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February 2014

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Summary

Results are presented for pressure-volume-temperature (PVT) gauging of a liquid oxygen/liquid nitrogen tank pressurized with gaseous helium that was supplied by a high-pressure cryogenic tank simulating a cold helium supply bottle on a spacecraft. The fluid inside the test tank was kept isothermal by frequent operation of a liquid circulation pump and spray system, and the propellant tank was suspended from load cells to obtain a high-accuracy reference standard for the gauging measurements.

Liquid quantity gauging errors of less than 2 percent of the tank volume were obtained when quasi-steady-state conditions existed in the propellant and helium supply tanks. Accurate gauging required careful attention to, and corrections for, second-order effects of helium solubility in the liquid propellant plus differences in the propellant/helium composition and temperature in the various plumbing lines attached to the tanks.

On the basis of results from a helium solubility test, a model was developed to predict the amount of helium dissolved in the liquid as a function of cumulative pump operation time. Use of this model allowed correction of the basic PVT gauging calculations and attainment of the reported gauging accuracy. This helium solubility model is system specific, but it may be adaptable to other hardware systems.

Symbols

C_1, C_2, C_3	calibration coefficients for reference gauging system (RGS)
LCR	load cell reading
LVI	liquid-vapor interface
MAWP	maximum allowable working pressure
m	mass
P	pressure
T	temperature
U	uncertainty
V	volume
x_{He}	mole fraction of helium
β	liquid fill fraction by volume
ξ	stretch coefficient for volume expansion due to pressurization
ρ	density

Subscripts

adj	adjusted for different sensed volumes
b	bottle
e	external
f	fluid
He	helium
i	initial condition
j	load cell index number
ℓ	liquid
PVT	pressure-volume-temperature gauging method
RGS	reference gauging system (tank-weighing system)
sat	saturation
sol	soluble or dissolved in liquid
t	tank
u	ullage
v	saturated vapor
0	reference condition at zero internal-to-external pressure difference

Superscripts

*	corrected for effect of external volumes

Overview of Pressure-Volume-Temperature Gauging

If a spacecraft's cryogenic propellant tank is pressurized with gaseous helium (GHe), the pressure-volume-temperature (PVT) liquid quantity gauging method may be an attractive low-gravity gauging option because it requires little, if any, additional hardware. PVT gauging has been utilized successfully in communications satellites with storable propellants (Refs. 1 and 2). For cryogens, PVT gauging has been examined analytically (Ref. 3) and experimentally (Ref. 4). In the earlier study (Ref. 4), a liquid nitrogen (LN_2) tank was pressurized with GHe from the test facility supply system. The interest at that time was to determine if PVT gauging was suitable for cryogenic propellant tanks, with the focus on behavior within the LN_2 test tank. In the present study, a larger liquid oxygen (LO_2)/LN_2 tank was pressurized

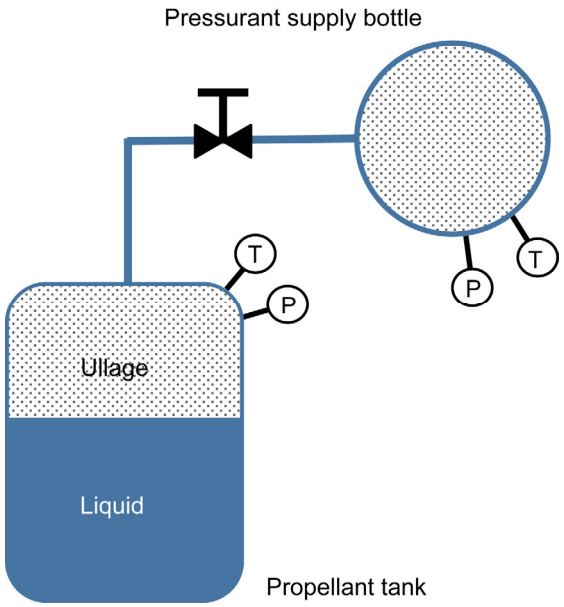


Figure 1.—Simplified pressure-volume-temperature schematic showing locations of pressure, *P*, and temperature, *T*, gauges.

with GHe stored at cryogenic temperature and high pressure in a dedicated supply tank somewhat representative of a supply system used on flight systems.

The PVT method is based on conservation of pressurant mass. Therefore, the key operational requirement is that no venting or leakage of the pressurant gas is allowed. Helium is most commonly used. Other gases could be considered, but only if they are noncondensable in the liquid propellant of choice. Gauging is most accurate when the propellant tank and the supply bottle are isothermal and at steady-state or quasi-steady-state thermal conditions. The test results presented here are for the isothermal case and demonstrate the achievable accuracy of the PVT technique under ideal conditions. Accurate gauging may be possible for conditions deviating from these ideal conditions, but this will require further study.

The hardware and required instrumentation are represented in Figure 1. Both the GHe supply bottle and the propellant tank must have accurately known volumes, and both must be equipped with suitable pressure and temperature sensors. In the isothermal model that follows, line effects are neglected, meaning either that the volumes of the transfer line on both sides of the valve are negligibly small or that the temperatures and fluid compositions in the lines are considered identical to those of the tank volumes connected to the lines. The primary PVT calculations steps follow:

(1) Determine the total GHe mass from initial conditions. Assume that all GHe mass initially resides in the GHe supply bottle, with no GHe initially present in the propellant tank:

$$m_{bi} = \rho_{bi} V_b \quad \text{where} \quad \rho_{bi} = f(T_{bi}, P_{bi}) \tag{1}$$

Here ρ is density, T is temperature, P is pressure, and the subscripts b and i refer to bottle and initial condition.

(2) At a later time, after the propellant tank is pressurized with GHe, determine how much GHe remains in the supply bottle m_b and how much has been transferred to the propellant tank:

$$m_b = \rho_b V_b \quad \text{where} \quad \rho_b = f(T_b, P_b) \tag{2}$$

$$\Delta m = m_{bi} - m_b \tag{3}$$

(3) Assume that the GHe transferred to the propellant tank uniformly occupies the entire ullage volume at a partial pressure P_{He} equal to the total tank pressure P_t minus the propellant's vapor pressure P_{sat}:

$$P_{\mathrm{He}} = P_t - P_{\mathrm{sat}} \quad \text{where} \quad P_{\mathrm{sat}} = f(T_t) \tag{4}$$

(4) Obtain the density of GHe in the ullage using the GHe partial pressure and tank temperature. Combine this with the mass of GHe transferred to the ullage to calculate the ullage volume V_u:

$$V_u = \Delta m / \rho_{\mathrm{He}} \quad \text{where} \quad \rho_{\mathrm{He}} = f(P_{\mathrm{He}}, T_t) \tag{5}$$

(5) This can be converted to a volumetric liquid fill fraction β:

$$\beta = 1 - (V_u / V_t) \tag{6}$$

where the subscript u refers to ullage.

(6) If the quantity of interest is the amount of liquid propellant mass m_l, then the PVT result must be converted:

$$m_l = \rho_l \beta V_t \quad \text{where} \quad \rho_l = f(P_t, T_l) \tag{7}$$

This last step will add additional uncertainty to the gauging measurement, especially if the liquid cryogen is not isothermal. This uncertainty arises from uncertainties in both the pressure and temperature measurements, which lead to uncertainty in the computed liquid density.

Test Apparatus and Instrumentation

Tests were conducted using a tank inside a 1.8-m-diameter by 3.0-m-high vacuum chamber (Fig. 2). The propellant tank, which was not insulated, had a main diameter of 1.22 m and an overall height of 1.91 m (Fig. 3). The propellant tank was suspended from the vacuum chamber lid via three load cells used to weigh the tank. The load cells served as a reference gauging system (RGS) for determining the accuracy of the PVT measurements. A fourth load cell connecting the bottom of the propellant tank to a pivoting loading beam mounted to the facility floor allowed calibration of the RGS. The calibration system was disconnected during tests. A submerged liquid pump was located inside the propellant tank, near the bottom (Fig. 4). The pump discharge flowed through a vertical pipe to two spray hoops in the tank ullage. Then, liquid was discharged through a large number of holes in the spray hoops, with a significant portion of the droplets directed upward to cool the upper tank wall and lid via direct contact. Two silicon diode sensor rakes were located near the tank centerline. One was used to measure temperatures from top to bottom inside the tank. The other held an array of point sensors used to detect the liquid level at 10 percent intervals. The propellant tank was equipped with a pair of pressure transducers for low- and high-range measurements.

Figure 5 shows the high-pressure tank, which was located outside the vacuum chamber to serve as a GHe supply bottle. The supply tank was wrapped with LN_2 cooling coils fed by an automated control system and covered with foam insulation. Three silicon diode sensors vertically distributed inside the tank were used to measure temperatures inside the supply tank. The GHe supply tank also was equipped with a pressure transducer for measuring pressures. A 1.2-cm-diameter GHe transfer line connected the supply tank to the propellant tank. Installed in the transfer line were a Coriolis flowmeter and two valves—one for control and the other for hard shutoff.

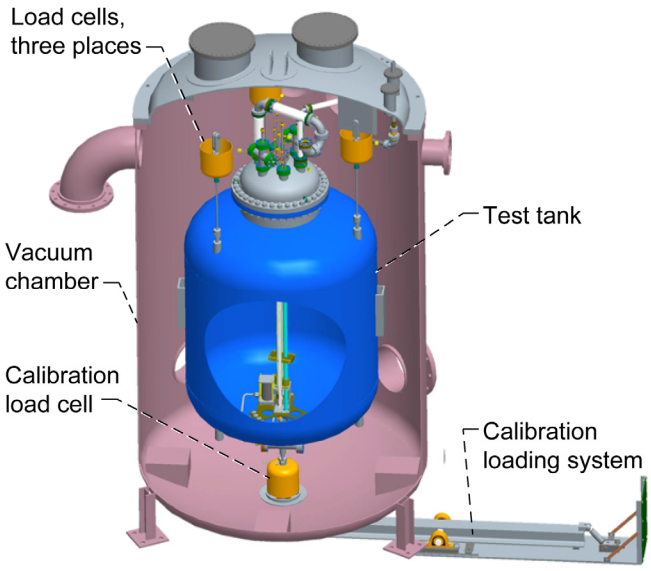


Figure 2.—Vacuum chamber, propellant (test) tank, and reference gauging system.



Figure 3.—Propellant tank suspended from vacuum chamber lid.

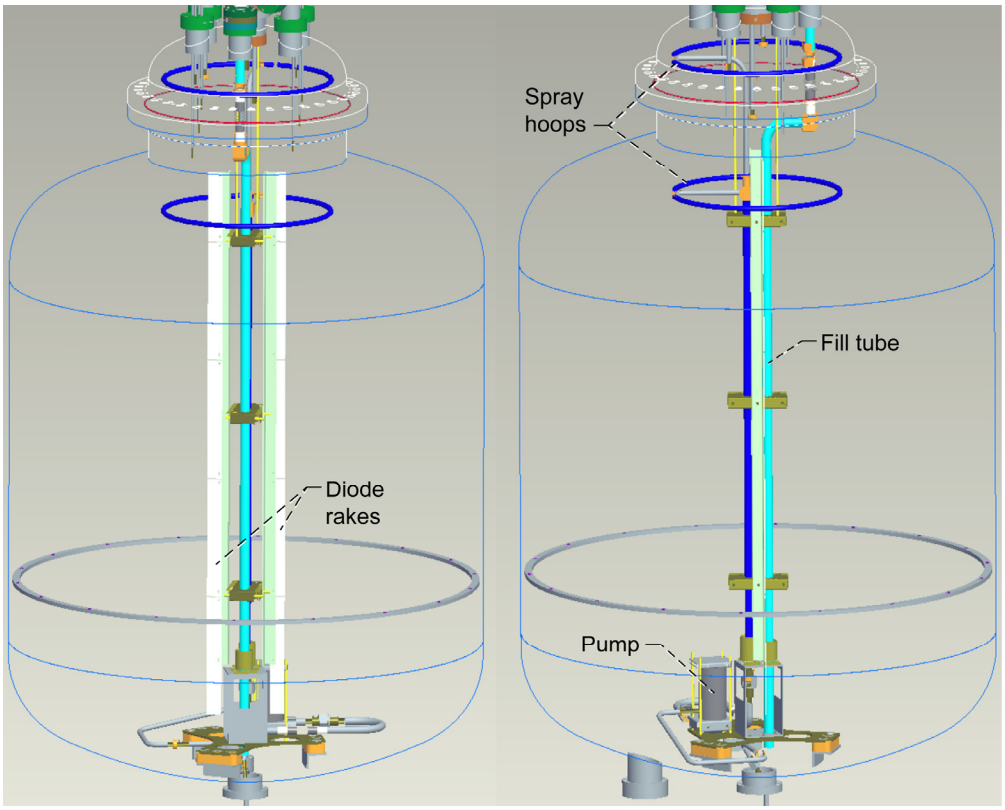


Figure 4.—Internal propellant tank components (two orthogonal views).



