some fraction to reach the top and pool there without mixing with the nitrogen. The volume of this region is about 680 cubic feet, less than 0.4% of the tank volume. If 50% mixing is assumed, then there is a nearly negligible boundary of about 340 cubic feet of mixed nitrogen and helium generated when the purge is first established.

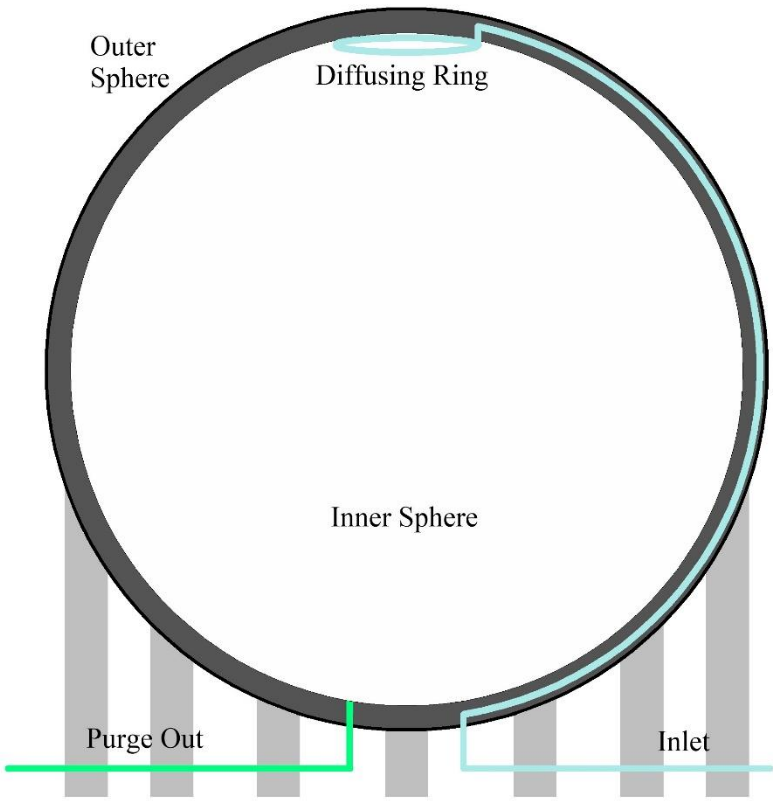

Figure 4. Sketch of the LH_2 tank showing the entry and exit locations for the purge.

4. Flow rates of helium vary from 130 standard cubic feet per minute (scfm) to 170 scfm with lower rates during the first half of the purging process. The model used an averaged, constant flow rate of 150 scfm (4.25 standard cubic meters per minute (scmm)).

5. It is assumed that only nitrogen and helium are present, ignoring the minor constituents as unimportant to the diffusion calculation. Making this assumption, the concentration of helium, ϕ_{He}, in units of fractional total volume, plus the concentration of nitrogen, ϕ_N, in units of fractional total volume, is always equal to 1, i.e., $\phi_{He} + \phi_N = 1$.

6. It is assumed that the concentration of helium and nitrogen in the tank are only functions of the height in the tank and time, but not transverse distance. This is reasonable once stratification in the top of the tank has occurred, evening out any transverse variations caused by the hole pattern along the fill ring. Height is referenced with the variable, z, with $z = 0$ at the bottom of the tank and let the variable t be time. Use the functions $\phi_{He}(t, z)$ and $\phi_N(t, z)$ to represent the concentration versus time and height in the tank. The goal of the model is to predict these functions at the bottom of the tank versus time, i.e., $\phi_{He}(t, 0)$ and $\phi_N(t, 0)$, and compare these to the measured data.

7. From the Chapman-Enskog theory using a Lennard-Jones potential, the value of the diffusion coefficient, D, at 300 K and one atmosphere pressure was calculated as 0.706 cm^2/sec, reference Higgins [9]. To verify this a literature search was conducted. Wasik and McCullah [11] found a value of 0.678 cm^2/sec at 296 K and Ellis and Holson [10] obtained a value of 0.707 cm^2/sec at 297 K.

   In considering the September 2023 purge data, it was found that there was significantly less mixing than predicted using a diffusion coefficient between helium and nitrogen of 0.706 cm^2/sec. The only ways to explain this are to either assume a higher flow rate of helium, a higher pressure, or a low temperature of the gas in the tank. Since flow rate and pressure were measured, it indicates that the nitrogen in the tank may have been cold. Upon further discussion, it was discovered that the tank was held at 8 psig for some time prior to the purge. Then, shortly before bringing in the helium, 12 to 16 hours were spent dropping the pressure of the nitrogen to 0.75 psig. This is a 33% drop in absolute pressure and from the ideal gas law would correspond to a 33% drop in temperature (i.e., from 300 K to about 200 K). The steel walls would supply some heat back to the nitrogen, preventing it from chilling to 200 K. However, this does indicate that the nitrogen was colder than ambient. Choosing a temperature where the model best fits the data yields, 263 K, and a corresponding diffusion coefficient at that temperature of 0.54 cm^2/sec [9]. The thickness of the inner tank walls and the time gap between dropping the pressure and starting the helium flow are not known, so higher fidelity cannot be added to this temperature.

8. The spherical shape of the tank is accounted for by varying the velocity at which the gases are flowing downward to account for the changing diameter. This is described in more detail in the analytical model subsection.

2.2 Analytical Model

In this section, the analytical model is developed. The diffusion equation is given by:

$$\frac{\partial \phi_{He}}{\partial t} = D\frac{\partial^2 \phi_{He}}{\partial z^2}. \tag{1}$$

Boundary conditions are required to solve this differential equation and they are listed below:

1. For all time the helium concentration is set to one at the helium injection ring. The helium injection ring is near the top of the tank at a height of 20.88 m above the tank bottom, i.e.,

   $$\phi_{He}(t, 20.88\,\mathrm{m}) = 1 \tag{2}$$

   Doing this excludes about 23 cubic meters from the tank volume.