Figure 5.—Gaseous helium supply tank prior to installation of liquid nitrogen cooling coils and insulation.

Table I shows the specifications for the instrumentation.

TABLE I.—INSTRUMENTATION SPECIFICATIONS

Instrument/measurement	Range	Uncertainty
Propellant tank pressure	0 to 0.7 MPa and 0 to 2.1 MPa	±0.11% of full scale
Gaseous helium supply-tank pressure	0 to 13.8 MPa	±0.3% of full scale
Silicon diodes	2 to 100 K	±0.25 K
Load cells supporting tank	0 to 900 kg	±0.03% of full scale
Calibration load cell	0 to 1800 kg	±0.03% of full scale
Flowmeter	0 to 2180 kg/hr	±0.05% of rate

A multistep process was used to determine the tank volumes. First, a small high-pressure gas cylinder was used as a source to pressurize the GHe supply tank. The volume of the cylinder was determined by weighing the cylinder with a laboratory scale when empty and again when filled with water. Then, the cylinder was connected to the GHe supply tank with a short, small-diameter transfer line equipped with a shutoff valve. The cylinder was purged, then pressurized with GHe and allowed to reach thermal equilibrium. Similarly, the GHe supply tank was purged and allowed to equilibrate, but at an initial pressure of approximately one atmosphere after being purged with helium. Next, the valve was opened, allowing GHe to flow into the supply tank until the pressures equalized in the cylinder and the supply tank. The volume of the supply tank was calculated using a mass balance (with a correction for the volume of the transfer line). Then, a similar process was performed to determine the propellant tank volume by pressurizing the GHe supply tank and then flowing GHe into the propellant tank. The resulting room temperature volumes were 0.4055 m^3 for the supply tank and 1.623 m^3 for the propellant tank. The volumes were measured after all internal hardware was in place; therefore, no corrections were necessary for displaced volumes. At test conditions, both tanks were at approximately 90 K. Correcting the measured volumes for thermal contraction involves a 0.8-percent reduction; thus, the adjusted cold volumes for the GHe supply tank and propellant tanks were 0.4024 $m^3 \pm 0.0025$ and 1.610 $m^3 \pm 0.016$, respectively. Uncertainty estimates were calculated using the methods of Coleman and Steele (Ref. 5) and the manufacturers' accuracy specifications for the laboratory scale,

pressure sensors, and temperature sensors. Both tanks had additional plumbing lines attached to them for filling, venting, and other purposes. These lines contain volumes external to the primary tank compartments, and the fluid in these volumes was generally not at the same temperatures as measured in the GHe supply and propellant tanks. These external volumes were estimated by measuring the lengths and diameters of the various lines connected to each tank and summing the calculated segment volumes. The external volume for the GHe supply tank was equal to 10 percent of the tank's volume uncertainty, whereas the external volume for the propellant tank was equal to 50 percent of the tank's volume uncertainty.

In an ideal tank-weighing system, the tank would have no connections to the surroundings other than the load cells that it was suspended from. However, the tank for these gauging measurements was necessarily equipped with fill, vent, and drain lines plus electrical leads for power and instrumentation. The RGS was calibrated by applying measured loads from 0 to 100 percent of the liquid full-scale weight; this was done at tank pressures of 0.34 and 1.65 MPa (the minimum and maximum test pressures) and was performed both before and after the gauging tests. Furthermore, the calibration data were collected with the test tank at both ambient and subambient temperatures. The tank was pressurized with nitrogen gas. Then, the mass of nitrogen was evaluated from the product of the tank volume and gas density, which was obtained from temperature and pressure data. The RGS had a slight, but noticeable, sensitivity to pressure: the flex hoses used in the fill and vent lines were thought to stiffen when pressurized and thus exert external forces on the tank. A calibration equation of the following form was used:

$$m_f = C_1 \sum_{j=1}^{3} \mathrm{LCR}_j + C_2 P_t + C_3 \tag{8}$$

with coefficients of C_1 = 1.006, C_2 = –6.879 kg/MPa, and C_3 = –766.3 kg, where m_f is the mass of the fluid, LCR_j is the load cell reading, and P_t is the total pressure in the tank. The resulting correlation fit the data (warm and cool conditions) to within ±0.25 percent of the full-scale LO_2 weight (±4.1 kg). The first coefficient is very close to the tank's dry mass. The second term is quite small, equal to 0.1 percent of the liquid full-scale mass at 0.34 MPa and 0.6 percent at 1.65 MPa.

So that the PVT results could be compared with those of the RGS, the RGS calculations from Equation (8) were converted to a liquid volumetric fill fraction:

$$\beta_{\mathrm{RGS}} = \frac{\left(m_f \middle/ V_t \right) - \rho_v - \rho_{\mathrm{He}}}{\rho_\ell - \rho_v - \rho_{\mathrm{He}}} \tag{9}$$

where v refers to saturated vapor.

The liquid and ullage were assumed to be isothermal. The vapor density in Equation (9), which is for pure saturated propellant vapor, was determined as a function of the propellant tank temperature, and the GHe density was determined as a function of the GHe partial pressure and propellant tank temperature. The propellant tank volume sensed by the load cells was slightly less than that sensed by the PVT method because of the fill line, vent line, and other attached volumes that extended outside of the vacuum chamber. This corresponded to a 0.1-percent difference in the sensed volumes. For a proper comparison of the PVT results to the RGS, the RGS result was adjusted (multiplied) by the ratio of sensed tank volumes (equal to 0.9986) for the two methods as follows:

$$\beta_{\mathrm{RGS,adj}} = \frac{V_{t,\mathrm{RGS}}}{V_{t,\mathrm{PVT}}} \beta_{\mathrm{RGS}} \tag{10}$$

The propellant tank was equipped with hardware to extract fluid samples for the chemical composition analysis. Three small-diameter tubes were positioned in the tank to extract samples at heights corresponding to the 20-, 50-, and 80-percent fill locations. Each sampling line was connected to an isolation valve outside of the vacuum chamber. On the opposite side of the isolation valves, each sampling line was connected to a 500-cm^3 accumulator volume plus a 75-cm^3 gas sample bottle that could be swapped out during testing. Additional valves allowed evacuation and venting of the lines.

Sensitivity Analysis

The various pressures, temperatures, and volumes input to the fundamental PVT measurement will inevitably have measurement errors associated with them. In this section, two example PVT measurements, at propellant tank pressures of 0.34 and 1.65 MPa, and over a liquid fill fraction range from 0.05 to 0.95, are used to illustrate the effect of measurement errors. The calculations are based on an LO_2 temperature of 92 K, a GHe supply temperature of 89 K, and a propellant-

TABLE II.—INPUT MEASUREMENT OFFSET TO PRODUCE A 1-PERCENT PRESSURE-VOLUME-TEMPERATURE GAUGING ERROR AT 5-PERCENT LIQUID FILL AND TWO TANK PRESSURES

Input	Offset direction	Propellant tank pressure	
		0.34 MPa	1.65 MPa
Supply tank volume, V_b	Negative	1.05 percent of V_b	1.05 percent of V_b
Propellant-tank to supply-tank volume ratio, V_t/V_b, or propellant-tank volume, V_t	Positive	1.04 percent of V_t	1.06 percent of V_t
Propellant tank temperature, T_t	Negative	0.18 percent of T_t	0.65 percent of T_t
Supply tank temperature, T_b	Positive	1.11 percent of T_b	1.23 percent of T_b
Propellant tank pressure, P_t	Positive	0.69 percent of P_t	1.02 percent of P_t
Supply tank pressure, P_b	Negative	1.10 percent of P_b	1.26 percent of P_b

tank to GHe-supply-tank volume ratio of 4.0. These values are representative of the experimental data to be presented later. The analysis assumed that the final pressure in the GHe supply tank would be 0.69 MPa greater than the propellant tank pressure. Therefore, an initial pressure in the supply tank was found that satisfied this requirement and was used in the analysis. Each PVT input was independently iterated to find the value that would produce a worst-case 1-percent gauging error (of full-scale propellant tank volume). In all cases, the 1-percent gauging error occurred at the minimum fill fraction (0.05). Table II shows the results.

Generally, the first five input items in Table II were constant or approximately constant, whereas the last item, supply-tank pressure, decreased with liquid fill. The offset direction shown in the table indicates whether a positive or negative offset will produce a positive error in the PVT gauging result, where a positive error is defined as a gauging result that is greater than the actual value. The absolute value of the PVT gauging error for a fixed input offset increased as the fill fraction decreased. This occurred with all of the input measurements listed in Table II. Figure 6 shows an example for the propellant tank temperature input.

As seen in Table II, supply-tank volume, propellant tank volume, supply-tank temperature, and supply-tank pressure measurement errors had a similar effect at both low and high propellant tank pressures. The case with a low propellant tank pressure was substantially more sensitive to errors in propellant tank temperature, and to a lesser extent, propellant tank pressure. Obtaining accurate gauging results was more difficult at a lower propellant tank pressure than at a higher propellant tank pressure.

A similar analysis was performed to determine the effect of a GHe leak in the two-tank system. If a constant GHe leak rate (mass/time) is assumed, the error increases with time, which in the present work roughly equated to decreasing fill fraction. A GHe leak always resulted in a negative PVT gauging error; that is, the PVT measurement was less than the actual fill fraction. The location of the leak (supply tank, propellant tank, or transfer line) was irrelevant. Increasing the propellant tank pressure caused a slight reduction in sensitivity to GHe leakage: at 0.34 MPa, a 1-percent gauging error (at 5-percent fill) resulted from a loss of 0.47 percent of the initial GHe mass in the supply tank, whereas at 1.65 MPa the same error would require a 0.75-percent loss.

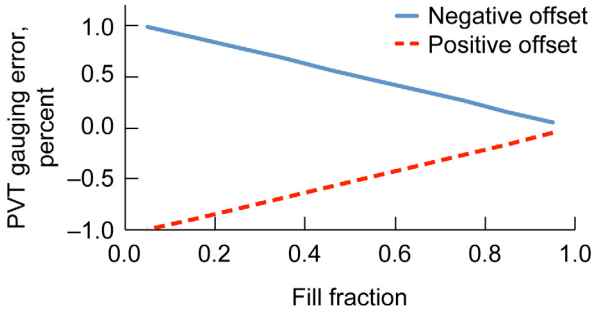


Figure 6.—Pressure-volume-temperature (PVT) gauging error with propellant tank temperature offset (error) equal to 0.65 percent of the propellant tank temperature at a pressure of 1.65 MPa. (See Sensivitiy Analysis section for other specifications.)