2. No diffusion occurs across the bottom shell of the tank, which is equivalent to the Neumann boundary condition where the spatial derivative is assumed to be zero. In order to resolve issues near the bottom of the tank this boundary condition is set to 0.5 m above the bottom, so that

$$\frac{\partial \phi_{He}}{\partial z}(t, 0.5\,\mathrm{m}) = 0 \tag{3}$$

3. The final boundary condition describes the starting situation. At $t = 0$ it is assumed the tank is filled with nitrogen everywhere, except at heights above 20.88 m. Therefore

$$\phi_{He}(t = 0, 0 \leq z < 20.88\,\mathrm{m}) = 0 \tag{4}$$

These boundary conditions allow the diffusion equation 1 to be solved but correspond to finding the solution with no incoming helium flow. To account for the helium flow and the shape of the tank, an iterative modeling approach is used consisting of two steps:

1. Calculate the diffusion model for a discrete time period that is relatively short compared to the convective flow of gases into the tank. For example, if the flow rate were 4.25 scmm, then at the injection ring, where the radius of the tank is 4 meters (area of 51.2 square meters), the gases would move down about 0.4 meters after a 5-minute period, which is small compared to the size of the tank (≈ 2%). Therefore, 5 minutes (300 seconds) was chosen as a reasonable time step. This discretization introduces some error into the calculations, in that the downward motion of the gas is ignored for this short time period, but it is considered an acceptable compromise between resolution and model computation run time.
2. After calculating the diffusion that occurs over the chosen time period, shift the concentration function downward to account for the gas flow and the tank shape. Again, assuming 5 minutes and a gas flow rate of 4.25 scmms, 21.25 cubic meters of gas has entered the tank and an equal amount has left the tank. The cross-sectional area of the tank, $A(z)$, as a function of height z is given by

   $$A(z) = \mathrm{Abs}\left(\pi z(2R - z)\right) \tag{5}$$

   which is used to shift the concentration function downward by a distance equal to the incoming gas volume divided by the cross-sectional area, i.e.,

   $$\phi_{He}(t, z) \to \phi_{He}\Big(t, z - \frac{21.25\mathrm{m}^3}{\mathrm{Abs}\left(\pi z(2R - z)\right)}\Big) \tag{6}$$

   where $R = 10.82$ meters. Next, this shifted helium concentration is used in step one as the new starting condition and then iterated through the two steps. This continues until the helium concentration at the bottom of the tank is sufficiently small (500 ppm was used in the results presented later in this report.).

2.3 Modeling Results

Figure 5 shows the measured helium concentration at the bottom of the tank during the purge transition and the predicted helium concentration using the model. The two match extremely well indicating that the mixing between the two gases is due to diffusion with minimal turbulent mixing.

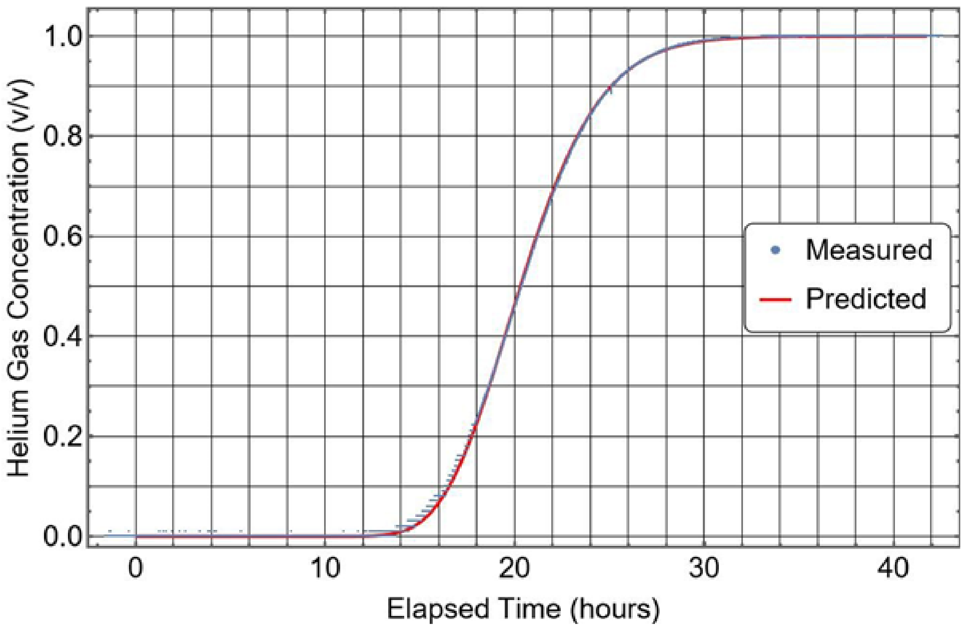

Figure 5. Measured and predicted helium concentrations at the exhaust of the tank assuming a GN_2 temperature of 263 K.

Note that the time when the helium concentration and the nitrogen concentration at the bottom of the tank are equal is independent of the diffusion coefficient. This 50/50 boundary starts at the top of the tank and migrates downward as the tank is filled but is not shifted by the diffusion since any nitrogen that moves into the helium regime is balanced by helium moving into the nitrogen-dominated region. The 50/50 boundary reaches the bottom of the tank at 20.33 hours, which corresponds to the time it would take to fill the tank if there were no diffusion. Checking this, 150 scfm flowing for 20.33 hours is 183,000 scf. The tank volume is 187000 scf, subtracting off the top and bottom segments ignored by the model yields a total that is low by 2%, likely a result of error accumulation from using the 5-minute step size. From the model, the nitrogen concentration reaches 500 ppm (0.05%) at 35.33 hours. Therefore, 15 hours of additional helium flow are required to account for diffusion during this purge process; totaling 135,000 scf of helium lost due to diffusion.

Figure 6 shows the helium gas concentration prediction if the nitrogen in the tank were at a temperature of 300 K and the measured concentration. The mismatch between the two led to the reconsideration of the tank temperature mentioned earlier.

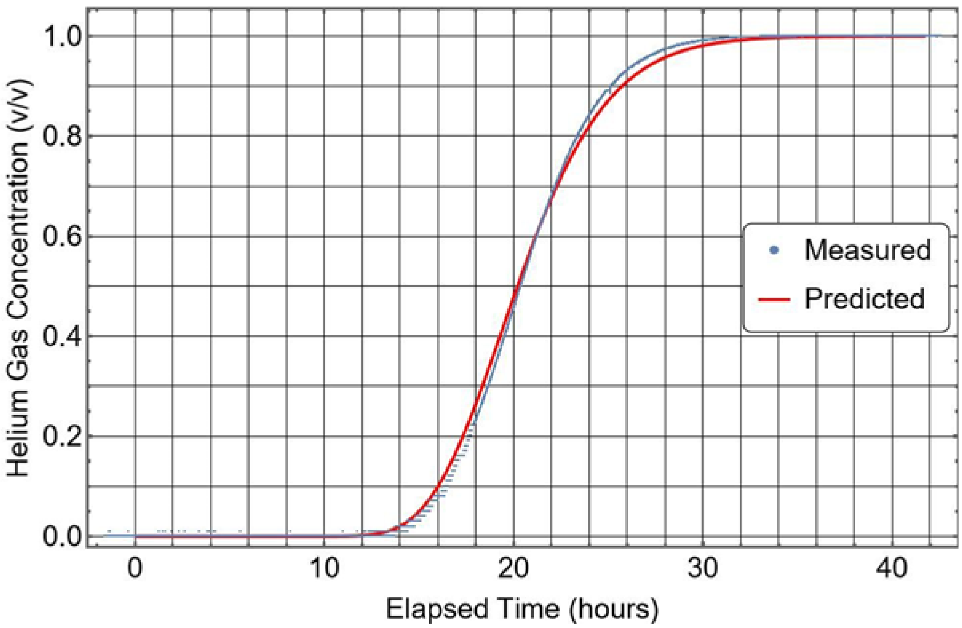

Figure 6. Helium concentration prediction at the tank bottom assuming the GN_2 is at 300 K compared to the measured data.

The model predicts that if the nitrogen were at 300 K, then the nitrogen concentration reaches 500 ppm at about 38 hours. This is 2.7 hours more than for the 263 K temperature, corresponding to about 24,000 additional standard cubic feet of helium. One might conclude from this that purging at lower temperature saves helium; however, the savings are not significant if the tank is purged cold and then allowed to warm back up to ambient. The helium in a tank at 263 K will expand as the tank warms up to 300 K, causing the excess to be vented to the atmosphere. This excess helium corresponds to about 26,000 standard cubic feet, about the same as was saved by purging at the lower temperature. Further complicating this, even if the tank were cold, the incoming helium enters the tank at ambient and, since it is not mixing with the nitrogen except at the interface, likely stays warmer than the nitrogen during the purge. Consequently, more analysis and measurement data are needed to determine if helium could be saved by purging at lower temperatures.

A preferable way to save helium is to increase the flow rate into the tank, up to the point where turbulent mixing becomes a problem (see Section 3.0 for an example of this). Figure 7 shows the helium concentrations for higher flow rates; 2 times (red), 3 times (green), and 4 times (blue) than used during the actual purge process. All the flow rate calculations shown here assume a temperature of 263 K to be consistent with the actual purge, but the general conclusions apply to other temperatures. As the flow rates are increased the tank fills more quickly and the effect of diffusion is diminished, saving helium. Table 1 summarizes the time to 50/50 (i.e., the time to fill the tank assuming no diffusion), the time needed to reach 500 ppm, the extra helium used for each flow rate, and the number of tank volumes of helium used as a figure of merit (FOM).

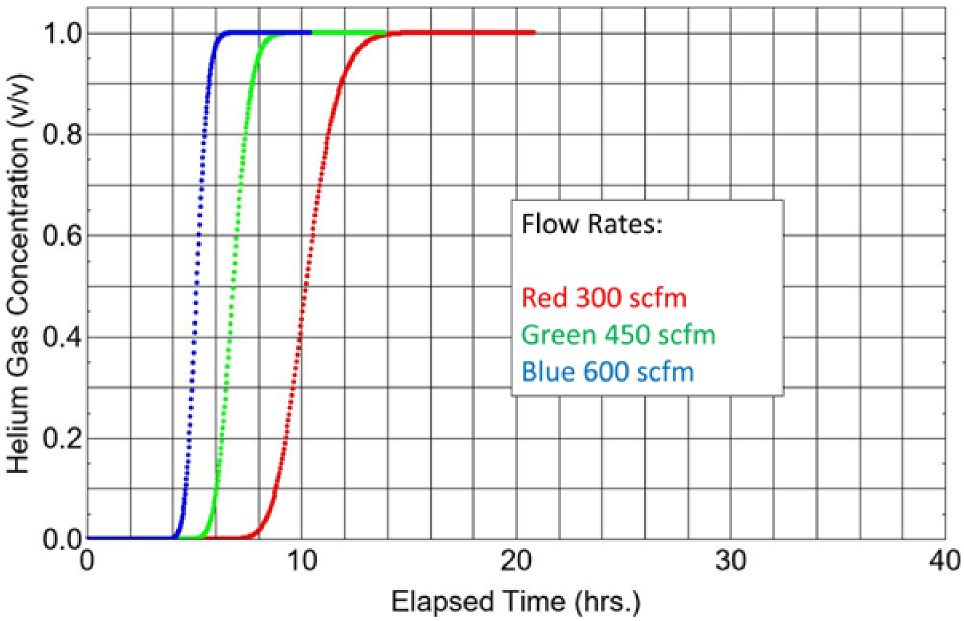

Figure 7. Predicted helium concentrations at the bottom of the tank for higher flow rates, 2 times, 3 times, and 4 times than used during the actual purge.

Table 1. Predicted time periods and extra helium usage for higher flow rates than used in the actual purge.