Test Matrix and Procedures

The tests reported herein, and listed in Table III, were all run in August 2007. These include nine PVT tests conducted at nominal propellant tank pressures of 0.34, 1.03, and 1.65 MPa. Six were LO_2 tests, and three were LN_2 tests. The PVT tests were conducted at starting fill fractions of 0.92 to 0.98, followed by approximate decrements of 0.1, to final fill fractions of 0.05 to 0.10. A test was typically conducted within 4 to 5 hr. A special test (test 25), discussed later, was conducted to collect data to characterize the rate and degree that GHe was dissolved into LO_2 for the specific test hardware and operations used in this study.

For all tests, the GHe supply tank was charged with the required amount of GHe and cooled to 90 K. The initial GHe mass was predetermined such that the supply tank pressure at the end of a gauging test run would exceed the propellant tank pressure by at least 0.7 MPa. For each test run, the propellant tank was filled to the starting fill level and allowed to reach quasi-steady-state tank wall and lid temperatures while the tank was vented to the atmosphere. The pump/spray system was operated intermittently to cool the unwetted tank lid. When the propellant tank and GHe supply tank were both filled and at near-isothermal conditions, a test run was started by closing the propellant tank vent and recording the initial conditions in the GHe supply tank.

The first PVT measurement was initiated by pressurizing the propellant tank to the desired pressure. This involved transferring GHe from the supply to the propellant tank and operating the pump to create isothermal conditions in the propellant tank. Pump/spray operation would cause a pressure reduction in the propellant tank. Therefore, multiple pressurization and mixing steps were performed to reach quasi-steady-state, isothermal conditions at the desired pressure. As

TABLE III.—COMPLETED TESTS

Test number	Propellant	Nominal propellant tank pressure, MPa
18	LO_2	1.03
19	LO_2	1.65
20	LO_2	0.34
22	LO_2	0.34
23	LO_2	1.03
24	LO_2	1.65
25	LO_2	1.08[a]
28	LN_2	1.65
29	LN_2	1.03
30	LN_2	0.34

[a]Initial condition.

will be discussed in the results section, true steady-state conditions cannot be attained if GHe is being dissolved in the liquid during active mixing of the propellant tank. Meanwhile, the pressure and temperature in the GHe supply tank were monitored to determine when the tank reached steady state. Conditions for a steady-state measurement were considered to exist if the computed value of GHe density in the supply tank was steady and if all liquid and ullage temperatures in the propellant tank were approximately equal. Real-time plotting of the data allowed monitoring of both tanks. After quasi-steady-state and isothermal conditions prevailed in both tanks, the propellant tank was drained to the next targeted liquid fill fraction and the procedures just described were repeated. The data system operated continuously, recording steady and unsteady data from both tanks as well as the RGS.

Liquid and ullage samples were collected during the tests conducted at nominal propellant tank pressures of 1.03 and 1.65 MPa. Samples were taken at 65- to 70-percent fill (one ullage sample and two liquid samples) and again at 30- to 35-percent fill (two ullage samples and one liquid sample). Then, the samples were sent to an independent laboratory for gas chromatography analysis (according to ASTM D1946) to determine the GHe concentrations.

Effect of Helium Solubility

GHe has a slow diffusion rate and low equilibrium solubility in LO_2 and LN_2 within the temperature and pressure ranges for typical spacecraft propulsion systems (Refs. 6 and 7). However, the amount of GHe in solution may become significant for PVT gauging when the tank contents are actively mixed for extended periods of time such as in the present experiment. Consequently, when high-accuracy PVT gauging results are desired, it may be necessary to account for the loss of GHe from the ullage to the liquid.

An estimate of GHe solubility in the liquid propellant under the test conditions showed that, under worst-case assumptions, dissolved GHe is significant and could affect PVT measurement accuracy. Test 25 was conducted and analyzed to provide more insight into the degree and rate of GHe infusion into LO_2 for this test program's specific test hardware and mixing operations. A simple mechanistic model was developed and used to determine the mass of soluble GHe as a function of the elapsed mixing pump operation time during the PVT tests. The GHe solubility correction to the PVT gauging measurement was on the order of 2 percent for LO_2 and 3 percent for LN_2. The reader is referred to Appendix A for a discussion of the worst-case estimate, an analysis of test 25 results, and model development for predicting the dissolved GHe mole fraction as a function of mixing time in the present PVT tests.

Corrections to the Calculated Pressure-Volume-Temperature Gauging Measurements Due to External Volumes

A number of external volumes were connected to the GHe supply and propellant tanks that could introduce errors if they were not appropriately accounted for in the gauging calculations. These external volumes were various plumbing lines that were dead-ended at shutoff valves outside of the vacuum chamber. The errors result from local thermodynamic conditions in these volumes that differ from the assumed isothermal states in the two tanks and from the assumed uniform mixture of GHe and vapor in the propellant tank. The net correction to the calculated PVT gauging measurements for external volume effects was about 0.5 percent for this work. Appendix B presents the details of this analysis.

Tank Volume Expansion Due to Pressure

The effect of tank stretch (or volume change due to pressurization) should be carefully evaluated in a PVT measurement system. For the present work, a structural analysis of the GHe supply tank was conducted to determine the tank's volume change as a function of pressure; the tank's known geometry, wall thickness, and construction material. At the supply tank's maximum allowable working pressure (MAWP), the volume increased by 0.13 percent at room temperature. The volume change was 7 percent less at LO_2 temperature. The percent volume change was assumed to be similar for the propellant test tank and the small high-pressure gas cylinder used in the GHe supply tank volume measurement at the respective MAWPs of these vessels. The stretch coefficient ξ defined as

$$\xi = \frac{\Delta V / V_0}{\text{MAWP}} \tag{11}$$

was used to calculate the appropriate tank volumes as a function of pressure:

$$V = V_0(1 + \xi P) \tag{12}$$

where the subscript zero refers to conditions at a zero internal-to-external pressure difference. Tank stretch can have an impact in several ways. First, the tank stretch can alter the measured volumes of the GHe supply tank and the propellant tank. This was investigated and found to be negligible in

comparison to the other sources of tank volume measurement error. Second, the effect of tank stretch could change the calibration of the RGS. The most significant change to the calibration coefficients for the RGS was in the tank pressure coefficient C_2 of Equation (8) (because of the slight change in propellant tank volume from the low to high calibration pressures), but the resulting difference in calculated fluid mass was negligible. Third, the fill level determined from the RGS using Equation (9) can change because of the small increase in the propellant tank volume. This effect was negligible at low tank pressures, but a small discernible change resulted at high tank pressures and varied with fill fraction. For the present work, the maximum effect was a 0.1-percent difference at 99-percent fill and a propellant tank pressure of 1.65 MPa. This effect reduced the value of the propellant tank liquid fill fraction computed from the RGS measurements. The fourth effect of stretch is on the PVT measurement itself. Stretch of the GHe supply tank caused a small reduction in the measured fill fraction, whereas stretch of the propellant tank caused the opposite effect. For the present work, these two effects very nearly canceled each other. Each of the effects caused an approximate 0.1-percent change in fill fraction as the fill fraction approached zero at the 1.65-MPa test pressure. The changes became negligible at higher fill fractions and at all fill fractions at lower pressures. The combined effects of stretch on the GHe supply and propellant tanks on the PVT measurements for the present work are negligible in all cases. Because all of the effects of tank stretch in the present work were minor in comparison to other sources of error and uncertainty, tank stretch effects were omitted from further analysis in the present results.

Experimental Gauging Results

The quasi-steady-state PVT results obtained at a nominal propellant tank pressure of 1.65 MPa are plotted in Figure 7 as a function of fill fraction. Similarly, the results for 1.03 and 0.34 MPa are shown in Figures 8 and 9. The results are presented as the percent difference between the PVT result and the RGS based on the total tank volume. The PVT results were corrected for the effects of GHe solubility and external volumes, as discussed previously in this report; and the RGS results were adjusted to the sensed tank volume of the PVT method using Equation (10). In each figure, estimated error bars—which represent only the error for the PVT measurement, are shown for one of the tests. There is also a smaller, but significant, error associated with the RGS. The reader is referred to Appendix C for a discussion of the analysis used to estimate the error bars, details regarding the percentage contributions of the various uncertainty terms to the overall estimate of the PVT measurement error, and the RGS uncertainty estimate.

In Figure 7, the results for high propellant tank pressure have an orderly, repeatable trend with minimal scatter. There

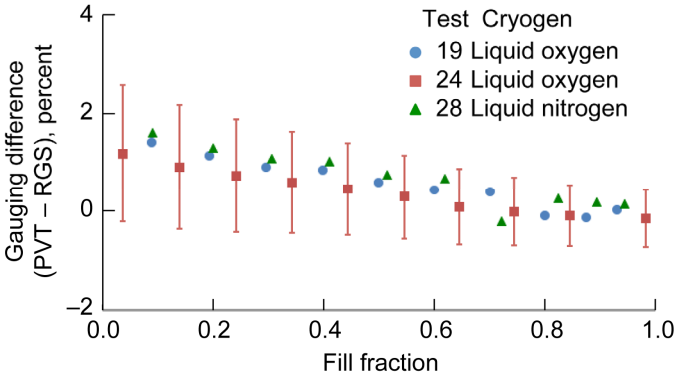


Figure 7.—Pressure-volume-temperature (PVT) gauging results for nominal 1.65-MPa propellant tank pressure; RGS, reference gauging system.

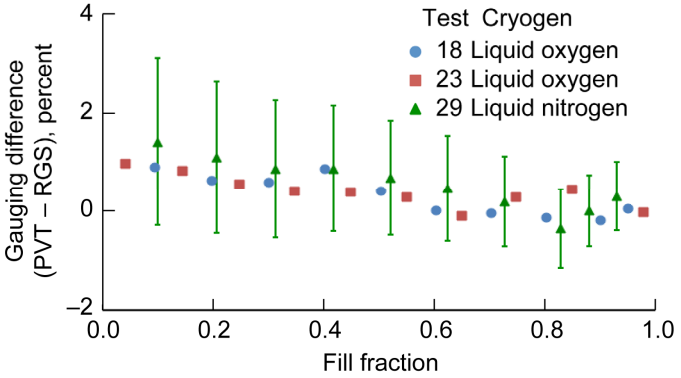


Figure 8.—Pressure-volume-temperature (PVT) gauging results for nominal 1.03-MPa propellant tank pressure; RGS, reference gauging system.

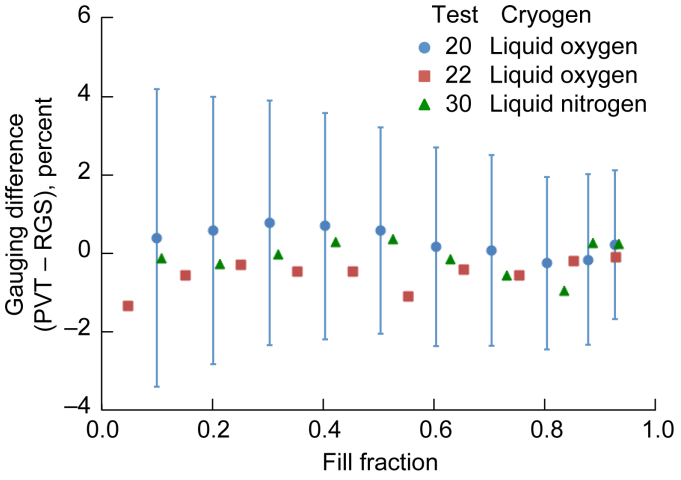


Figure 9.—Pressure-volume-temperature (PVT) gauging results for nominal 0.34-MPa propellant tank pressure; RGS, reference gauging system.

is no significant difference between the two LO_2 tests (tests 19 and 24) or the LN_2 test (test 28). The measurement error is very near zero at high fill fraction and increases to maximum values of less than 2 percent at fill fractions of 0.05 to 0.1. This behavior is consistent with the earlier discussion of input errors and could be due to offsets of any of the values input (tank volumes, pressures, or temperatures) to the PVT measurement or some combination thereof. The GHe solubility correction for LN_2 was greater than for LO_2 (see App. A). The good agreement of the PVT results for both propellants indicates that the solubility correction has high fidelity.