Flow Rate (scfm)	time to 50/50 (hours)	time to 500 ppm (hours)	extra helium used (scf)	Tank volumes (FOM)
150	20.33	35.33	135000	1.72
300	10.25	15.13	88000	1.47
450	6.85	9.42	70000	1.37
600	5.12	6.77	60000	1.32

Figure 8 shows the helium concentrations for lower flow rates; 106 scfm, 53 scfm, and 35 scfm, than that used during the actual purge process. As the flow rates are reduced the tank fills more slowly, and the effect of diffusion is increased, resulting in the use of more helium. Table 2 summarizes the time to 50/50 (i.e., the time to fill the tank assuming no diffusion), the time needed to reach 500 ppm, the extra helium used for each flow rate, and the number of tank volumes of helium used as a FOM.

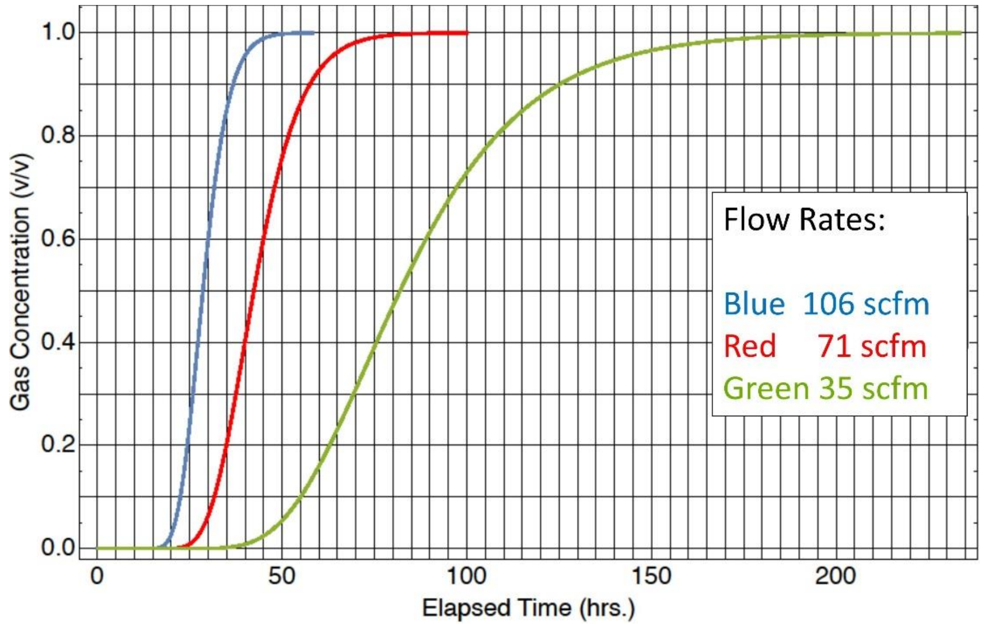

Figure 8. Predicted helium concentrations at the bottom of the tank for lower flow rates, 106 scfm, 71 sfcm, and 35 scfm.

Table 2. Predicted time periods and extra helium usage for lower flow rates than used in the actual purge.

Flow Rate (scfm)	time to 50/50 (hours)	time to 500 ppm (hours)	extra helium used (scf)	Tank Volume (FOM)
150	20.33	35.33	135000	1.72
106	28.6	55.13	169000	1.90
71	42.3	94.17	220000	2.18
35	82	243.3	342000	2.83

An approximate analytical fit of the extra helium required versus flow rate, using both the lower and higher fill results, is given by Equation 7 and is plotted in Figure 9.

$$\text{excess helium(scf)} = \frac{3.02\text{x}10^6}{(\text{flowrate(scfm)} - 0.4(\text{scfm}))^{0.617}} \tag{7}$$

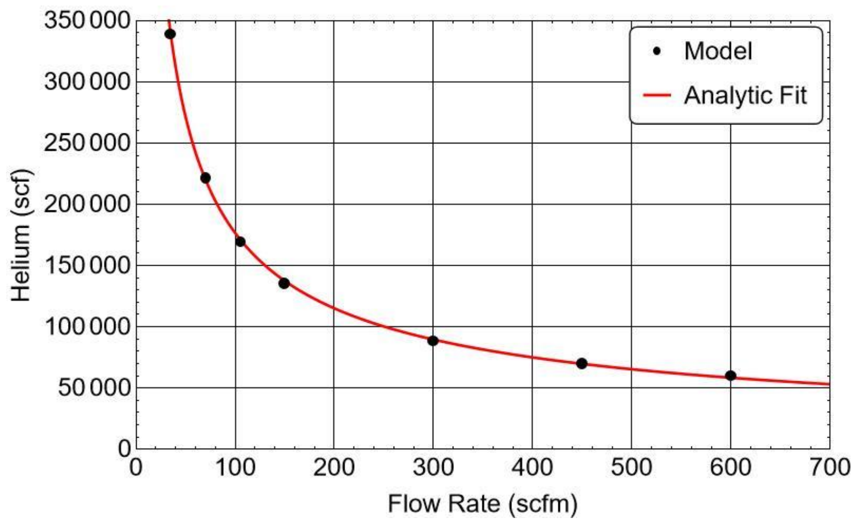

Figure 9. Additional helium used to overcome diffusion versus flow rate, model results and analytic fit given by Equation 7.

For flow rates approaching 0.4 scfm, this expression predicts that infinite helium will be required to achieve the purge, which is not physical. However, at very low fill rates the nitrogen will diffuse upward into the helium at a rate similar to the movement of the gases downward, causing the purge to take a very long time and resulting in immense helium usage.

It was requested by a representative of KSC ground operations that the model predict the helium concentration in the tank versus height if the purge process had to be stopped before completion and not resumed for some time-period. Figure 10 shows the results of this analysis. The blue plot shows the predicted helium concentration in the tank when the 50/50 helium-to-nitrogen ratio is at the halfway height location in the tank, using a temperature of 263 K and a flow rate of 150 scfm. Assuming the purge stops that this time, the three other plots show the helium concentration in the tank after 24 hours (green), 4 days (orange) and 16 days (red). After only 24 hours of delay nitrogen has diffused to the top of the tank at a concentration greater than 1,000 ppm (0.001 volume ratio), indicating that a substantial amount of helium, approximately the volume of the tank, will be needed to reach the 500-ppm purge criteria.

The diffusion modeling has shown that using piston purging on the new LH_2 tank resulted in diffusion limited purging with no measurable turbulent mixing. However, the modeling does indicate that an additional 47000 scf of helium could have been saved by doubling the flow rate, reducing the diffusion time between the two gases. Higher flow rates provide less savings and may introduce turbulent mixing. The model also indicates, in agreement with common sense, that once the purge starts it should not be stopped. Delays allow diffusive mixing, potentially requiring significant additional helium to complete the purge.

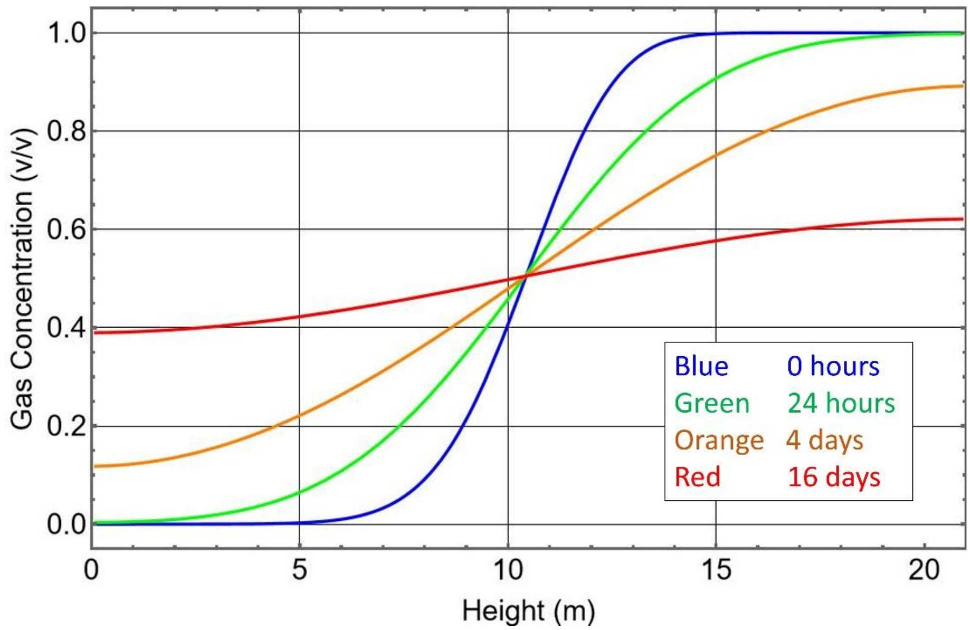

Figure 10. Helium concentration in the tank versus height from the bottom assuming the flow is stopped for the time shown after the tank has been partially purged.

3.0 The Space Shuttle Program External Tank

The Michoud Assembly Facility [12] fabricated the Space Shuttle ETs [13], delivering them to the KSC filled with nitrogen. At KSC, the tanks were stored in the Vehicle Assembly Building (VAB) until used in the assembly of the Space Shuttle. Figure 11 shows ET-124 being lifted in the VAB. Each ET contains a hydrogen tank and an oxygen tank. The ET hydrogen tank, like the Pad LH_2 storage tanks, must have a purge transition, replacing the nitrogen with helium, before introducing LH_2. In 2008 during the purge of several ET LH_2 tanks, the exit gases were monitored, gathering information that might eventually be used to improve the process.

Monitoring of the purge was done by positioning a sample tube just outside of the exit port (the 17-inch disconnect) of the ET LH_2 tank. This tube ran to a calibrated mass spectrometer that monitored helium and nitrogen, as well as oxygen and argon. Several tank purges were measured (ET-127, ET-128, and ET-129 are presented here), yielding observations and suggestions to help conserve helium, such as using a continuous monitor instead of taking samples and waiting for lab results to determine the gas concentrations in the tank. However, the data were not studied to determine the degree of turbulent versus diffusive mixing, which might provide additional insight into improving the process.

The diffusion model for the ET hydrogen tank is like the one described above with a few changes. The temperature is assumed to be 300 K, so a diffusion coefficient between helium and nitrogen of 0.706 cm^2/sec is used. The ET LH_2 tank is modeled as a cylinder with a flat top and flat bottom, ignoring the curved domes in the actual tank, but yielding the same volume as the actual tank. The tank inner radius is 4.2 meters and the effective height is 27 meters, yielding a volume of 53,000 ft^3 (1500 m^3). Helium enters the tank through a diffuser at the top of the tank at an approximate flow rate of 3,000 scfm (this varies and will be adjusted to fit the data for each purge). There are other gases present in relatively small amounts (e.g., it is estimated that the ET LH_2 tank arrives at KSC with about 10% air mixed with the nitrogen based on argon concentrations), as seen by the mass spectrometer, but for the model it is assumed that only nitrogen and helium are present. The boundary conditions are the same as for the LH_2 storage tank; helium at the top, nitrogen throughout at the start of the purge, and no diffusion across the bottom of the tank. Finally, the time step used for the iterations in the model is decreased to 10 seconds due to the high flow rate used in in these purges.