The results for the intermediate propellant tank pressure shown in Figure 8 are quite similar to the results in Figure 7. The same overall trend is seen but with slightly more data scatter at high fill fractions. The overall dataset is somewhat more centered about 0-percent error, and all the data points are within a ±1.5-percent error band. The instrumentation used for the results at the intermediate and high propellant tank pressure tests was identical, and the increased scatter at the intermediate pressure may be due to various input measurement errors/offsets being a greater percentage of the input values at this pressure.

At the lowest propellant tank pressure (0.34 MPa), a lower range pressure transducer was utilized in the propellant tank (LO_2 tests 20 and 22). Figure 9 shows the results. During the LN_2 test (test 30), the lower pressure range transducer produced readings that grew progressively different from the readings of the higher range transducer (which remained in service). The authors' best judgment is that this anomalous behavior indicated a gradual failure of the low-range pressure transducer during the LN_2 test. For the analysis of the LN_2 data, the offset between the two pressure transducers from the LO_2 data were subtracted from the high-range transducer readings and used as the input propellant tank pressure. Therefore, the results in Figure 9 for test 30 were not obtained in the exact manner as the other data and should be viewed with caution. Figure 9 again shows good PVT gauging accuracy with errors within 1.5 percent. There is more scatter, and although the two LO_2 test series show similar behavior, repeatability is not as good as at the intermediate and high propellant tank pressures. This result is not unexpected because prior analysis has shown that PVT gauging will have more uncertainty at low propellant tank pressures. Figure 9 does not exhibit the same trend of increasing error as fill fraction decreases that is observed in Figures 7 and 8. One could thus speculate that the high-range pressure transducer used in the higher pressure tests had a more positive error or offset (percent of input, as discussed in the sensitivity analysis) than the low-range transducer.

Figure 10 shows an example of the effects of the corrections for external volumes and GHe solubility for test 24 (LO_2 at 1.65 MPa). The effects are typical of the other tests. The correction for the external volumes was relatively small and reduced the gauging result by a nearly constant value for all fill fractions. The correction for solubility was significantly greater and increased the PVT result by as much as 2 percent at the lower fill fractions. (The maximum correction is about 3 percent for the LN_2 tests.) Note that the solubility correction removed the kink in the fill fraction dependence exhibited by the basic PVT results. The kink occurs at the fill fraction where the propellant tank mixing turnover time (as discussed in App. A) was reached. The solubility model takes this into account, removes the kink, and results in a linear trend of gauging error versus fill fraction.

Overall, all of the quasi-steady-state PVT data agreed with the RGS to within 1.5 percent of full scale (tank volume). This agreement gives us confidence that the tank volume, temperature, and pressure measurements were free from substantial errors, that the GHe solubility model used to correct the basic calculation is valid, and that no significant GHe leaks existed in the test hardware.

Thus far, PVT gauging results have been shown for quasi-steady-state conditions. To obtain steady-state conditions, a sufficient hold time is necessary to allow the GHe supply tank to attain a steady pressure and temperature after GHe has been transferred to the propellant tank. The tests at the nominal 1.65-MPa propellant tank pressure had the largest temperature drop during GHe transfer and required about 15 min to attain a new steady-state condition. The calculated supply tank GHe density would reach a steady-state value more quickly than 15 min (i.e., although pressure and temperature could both be increasing, the pressure-to-temperature ratio had become constant), so a shorter wait (~10 min) for equilibrium conditions in the supply tank was acceptable. The time required to return to steady-state supply-tank conditions was less for the lower-pressure tests.

Steady-state thermodynamic conditions could never be truly attained in the propellant tank because heat leak into the tank caused the liquid temperature to rise continually. Running the mixing pump and spray system would produce isothermal conditions in the propellant tank while adding additional heat

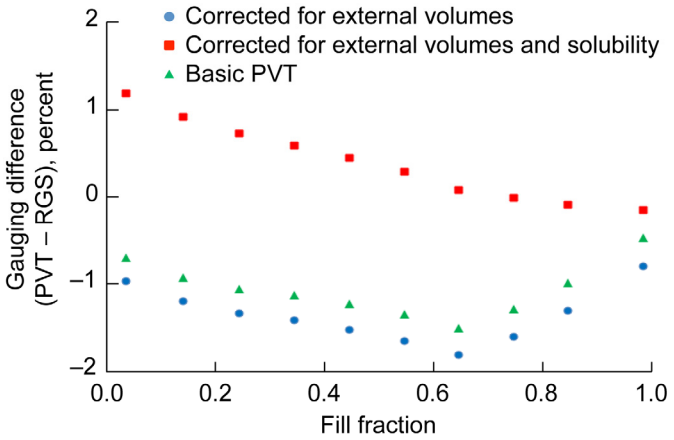


Figure 10.—Example of typical effects of external volume and helium solubility corrections to basic pressure-volume-temperature (PVT) result; test 24—liquid oxygen at 1.65 MPa; RGS, reference gauging system.

to the tank. Longer pump operating times were necessary for the higher pressure tests because more warm GHe was transferred to the propellant tank in these tests and had to be mixed with the tank contents. (The transferred GHe warmed up because the transfer line was not well insulated.) Intermittent pump operation, chosen for this work, produced a sawtooth response in tank pressure—the pressure dropped when the pump was operating and rose when the pump was off. At the higher fill fractions, GHe was driven into solution in the liquid when the pump was operating. Therefore, at high fill fractions (after GHe flow was completed), the sawtooth pressure response had a decreasing overall trend with time, but at lower fill fractions, the sawtooth pattern had more consistent maximums and minimums.

Although PVT is not considered to be an accurate real-time measurement technique, examination of real-time gauging results may be of interest. In Figures 11 and 12, the real-time PVT gauging results are shown for two example tests. These figures also show the times corresponding to steady-state results, the timeline for pump operation, and the timeline for GHe transfer to the propellant tank. Figure 11 shows the results for test 24 (LO_2) at a propellant tank pressure of 1.65 MPa. In this test, the test procedure was to operate the pump while GHe was transferred to the propellant tank. This procedure kept the propellant tank close to isothermal conditions at all times. The real-time gauging results are surprisingly good and are typically within 0.5 percent of the steady-state results. The occasional negative spikes occur when the pump was started. The positive error trends in the real-time gauging occur when GHe was transferred to the propellant tank, and the negative trends occur after GHe flow was stopped. The transient conditions in the supply tank, discussed earlier, existed during these positive-negative error trends. The second example, shown in Figure 12, is for test 20 (LO_2) at a propellant tank pressure of 0.34 MPa. In this case, the real-time errors were much larger (up to –6 percent) because the pump was operated less frequently; thus, more substantial thermal stratification was present in the ullage. Operating the pump would return the tank to isothermal conditions (within minutes), and accurate quasi-steady-state results were then obtained. Rigorous mixer control logic was not implemented for the tests. The examples in Figures 11 and 12 show the effect of the mixer operation history on real-time results.

Sample extraction had a very small effect on the gauging results. The liquid sample extraction caused a minor drop in fill fraction with a corresponding removal of dissolved GHe from the propellant tank. The change in fill fraction itself did not alter the accuracy of the PVT or RGS measurements. The mass of dissolved GHe in the liquid samples was essentially negligible, but nevertheless, it was included in the calculation of expelled mass. The removal of ullage samples had an effect on the order of 0.1 percent of the total mass of GHe in the tank at the time of sample withdrawal. This percentage was insensitive to propellant tank pressure and was about the same

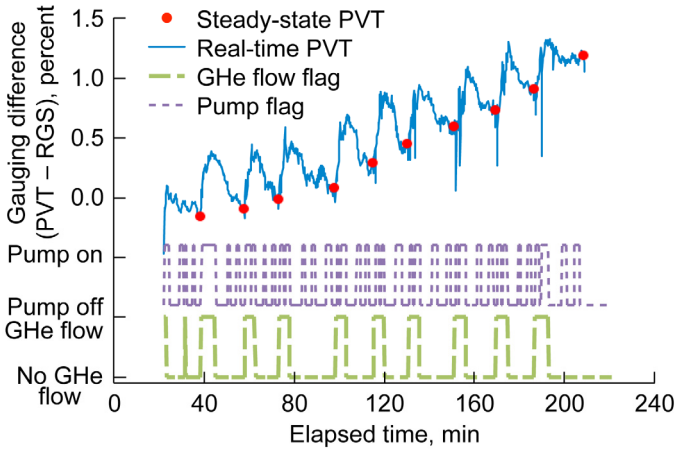


Figure 11.—Real-time pressure-volume-temperature (PVT) gauging results for nominal 1.65-MPa propellant tank pressure (liquid oxygen test 24); RGS, reference gauging system; GHe, gaseous helium.

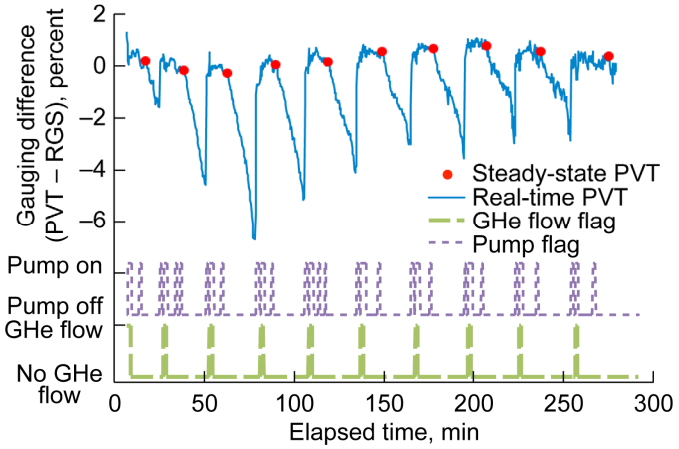


Figure 12.—Real-time pressure-volume-temperature (PVT) gauging results for nominal 0.34-MPa propellant tank pressure (liquid oxygen test 20); RGS, reference gauging system; GHe, gaseous helium.

at both the high and low fill fractions where samples were collected because a single ullage sample was extracted at the high fill level, whereas two ullage samples were withdrawn at the lower level where the ullage volume was approximately twice as large. The PVT gauging result had no effect prior to sampling when fill fractions were greater than 0.7, had a negative shift of about 0.03 to 0.04 percent after the first sample collection event when fill fractions were from 0.7 to 0.4, and had a negative shift of about 0.06 to 0.07 percent when fill fractions were less than 0.4. The negative shift was similar to the effect of a GHe leak as discussed earlier. These effects were considered to be negligible and were not factored into the PVT gauging results presented herein.

The results of the gas species concentration analyses of the extracted samples can be compared with the assumptions used to model the PVT method. The ullage sample compositions

can be compared with the Dalton model (which for a mixture, assumes that the mole fraction of each component equals the partial pressure of that component divided by the total pressure). Figure 13 compares the GHe mole fraction in the ullage from the Dalton model with the experimental values (gas chromatograph analysis of the samples). The GHe mole fractions from the sample analysis are about 3 percent lower than what the Dalton model predicted. The results for LO_2 and LN_2 are similar.