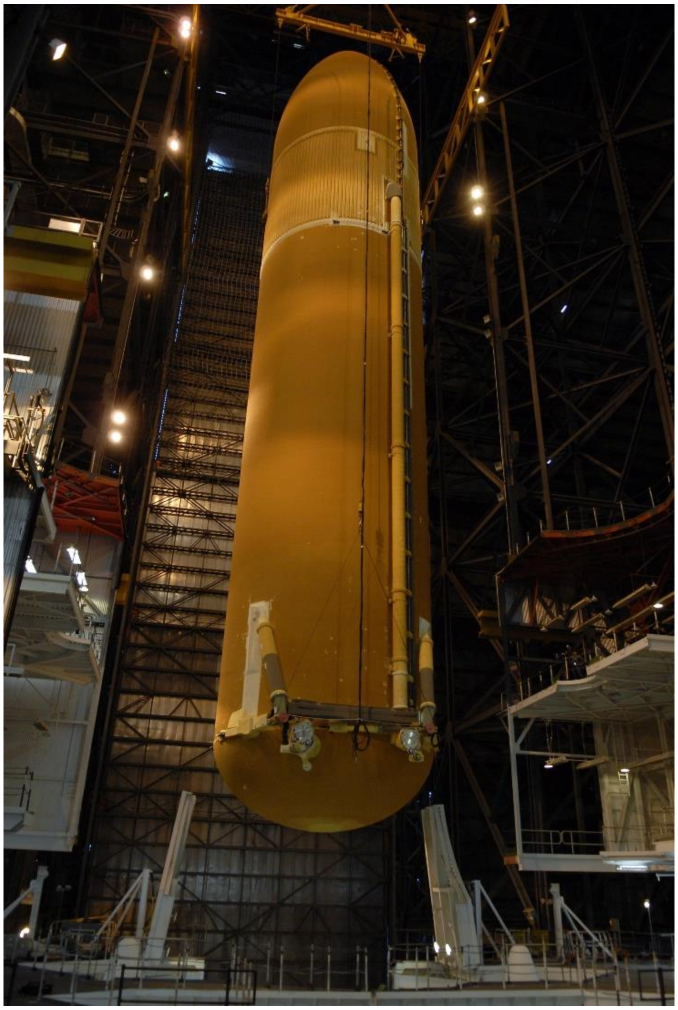

Figure 11. ET-124 being lifted in the KSC vehicle assembly building. (source Wikipedia, public domain, no copyright)

The model predictions are shown with the measured data in Figure 12, Figure 13, and Figure 14, corresponding to ET-127, ET-128, and ET-129. The respective flow rates, obtained by fitting to the data, are 2970 scfm, 2950 scfm, and 3050 scfm. Before the start of the purge, the 17-inch disconnect is opened at the bottom of the tank, allowing air to enter the tank, which is seen in the data as a reduced nitrogen measurement. As the purge commences, the air is displaced and replaced with the downward propagating nitrogen. Then, at about 19 minutes, there is a sudden transition from nearly 100% nitrogen to a 50/50 mixture of nitrogen and helium that matches the diffusion model. But after that the mixture does not follow the model, showing a slower transition to all helium. It is conjectured that the high flow rates cause turbulent mixing of the helium with the nitrogen at the top of the tank. This mixture pushes the nitrogen downward leaving a transition or boundary layer between the helium/nitrogen mix and the nearly pure nitrogen that mixes through diffusion. However, the helium/nitrogen mix continues to mix with the helium entering the tank displacing nitrogen upward, resulting in the slow displacement of the remaining nitrogen.

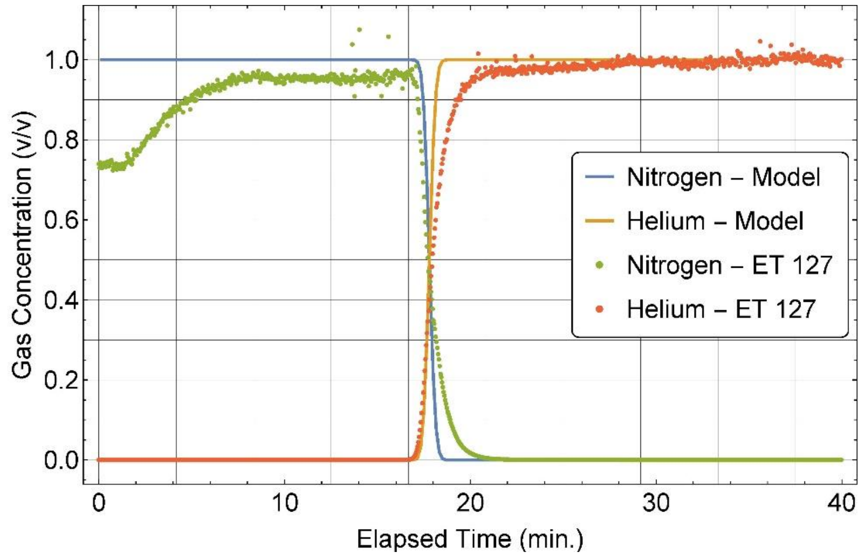

Figure 12. Prediction and measurement for the purge of ET127.

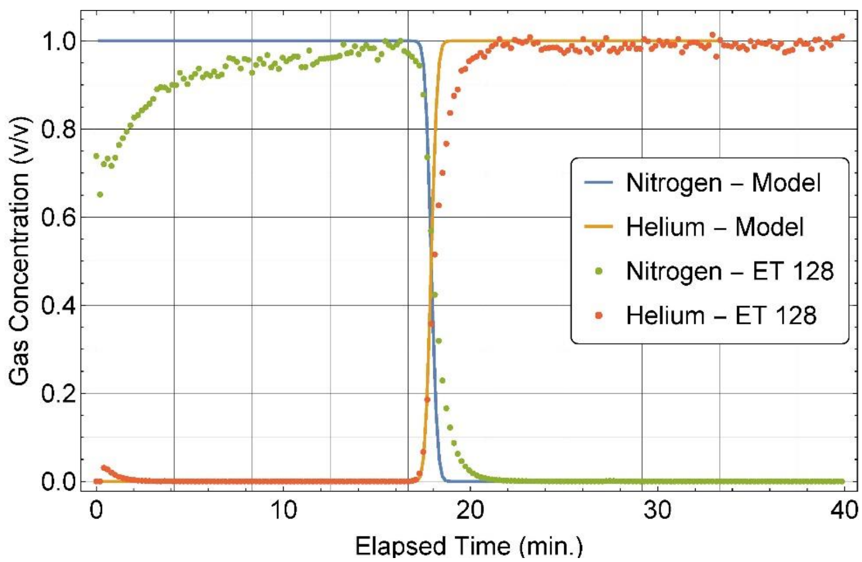

Figure 13. Prediction and measurement for the purge of ET128.