Figure 14 compares the GHe mole fractions from the analyzed liquid samples with the predicted values from the GHe solubility model. The higher solubility of GHe in LN_2 in comparison to LO_2 is readily evident. The sampled and solubility-model-predicted values compare quite well, considering that these values were near the reported detection limit of 0.1 mol% for the gas chromatography method used to analyze the samples. The results shown in Figures 13 and 14 are for samples collected from the 1.03- and 1.65-MPa tests, excluding test 18. The results from test 18 were deemed unreliable because they were inconsistent with all other data.

The earlier sections in this document address only PVT gauging applied to an isothermal propellant tank. During the test program, a special test was conducted to obtain data under conditions where the propellant tank was intentionally allowed to thermally stratify as GHe was added to the tank and liquid was expelled. For this test only, the mixer pump in the propellant test was never operated. A single test point from this test, at an approximate 10-percent liquid fill level, is thoroughly analyzed in Appendix D. An accurate gauging result—within 2 percent of tank volume—is shown to be possible by accounting for the temperature and GHe concentration profiles in the tank. Implementation of the stratified PVT gauging method in a low-gravity environment will require an extensive development effort in the areas of liquid versus vapor phase determination, multidimensional

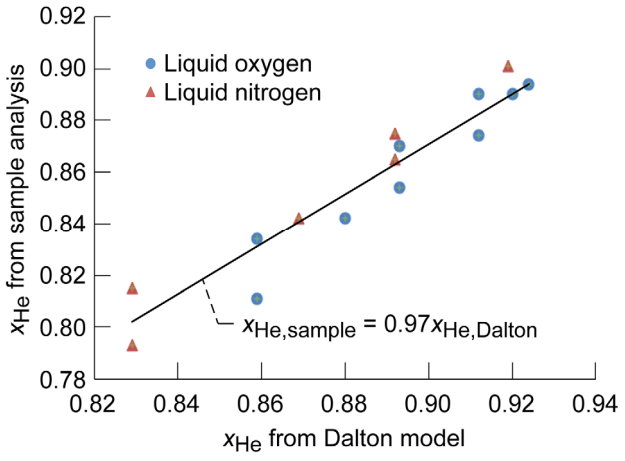


Figure 13.—Comparison of helium mole fractions, x_{He}, in ullage from Dalton model and analyzed samples.

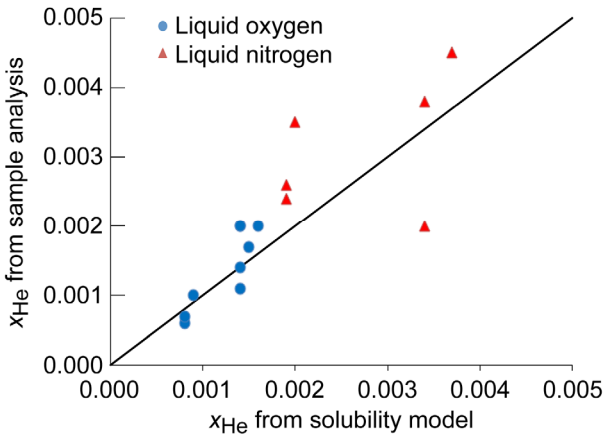


Figure 14.—Comparison of helium mole fractions, x_{He}, in liquid from solubility model and analyzed samples.

numerical integration of the fluid volume and density, and real-time measurement or modeling of local GHe concentration.

Summary of Results

Pressure-volume-temperature (PVT) gauging experiments were successfully completed for liquid oxygen (LO_2) and liquid nitrogen (LN_2) tests using gaseous helium (GHe) pressurization. Helium was supplied by a cryogenic high-pressure supply tank that simulated a cold GHe supply bottle on a flight system. Gauging errors of less than 2 percent of propellant tank volume were demonstrated at nominal tank pressures of 0.34, 1.03, and 1.65 MPa. The measured PVT errors are relative to reference gauging measurements from a calibrated, high-accuracy system composed of calibration-standard load cells, which weighed the tank.

The reported results were obtained for quasi-steady-state conditions in an isothermal propellant tank. Isothermal conditions were obtained by frequent operation of an ullage spray system fed by a submerged liquid circulation pump. Use of the PVT method when a thermally stratified ullage exists in the propellant tank requires further study.

Obtaining accurate PVT measurements required careful attention to second-order effects, including the solubility of GHe in the liquid propellant and corrections for small external volumes attached to the propellant tank, such as the vent and fill lines—where the thermodynamic conditions differ from the isothermal and well-mixed conditions in the tank's ullage. Tank stretch, or volume change due to pressure, was not significant in the present work, but it should be carefully evaluated in flight systems with thin-walled, lightweight tankage.

A special GHe solubility test was performed, and the data were used to develop and validate a model to predict the amount of GHe dissolved in the liquid propellant as a function of pump operation time. This simple solubility model allowed the basic PVT calculations to be adjusted for GHe lost from the ullage when GHe was dissolved in the liquid. The

solubility model is considered to be specific to the test hardware of the present experiments, but it can be adapted to other PVT gauging applications.

During the tests at intermediate and high propellant tank pressure, samples were extracted from both the ullage and the liquid regions of the propellant tank. Helium mole fractions obtained from chemical analysis of these samples were in reasonably good agreement with values predicted from the solubility model for the liquid and from the partial pressure (Dalton) model for the ullage.

Data also were obtained for real-time PVT gauging as the propellant tank fill fraction was reduced. If the ullage was allowed to stratify thermally, gauging accuracy was substantially degraded. When the ullage was kept in a near isothermal state by operation of the pump/spray system as GHe was transferred to the propellant tank, PVT gauging accuracy was only slightly degraded, by 0.5 percent.

Appendix A.—Helium Solubility Analysis and Correction

An upper bound of the amount of GHe in solution for the PVT gauging method can be estimated when the propellant tank is at the maximum expected temperature, pressure, and liquid fill fraction. Then, a published correlation derived from experimental solubility data (Ref. 6) can be used to predict the equilibrium mole fraction of GHe in LO_2. For the range of temperature, pressure, and initial fill fraction of interest in the present work, the worst-case scenario resulted in an LO_2 PVT measurement error of 3.8 percent of full scale (resulting in a PVT measured fill level lower than the true value). This upper bound estimate assumes that the entire liquid volume is infused with GHe at the initial fill level (95 percent) prior to any expulsion of liquid. At this high initial fill level, the amount of GHe in solution is about 75 percent of the amount initially present in the ullage. There would be no further change in the amount of soluble GHe if the temperature and pressure remained the same: the dissolved GHe would be expelled with the liquid as the tank was drained. Under this scenario, the PVT measurement error is a constant offset at all fill levels. The total soluble GHe is about 4 percent of the GHe required to expel liquid and maintain tank pressure to a fill level of 5 percent. The values given apply to tank pressures from 0.4 to 1.8 MPa.

A similar correlation for equilibrium mole fractions in helium-nitrogen systems (Ref. 7) also was used. The worst-case PVT measurement error was 4.8 to 4.9 percent for LN_2, similar to the helium-oxygen behavior discussed earlier, but slightly larger.

Because the magnitude of the worst-case GHe solubility effect was greater than the desired gauging measurement accuracy, further study was warranted. The rate due to diffusion only under quiescent tank conditions is known to be very slow (the entire liquid mass would take weeks to reach equilibrium solubility), but the forced convection of the liquid due to pumping through the spray hoops could greatly increase the solubility rate.

A special test (test 25) was conducted to experimentally evaluate the rate and degree of GHe solubility in LO_2. In this test, the propellant tank was filled to 91 percent and quickly pressurized with GHe to an initial pressure of 1.08 MPa. The liquid pump was operated continuously for several hours, spraying liquid into the ullage and circulating the tank contents by ingesting liquid from the bottom of the tank. Figure 15 shows the pressure and average fluid temperature history. The start time (0 min) was defined as the start of GHe flow into the tank. Helium flow was stopped at 2.27 min. After the initial spike, tank pressure collapse was seen when the pressure dropped quickly as the GHe (which was warm because of heating as it flowed through the transfer line) cooled to the average tank fluid temperature. There was a small but significant increase in temperature coinciding with

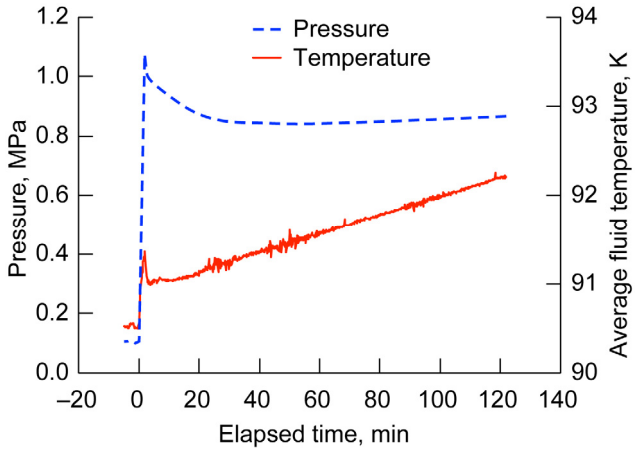


Figure 15.—Pressure and temperature histories for special solubility test 25.

GHe inflow. The otherwise steady increase in temperature was attributed to the combined energy input from heat transfer through the tank wall and energy dissipation from the pump. After the initial pressure collapse, the pressure continued to decrease for approximately 40 min. This pressure decrease was attributed to GHe leaving the ullage (and reducing the GHe partial pressure) as it was dissolved into the liquid. The dissolution process was thought to take place primarily within the small liquid droplets exiting the spray hoops and falling through the ullage or within the thin liquid films flowing down the tank sidewall. The free surface of the liquid may also have been agitated because of the droplets impinging on the free surface, thus promoting additional dissolution. When the pressure reached a minimum, the liquid was thought to have reached a state of substantial GHe infusion throughout its entire volume. After this, the pressure slowly increased, primarily as a result of the energy input from wall heating and pump operation. The minimum pressure occurred at a time approximately equal to the mixing turnover time for the tank. The mixing turnover time is the time it takes for the entire liquid volume to pass through the pump and is calculated as the liquid volume divided by the pump's volumetric flowrate.

Figure 16 shows the temperature profile near the tank's central axis at various times. The addition of warm GHe caused an increase in temperature in the ullage as seen at 2.1 min. At 4, 10, 15, and 20 min, a slightly warmer liquid layer propagated toward the tank bottom. From 30 min on, the fluid temperature was uniform. This temperature profile is consistent with a slightly warmer layer forming at the liquid surface and spreading downward until it extends completely to the tank bottom. A similar process is thought to have occurred with the GHe-infused layer.

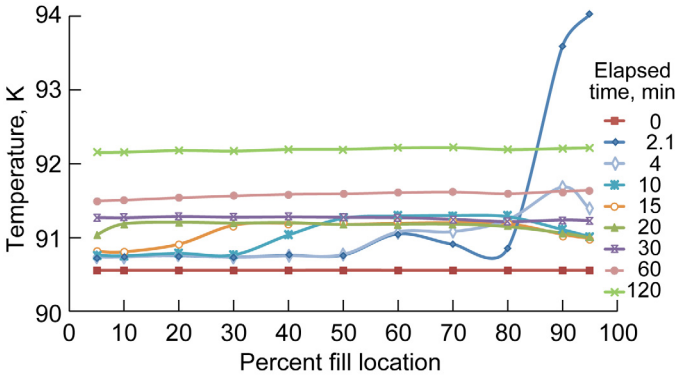


Figure 16.—Tank temperature profiles for special solubility test 25 at various times.

A computational model was developed to predict the dissolved GHe mass in the PVT tests using the results of test 25 as a starting point. The model is based on conservation of GHe mass (sum of GHe in ullage and in solution) and propellant mass. It uses the helium-oxygen solubility correlation of Zimmerli et al. (Ref. 6) to calculate the equilibrium value of dissolved GHe. Key points and assumptions of the model follow:

(1) The initial conditions for fill fraction, pressure, and temperature were matched to the experimental data. The initial infused GHe mass was zero.
(2) The temperature history was specified with two linear curve fits to the experimental data—one for the period of GHe addition and the other for the remainder of the test duration. (The step up in temperature increase was fitted, but the spike was not.) This was done to remove the influence of noise in the temperature data, which is evident in Figure 15. Using the temperature history simplified the problem, so it was not necessary to solve for an energy balance.
(3) Vapor properties were at the saturated state for the given temperature.
(4) The mass of GHe added to the tank was found by numerical integration of readings from the flowmeter placed in the GHe transfer line. At 2.27 min, the GHe flow was shut off and the mass of GHe in the tank remained constant for the remainder of the test.
(5) For each time step, the incremental liquid mass pumped through the spray hoops was infused with the equilibrium quantity of soluble GHe at the current tank average temperature and pressure.
(6) A layer of GHe-infused liquid formed at the liquid-ullage interface. Its thickness and volume increased with time until the entire liquid volume was infused with GHe.
(7) The average mass fraction of GHe in the infused liquid volume was updated at each time step. The average mass fraction of the infused volume was allowed to be less than or greater than the value based on the current tank temperature and pressure. The latter situation generally occurred when pressure was decreasing.
(8) The total tank pressure was iterated at each time step to satisfy the GHe mass balance. When the solution was obtained, the partial pressure of the GHe was determined and the masses of GHe in the ullage and in solution were found.

Figure 17 compares the predicted tank pressure history with the experimental results. The model matched the pressure data reasonably well. However, it did not match the spike (which is not thought to be important), and it predicted a slower rate of pressure drop while the GHe-infused liquid volume was growing. The faster rate of pressure drop of the experimental data indicates that the amount of GHe dissolved in the infused GHe layer during this phase actually exceeded the equilibrium value. The model also predicted a more prominent minimum pressure (when the turnover time was reached), whereas the actual data have a broader minimum pressure, indicating that the actual transition from pumping pure propellant to GHe-infused propellant was not an abrupt process.

Figure 18 shows the predicted GHe mass fraction in the infused liquid volume. The "instantaneous response model" mass fraction, obtained by assuming that the entire infused volume had a GHe mole fraction based on the current tank pressure and average temperature, is included for comparison. After a sufficiently long time, when the liquid had circulated through the pump several times and the pressure and temperature were slowly rising because of heat input, the infused liquid model and instantaneous response model were in good agreement. When pressure was changing more rapidly, the infused liquid model predicted a GHe mass fraction that lagged behind the instantaneous response calculation, as expected. Differences between the two models were relatively minor and unimportant to the resulting correction to the PVT gauging results.

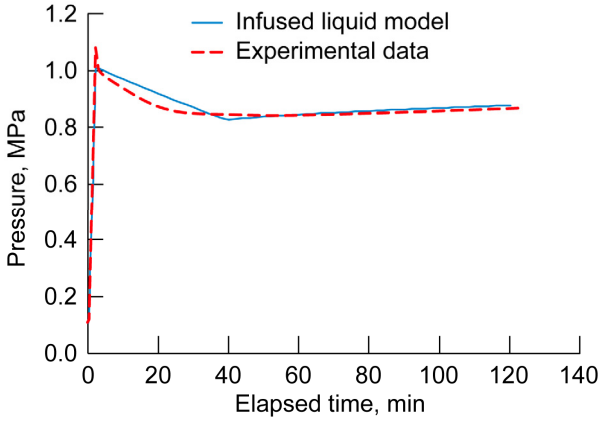


Figure 17.—Comparison of predicted and experimental pressure histories for special solubility test 25.

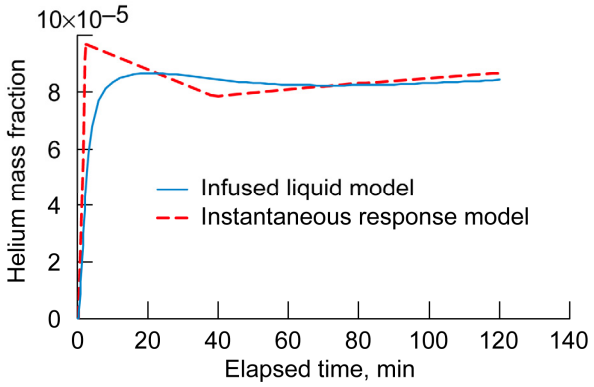


Figure 18.—Comparison of infused liquid model's predicted soluble helium mass fraction for special solubility test to instantaneous response model's value based on measured pressure and spatially averaged temperature.

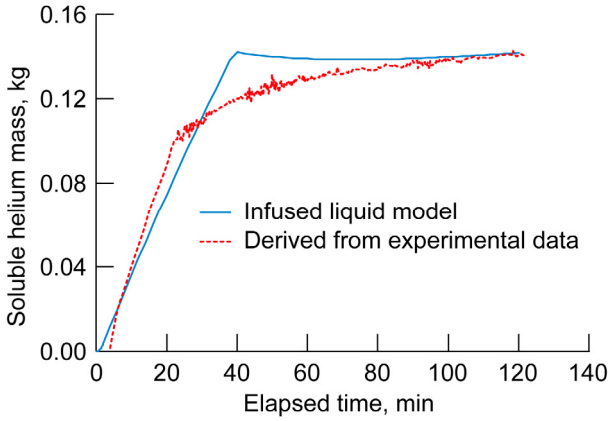


Figure 19.—Comparison of predicted and experimental soluble helium mass histories for special solubility test 25.

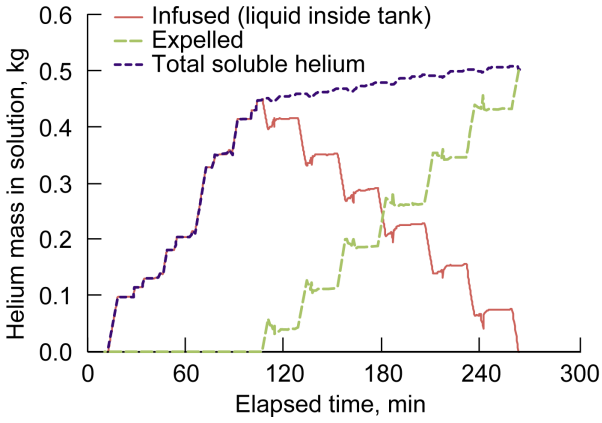


Figure 20.—Soluble helium mass histories for pressure-volume-temperature test 19.

Figure 19 compares the time-dependent predicted soluble GHe mass from the model with experimentally derived values. The experimentally derived values were obtained by integrating the GHe flowrate into the tank and then subtracting the GHe mass in the ullage (found by using pressure and temperature to obtain the oxygen partial pressure, the GHe partial pressure, the GHe density, and the fill fraction based on the load cell readings). The uncertainty for this calculation was high during the initial phase when the temperature and pressure spikes occurred (most likely creating nonuniform ullage conditions), but otherwise, this calculation is thought to be reasonably accurate. Figure 19 shows that the experimentally derived curve is steeper initially and then more rounded. The sharp bend in the model's prediction occurred when the tank turnover time was reached. The predicted and experimentally derived values for soluble GHe mass are in good agreement when the elapsed time is large. The final predicted mass fraction of 8×10^{-5}, corresponding to a mole percent of 0.07 percent, is below the sample analysis detection limit and, therefore, could not be compared with a sample analysis. Overall, we think that the agreement is reasonably good for a simple model and that the model is useful and sufficient for a more refined analysis of the PVT test data.

This model required a few additional features for predicting the mass of soluble GHe in the PVT tests:

(1) During PVT gauging, the pump was operated intermittently. Therefore, the GHe-infused liquid volume grew only when the pump was on.
(2) If liquid was expelled before the turnover time was reached (pumped volume was less than the liquid volume), the expelled liquid was free of infused GHe.
(3) If liquid was expelled after the turnover time was reached, the infused volume decreased and the expelled liquid had the same GHe mass fraction as the infused volume.
(4) The mass of expelled soluble GHe was integrated over time and accounted for in the overall PVT GHe mass balance.

Figure 20 shows an example of the predicted GHe solubility for test 19 (LO_2 at 1.65 MPa). Similar trends were obtained for the other tests with lesser amounts of GHe going into solution at the lower test pressures. There was no expelled GHe (soluble GHe in the expelled liquid) until the fill fraction dropped to about 0.6 (at approximately 110 min in the example). The total soluble GHe was the sum of GHe infused in the liquid inside the tank plus GHe infused in the expelled liquid. The rate at which GHe was lost to solubility was greatest early in the tests because initially there was no soluble GHe in the liquid being pumped through the spray hoops. Later, when all the liquid was infused with GHe and liquid was expelled, the slow increase in total soluble GHe was due to the increasing propellant tank temperature.

Generally, the amount of GHe in solution, as a percentage of total GHe transferred to the propellant tank, decreased with fill fraction for all tests. At the minimum fill fraction (0.05 to 0.10), the soluble GHe as a percent of total transferred GHe was about 2 percent for LO_2 and 3 percent for LN_2. These values are less than the worst-case estimates because some of the liquid was removed from the propellant tank before the entire liquid volume had become infused with GHe at the equilibrium mole fraction.

Appendix B.—Correction for Effects of External Volumes

The analysis was simplified by grouping the fluid temperatures into three classifications: the known GHe supply and propellant tank temperatures were defined as "cold," the "warm" ambient temperature was assumed to be 290 K, and the "cool" temperature was the average of the warm and cold temperatures. The fluids in the external volumes of the GHe supply tank and in the portion of the lines attached to the propellant tank, but outside the vacuum chamber, were assumed to be at the warm temperature; most of these lines were not insulated and were exposed to outdoor ambient conditions. The fluids in the remaining portions of volumes attached to the propellant tank but inside the vacuum chamber were assumed to be at the cool temperature; these lines also were uninsulated but were within a vacuum environment. The assumption of cool temperatures was partially verified by temperature measurements inside the fill and vent lines. Further assumptions (discussed shortly) were made regarding the fluid composition inside the various external volumes. The revised equations that include these corrections follow:

Mass of GHe transferred from the GHe supply tank:

$$\Delta m^* = (\rho_{bi} - \rho_b)(V_b - V_{be}) + (\rho_{bei} - \rho_{be})V_{be} \qquad \text{(B1)}$$

where b, e, and i refer to bottle, external, and initial.

Mass of GHe in the propellant tank ullage excluding the extended tank volumes:

$$m^*_{\mathrm{He},u} = \Delta m^* - \sum m_e \qquad \text{(B2)}$$

Total propellant tank ullage volume including the extended propellant tank volumes:

$$V^*_u = \frac{m^*_{\mathrm{He},u}}{\rho_{\mathrm{He}}} + \sum V_{te} \qquad \text{(B3)}$$

Details of individual corrections follow:

(1) All of the various lines attached to the GHe supply tank contained warm, pure GHe. The total volume of these lines was 0.08 percent of the GHe supply tank volume. The result was about a 0.05-percent reduction in the calculated Δm. The resulting PVT fill level measurement correction increased from 0 percent at 100-percent fill to 0.05 percent at 0-percent fill.

(2) The GHe transfer line attached to the propellant tank was assumed to contain pure GHe. There were warm and cool segments. The total volume of this line was 0.09 percent of the propellant tank volume. This adjustment caused a 0.05-percent reduction in the measured fill level.

(3) The propellant tank vent line initially contained vapor, but GHe entered the vent line during the initial propellant tank pressurization, so the vent line was assumed to contain the same mixture composition as the ullage. The total volume of this line was 0.26 percent of the tank volume. It also had warm and cool segments. This correction reduced the PVT result by 0.15 percent.