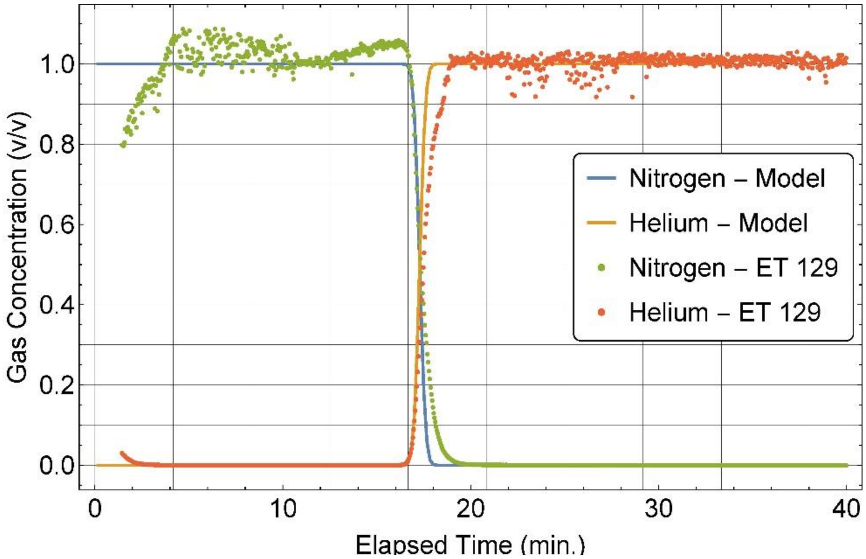

Figure 14. Prediction and measurement for the purge of ET129.

The conclusion, based on the modeling, is that the helium flow rate should be reduced to minimize turbulent mixing. However, in practice, the ET purge was limited by moisture removal, requiring the helium purge to run for up to 60 minutes to reduce the dew point in the tank. The 2008 study suggested purge first with dry nitrogen to remove most of the moisture and the use warm helium to further help dry out the tank. It was also suggested that real time monitoring be added to help indicate when the purge was sufficient. Incorporating these suggestions and slowing down the helium flow rate would have resulted in significant helium savings.

4.0 The SLS Core Stage

The Artemis Program [14] plans to return humans to the Moon. The payloads for this program will be lifted using the SLS, a heavy-lift expendable launch vehicle. The CS, like the Space Shuttle ET, contains large liquid oxygen and LH_2 tanks, as well as the main engines, see Figure 15. The first successful launch of the SLS occurred on November 16, 2022, after scrubs on August 29 and September 3.

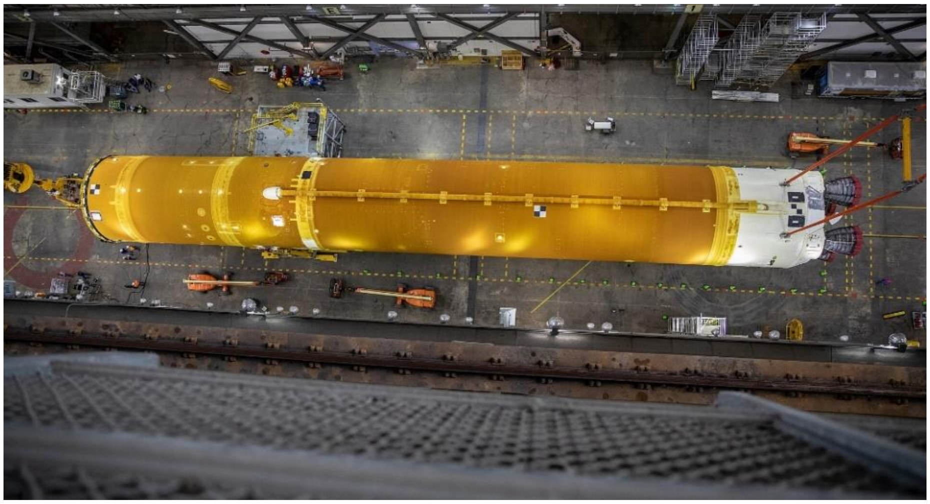
Figure 15. SLS CS in the VAB at KSC. (source Wikipedia, public domain, no copyright)

The August 29th scrub occurred at 13:40 Greenwich Mean Time (GMT) after which the LH_2 in the CS was drained. At 23:55 GMT the remaining gaseous hydrogen/helium mixture was purged using helium. The starting mixture was a combination of hydrogen and helium left over after the draining process. The helium flow rate was 7,263 scfm from the top of the tank and the volume of the tank is 73,077 cubic feet. The concentration of hydrogen was measured at the bottom of the tank intermittently during the flow through purge as seen in Figure 16. The purge operation after the draining of the liquid hydrogen used more than one half million cubic feet of helium.

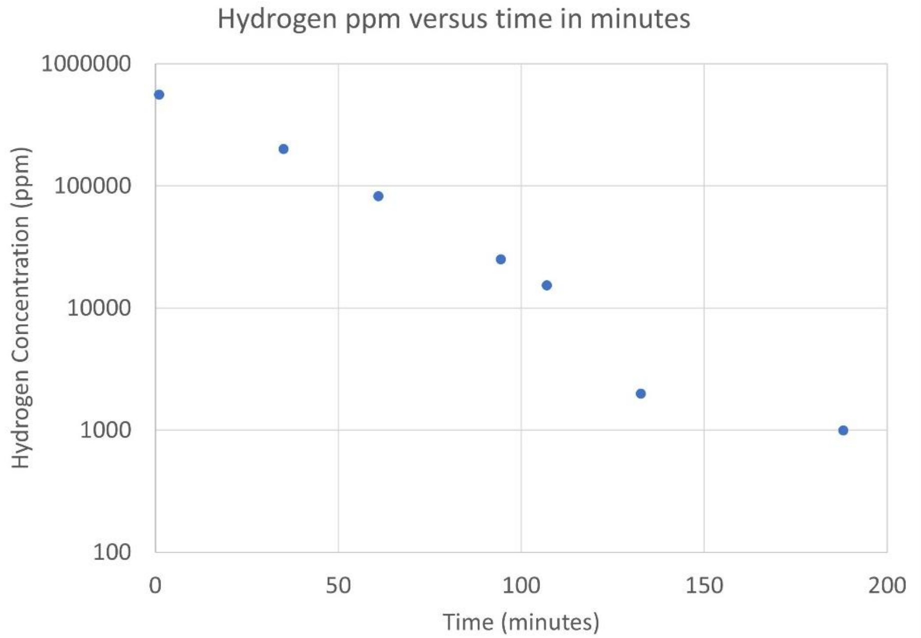

Figure 16. Hydrogen concentration data versus time for the inerting purge of the SLS CS hydrogen tank.