(4) The fill and drain lines, plus a set of liquid extraction lines used for a separate test series of Joule-Thomson devices, would not ingest GHe unless the tank was either empty or almost empty and could, therefore, be assumed to contain pure vaporized propellant. The temperature of these line volumes was not important because there was no impact on the GHe mass balance. However, the volumes were part of the overall propellant tank volume. The total volume of these lines was 0.13 percent of the tank volume. Correcting for these external volumes reduced the calculated fill level by 0.13 percent.

(5) Sampling lines used to extract both ullage and liquid samples for the chemical composition analysis had the smallest volume of all the external volumes considered and could be neglected in this regard. However, when samples were withdrawn, the GHe mass balance could be affected. This is discussed in the Experimental Gauging Results section.

Appendix C.—Uncertainty of Pressure-Volume-Temperature Measurements

An uncertainty analysis was performed on a few representative PVT tests (tests 20, 24, and 29) to obtain rigorous estimates of the PVT gauging measurement error for the tests reported herein. The methodology used was based on the work of Coleman and Steele (Ref. 5). The analysis was applied to Equations (1) to (6), where Equation (5) was revised to include the mass of GHe dissolved in the liquid m_{sol} as follows:

$$V_u = \frac{\Delta m - m_{sol}}{\rho_{He}} \tag{C1}$$

Interested readers are referred to a similar analysis by Van Dresar (Ref. 3) for further details. A key result of this earlier work was the development of a relationship expressing the uncertainty of the GHe density in the propellant tank's ullage as the sum of the effects of temperature and pressure measurement uncertainty:

$$U_{\rho_{He}}^2 = \left[\frac{\rho_{He}}{P_{He}}\left(\frac{P_{He}}{T_t} - \frac{dP_{sat}}{dT}\right)\right]^2 U_{T_t}^2 + \left(\frac{\rho_{He}}{P_{He}}\right)^2 U_{P_t}^2 \tag{C2}$$

Note that there is an indirect effect of ullage temperature measurement uncertainty (the dP_{sat}/dT term) on the uncertainty of the GHe density in the propellant tank's ullage. This arises from the use of Equation (4) where the propellant's vapor pressure is used to determine the partial pressure of GHe in the ullage. The expression dP_{sat}/dT was calculated using the Clausius-Clapeyron Equation.

Table IV shows the uncertainty values input to the analyses. Most of the values were previously discussed in the main body of this report. There was one addition: the uncertainty of the dissolved GHe mass was taken to be 20 percent on the basis of the data plotted in Figure 19. As will be seen shortly, the GHe solubility uncertainty played a small part in the overall PVT uncertainty result.

Figure 7 shows error bars based on the uncertainty calculations for test 24 (LO_2 at 1.65 MPa). The uncertainty ranges from 0.6 to 1.4 percent of the full-scale propellant tank volume, with the largest uncertainty occurring at the lowest fill fraction. Results for the other tests at this propellant tank pressure should be similar. Uncertainties also were calculated for test 29 (LN_2 at 1.03 MPa), with identical uncertainty value input as for the analysis of test 24. As shown in Figure 8, the uncertainty ranged from 0.7 to 1.7 percent of full-scale volume—slightly greater than, but otherwise very similar to, the higher propellant tank pressure case shown in Figure 7. The differences in the error bar ranges between the LO_2 and LN_2 cases are minor for Figures 7 and 8. Figure 9 shows the error bars for test 20 at the lowest propellant tank pressure. The PVT gauging uncertainty for this test ranged from 1.9 to 3.8 percent, with the uncertainty increasing as the liquid fill fraction decreased. The low-range pressure transducer for the GHe supply tank was over ranged (and was valved off) at the start of all 0.34-MPa tests (e.g., test 20), and it could not be used as planned. The higher uncertainty of the lowest propellant tank pressure tests is partly due to the greater uncertainty of the GHe supply pressure measurement (because of less than optimal sizing of the pressure transducer) and, in the case of test 30, the likely failure of the low-range propellant tank pressure transducer (which was not addressed in the uncertainty analysis).

There is another source of uncertainty or error not included in the error bars of Figures 7 to 9. This is the possible error of the RGS. Earlier, in the discussion of the calibration of the RGS as a function of applied load (simulated liquid fill fraction) and propellant tank pressure and temperature, the goodness of fit of the correlation was ±0.25 percent of the full-scale LO_2 weight. There is no apparent trend of the error with any of the listed parameters. This uncertainty source is small, but not negligible, especially at the higher fill fractions and higher propellant tank pressures where the PVT uncertainty is lowest.

TABLE IV.—UNCERTAINTY VALUES USED IN UNCERTAINTY ANALYSES

Uncertainty terms	Test 24 (LO_2 at 1.65 MPa) Test 29 (LN_2 at 1.03 MPa)	Test 20 (LO_2 at 0.34 MPa)
Propellant tank volume	±1.0 percent	Same
Helium supply tank volume	±0.6 percent	Same
Propellant tank pressure	±0.11 percent of full scale (±2.27 kPa)	Same (±0.76 Pa)
Helium supply tank pressure[a]	±0.10 percent of full scale (±13.8 kPa)	Same
Propellant tank ullage temperature	±0.25 K	Same
Helium supply tank temperature[a]	±0.25 K	Same
Helium mass dissolved in liquid propellant	±20 percent	Same

[a]Both initial condition and time of gauging measurement.

Figures 21 and 22 show the uncertainty percentage contributions for the highest (1.65 MPa) and lowest (0.34) propellant tank pressure tests. The sources of uncertainty are the nine terms listed in the leftmost column of Table IV. A comparison of Figures 21 and 22 shows that the two cases are very different. For the high-pressure case, the GHe supply-tank temperature measurement was the major contributor of uncertainty at high propellant tank fill fractions. As the fill fraction dropped, the GHe supply-tank temperature contribution diminished, and the largest source of uncertainty became the propellant tank volume uncertainty. For the low propellant tank pressure example, the GHe supply tank pressure measurement dominated the uncertainty at high propellant tank liquid fill fractions and remained a major source of uncertainty as the fill fraction was reduced. At the lower fill fractions, the propellant tank temperature uncertainty became a major source of uncertainty. If the full-scale range of GHe supply tank pressure transducer had been better matched to the initial conditions for this test, its contribution would have been reduced and the other terms would have been more significant, especially the uncertainty of the propellant tank temperature.

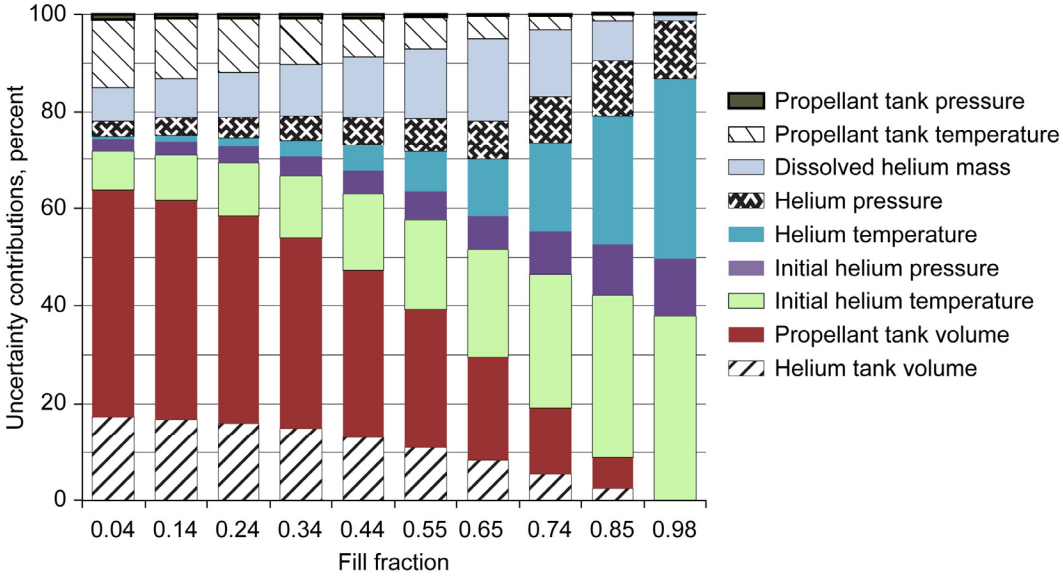


Figure 21.—Uncertainty percentage contributions for test 24—liquid oxygen at 1.65 MPa.

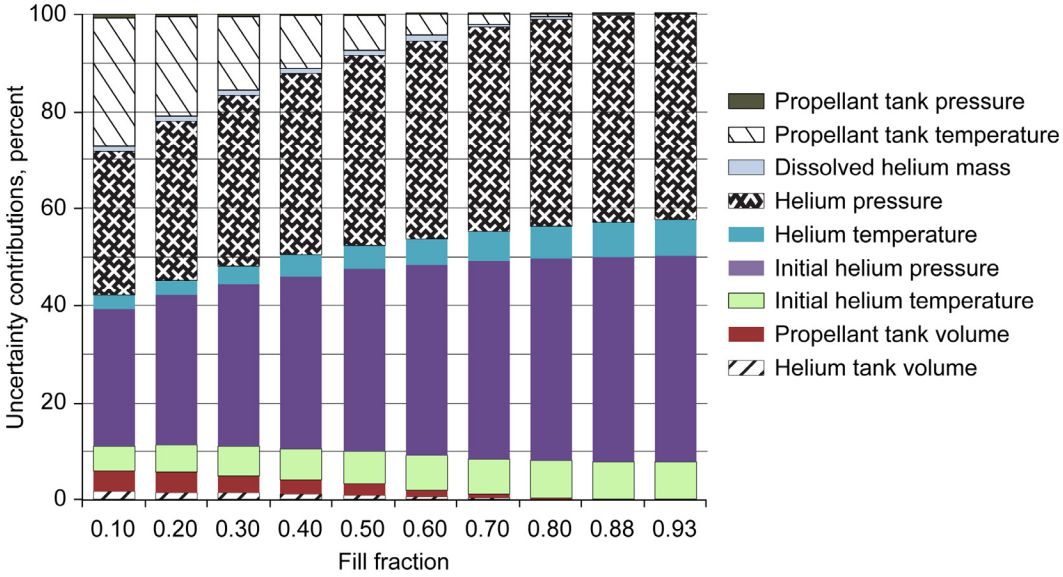


Figure 22.—Uncertainty percentage contributions for test 20—liquid oxygen at 0.34 MPa.

Appendix D.—Pressure-Volume-Temperature Gauging of a Thermally Stratified Propellant Tank

A thermally stratified PVT gauging test was conducted to investigate the applicability of the PVT method to a case with substantial thermal stratification within the propellant tank. The test apparatus was the same as used for the isothermal PVT tests. For the thermally stratified PVT test, the propellant tank's liquid pump was not operated, thus allowing thermal gradients to develop in the propellant tank because of heat input from the external environment, warm tank lid, and GHe pressurant. The GHe supply tank was kept at room temperature, about 290 K, compared with the 90 K supply temperature used for the isothermal PVT tests. The single test point analyzed in this appendix was from an LO_2 test at a liquid fill level of approximately 10 percent. The propellant tank pressure was 1.28 MPa, and the temperature profile is shown in Figure 23, where the symbols denote test data. The solid line is a fitted profile generated by a piecewise cubic Hermite interpolating polynomial, which preserves the shape of the data and respects monotonicity. Figure 23 shows that that the propellant tank condition was far from isothermal. Determining an average propellant tank temperature that will result in an accurate PVT gauging measurement may not be realistic.

One can start by noting that the previously presented analysis for the mass transferred from the GHe supply tank to the propellant tank (i.e., Eqs. (1) to (3)) is still valid. The only difference is that the supply tank temperature was at room temperature and consequently, there was no need to treat the external supply tank volumes separately because they were also at room temperature.