The piston purging operation described and modeled earlier in this memorandum with two gasses with different densities but essentially at the same temperature, does not lend itself to this situation where there are two gasses at very different temperatures during the purge process. The dominant buoyant gas switches during this tank inerting process; warm helium at the start of the purge and warm hydrogen near the end of the purge. As the warm helium gas is introduced at the top of the tank to help push the cold hydrogen out of the bottom, the helium is the most buoyant gas (by far). However, as the tank empties, the GHe introduced at the top begins to cool and the cold residual hydrogen gas begins to warm and rise.

After drain is complete, any GHe introduced at the top of the tank will gradually cool becoming the denser gas. As it falls it causes additional turbulent mixing as the residual hydrogen gas rises from below. This turbulent mixing makes any attempt to inert the tank very difficult and inherently inefficient.

Perhaps a more efficient approach to minimizing helium usage would be to introduce helium from the bottom of the tank. Injecting the warm helium at the bottom and venting the accumulating hydrogen gas from the top benefits from concentrating the gas-to-gas heat exchange process near the bottom of the tank and minimizes any turbulent mixing in the center section and above. This would allow for less mixing and a higher hydrogen concentration output from the top of the tank.

If the SLS CS would be allowed to reach thermal equilibrium after the drain operation (~24 to 48 hours after drain) then a piston purge could remove the hydrogen using far less helium. The SLS core LH_2 tank is 4.2 meters in radius and the effective height is 122.6 feet. The diffusion coefficient between helium and hydrogen is 1.596 cm^2/sec [9] at 300 K (more than twice that of nitrogen and helium). Assume the tank is initially filled with hydrogen and that helium is brought into the tank from the bottom (helium is denser than hydrogen). Running the model, with a time step of 5 seconds due to the high flow rate, shows that a diffusion-limited purge would have completed the transition in under 15 minutes; see Figure 17.

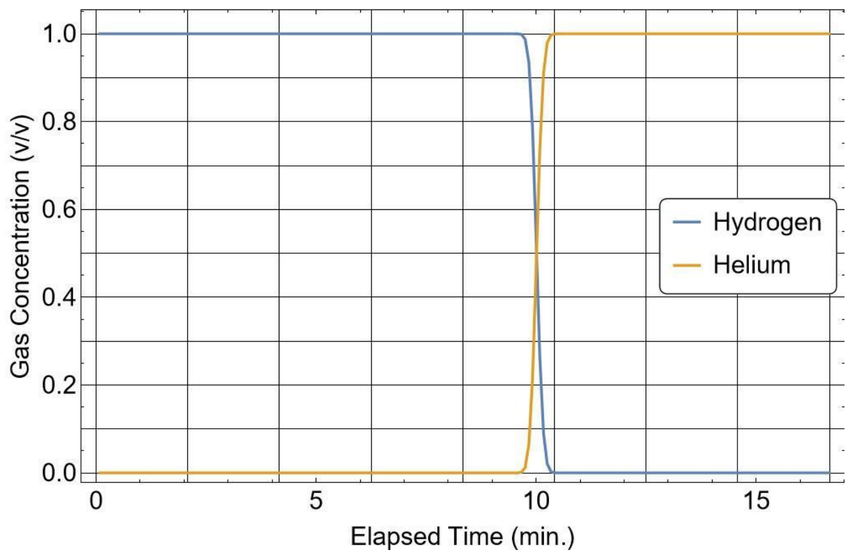

Figure 17. Hydrogen concentration versus time for the inerting purge of the SLS CS hydrogen tank assuming diffusion-limited piston purging.

Unfortunately, the ground system is not designed to provide the same high flow rate helium purge from the bottom of the tank as it has available from the top of the tank. Future work is required to study, optimize and implement a more efficient method of inerting the CS hydrogen tank after a launch scrub and drain. This new approach would need to balance the operational needs of the program and the desire of realizing significant cost savings and preserving a finite natural resource.

5.0 Conclusions

Helium is a limited supply, natural resource and is in high demand, especially from the medical community, but also from aerospace, both government and industry. The cost of this commodity will increase, forcing measures to either capture used helium, or to minimize waste more carefully. By modifying purge processes used in large LH_2 tanks diffusion limited mixing can be approached, leading to a minimal amount of helium usage. Piston purging, carefully loading helium at one end of a vertical tank, and pushing the unwanted gas out the other end, has been shown to be an effective approach for saving helium, especially when combined with real time monitoring of the gas concentrations. For each case there is an optimal helium flow rate, balancing between too slow leading to increased diffusion (e.g., the new KSC LH2 tank) and too fast causing turbulence (e.g., the Space Shuttle ETs). However, piston purging is gravity dominated and may not be effective if there are lines attached to the tank where gas cannot easily flow out (e.g., sense lines). Incorporating a pressure cycling purge process may be necessary in these cases.

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14. ABSTRACT
Recently, the new 1.2-million-gallon liquid hydrogen (LH2) storage tank at the Kennedy Space Center Launch Complex 39 was purged, replacing nitrogen with helium, using a piston purge process. This purging approach had been used on Space Shuttle External Tanks (ET) in the past, but not on one of the large LH2 tanks. The result was a huge success, potentially saving more than 1 million cubic feet of helium and significant labor. To better understand this result, a diffusion-based purge model was developed. This report contains the potential helium savings achievable with an optimal diffusion limited purge.

15. SUBJECT TERMS
Helium Conservation; NASA Engineering and Safety Center; Diffusion Limited Purging; Liquid Hydrogen Tank

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