Proceeding with the isothermal analysis on the propellant tank (the subject of the main body of this report), a gauging result can be obtained for an assumed "averaged" propellant tank temperature. One can infer from Figure 23 that this temperature must fall between the minimum and maximum temperatures (94 and 172 K). Figure 24 shows the results of this approach. As the temperature was increased, the computed fill level dropped substantially from 33 percent to 0. Above 107 K, it was not possible for oxygen and GHe to coexist at the test pressure of 1.28 MPa. Lower temperatures, as low as the oxygen triple point, were possible if the propellant tank was actively cooled, as partially indicated by the dashed line. Clearly, applying the isothermal PVT calculation method to this thermally stratified example involves unacceptably high uncertainty in the gauging result.

As expected, the RGS was much less sensitive to the "average" propellant tank temperature. If Equations (8) and (9) are employed for this example, the resulting RGS gauging measurements are obtained as shown in Figure 25. The RGS calculation gave a liquid fill level ranging from 9.1 to 8.9 percent for the range of temperatures shown in Figure 24.

A detailed analysis is shown to demonstrate that an accurate PVT gauging result is possible if sufficient data are available

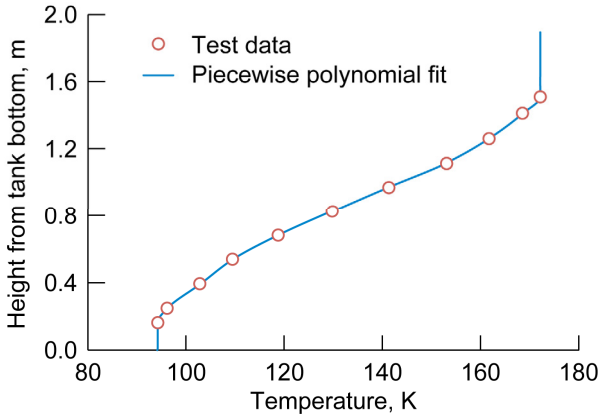


Figure 23.—Propellant tank temperature profile for thermally stratified example.

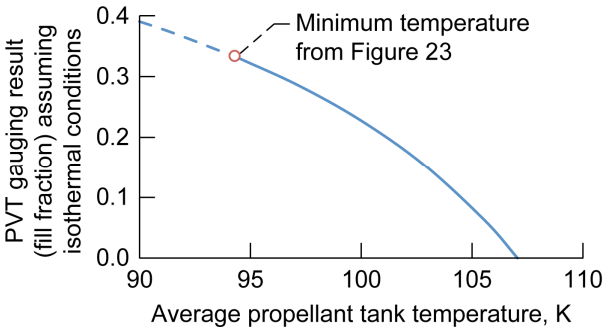


Figure 24.—Resulting pressure-volume-temperature (PVT) measurement when isothermal conditions were assumed for thermally stratified test example.

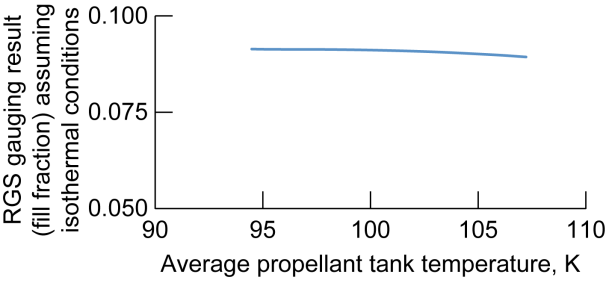


Figure 25.—Resulting reference gauging system (RGS) measurement when isothermal conditions were assumed for thermally stratified test example.

to quantify the thermal stratification, and to a lesser extent, the GHe concentration gradient. An increased level of complexity is required to produce a more accurate PVT gauging result. The additional complexity involves nonuniform temperature and GHe concentration profiles in the propellant tank's ullage. The available data were one dimensional; therefore, it was assumed that the temperature and GHe concentration profiles

were functions of the vertical position only. The temperature data were frequently measured and recorded over the entire duration of the test at distributed locations from the top to bottom of the propellant tank, but the GHe concentration was sampled only at a small number of locations at a limited number of times during the test. At the nominal 10-percent fill level, GHe concentration samples were available for three locations in the ullage corresponding to fill level locations of 20, 50, and 80 percent. This allowed us to estimate the GHe concentration profile as accurately as possible. The availability of GHe concentration data was the reason that this specific test point was chosen for the detailed analysis of a stratified PVT gauging measurement.

To make the fitted temperature distribution usable, a software function was developed to calculate the tank segment volumes as a function of height from the base of the tank. The tank consisted of five segments stacked as shown in Figure 26: bottom head, lower cylinder, truncated transitional head, upper cylinder, and top head. Each head had a 2:1 ellipsoidal geometry. For the detailed PVT analysis, the tank was further segmented into thin horizontal volume slices. The slice thicknesses were approximately 13 mm or less, with adjustments for thermal contraction. The slice containing the liquid-vapor interface (LVI) was divided into two parts, one for each phase. The temperature of each slice was obtained from the fitted temperature distribution. Volumes of each slice were computed by the software function. GHe densities were found for each slice by inputting the local temperature and GHe partial pressure to a fluid properties software program (Ref. 8).

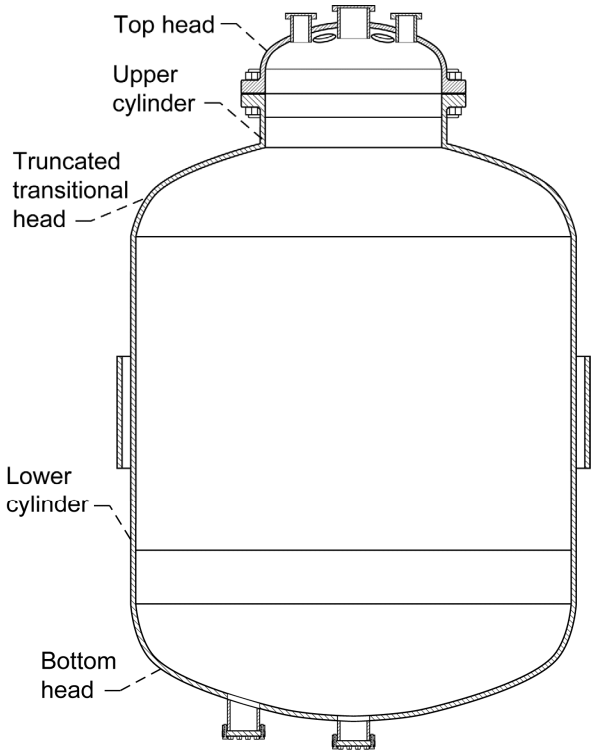


Figure 26.—Cross-sectional view of propellant tank.

The first slice-method analysis assumed a constant GHe partial pressure throughout the ullage. The method iterated the location of the LVI until the mass of GHe in the propellant tank ullage equaled the GHe mass transferred from the GHe supply tank. The partial pressure was obtained from Equation (4) using the temperature at the LVI location. The GHe mass in the propellant tank was obtained by numerically integrating over all the ullage slices. A similar slice-method analysis was used to calculate the gauging result from the RGS. In the RGS analysis, the masses of the liquid, propellant vapor, and GHe were each determined for all slices of the tank volume and numerically integrated. The analysis iterated the location of the LVI until the calculated total mass equaled the result from Equation (8). Table V shows the results of the slice analyses. Equation (10) was again used to convert the RGS results to the same tank volume basis used for the PVT measurements. The PVT result was in much better agreement with the RGS measurement (a difference of 3.2 percent of tank volume) when the thermal stratification data were included in the analysis.

Both the PVT and RGS slice analyses account for the propellant tank external volumes and the different temperatures and GHe concentrations in these external volumes. (See App. B for more details about the external volumes.) There is no correction for the external volume of the GHe supply tank because this tank was at room temperature for the stratified PVT test. The propellant tank volume calculated from the tank geometry was slightly larger than the measured volume reported earlier in this report, primarily because of the displaced volume from internal hardware such as the pump, instrumentation rakes and leads, and the spray bar system. The difference was about 0.025 m^3, or 1.6 percent of the tank volume, so the slice volumes were reduced by this amount to adjust for the displaced volume.

TABLE V.—GAUGING RESULTS FOR STRATIFIED PRESSURE-VOLUME-TEMPERATURE (PVT) EXAMPLE

Modeling approach	PVT fill fraction	RGS[a] fill fraction
Isothermal	0 to 0.33 (unreliable)	0.089 to 0.091
Fitted temperature profile with constant GHe concentration in ullage (first slice method)	0.063	0.095
Fitted temperature profile and fitted GHe concentration (second slice method)	0.096	0.097

[a]Reference gauging system.

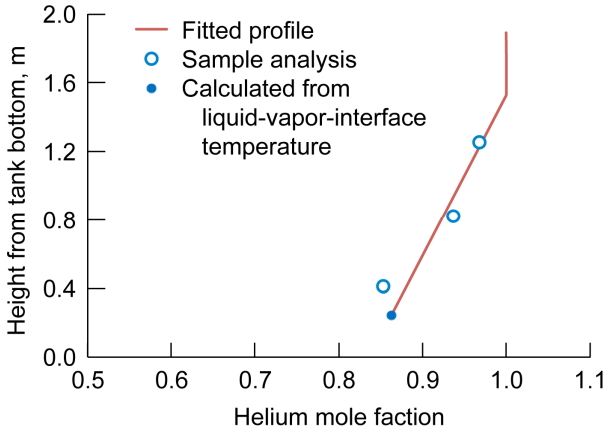


Figure 27.—Helium concentration for stratified pressure-volume-temperature test at fill fraction of 0.1.

Figure 27 shows the GHe concentration profile in the propellant tank. The experimental results (sample analysis) were obtained from gas chromatography of the extracted samples. The calculated and fitted results were generated by a second, more complex, slice analysis for the PVT and RGS measurement methods that accounted for nonuniform distributions of both temperature and GHe concentration. This analysis was identical to the first slice method discussed earlier except that it used a fitted linear GHe mole fraction distribution. It was assumed that the GHe mole fraction at the liquid-vapor interface (LVI) should equal the ratio of the GHe partial pressure to the total tank pressure, as is the case for the isothermal PVT measurement methodology. The curve-fit was constrained by the conditions that the GHe mole fraction could not exceed unity and that the fitted line should intercept the computed value at the LVI. In the numerical procedure, the unknown height of the LVI (in essence, the PVT gauging objective) was iterated until the GHe mass balance was satisfied. The corresponding temperature at this height (obtained from the piecewise polynomial fit shown in Figure 23) was used to find the propellant's vapor pressure. The GHe partial pressure was obtained using Equation (4), and the GHe mole fraction was calculated by dividing the GHe partial pressure by the total tank pressure. The linear fit of the GHe concentration profile was recalculated during each iteration because the LVI location and GHe mole fraction at the LVI were updated every iteration.

Results from the second analysis are also shown in Table V. The difference between the PVT and RGS measurements was reduced further, to within 0.1 percent of the tank volume. Again, the change in the RGS result was much smaller than the change in the PVT result, but it was still significant.

These results show that an accurate PVT result can be obtained given sufficient information about the temperature and GHe concentration profiles within the propellant tank. For the example shown, with a settled normal gravity liquid orientation in the tank, a relatively simple one-dimensional analysis could be successfully used because of several reasons. First, the liquid and ullage regions were separated by a simple well-characterized interface that was perpendicular to the tank's axis of symmetry. Second, posttest GHe concentration data were available from chemical analysis of the extracted samples. Clearly, further development of this method will be required to perform stratified PVT measurements in real time.

Application of the second method is not considered to be practical in spaceflight systems because of the difficulty of obtaining real-time GHe concentration data. Use of the first method will be possible if distributed temperature sensors are available to capture the temperature distribution within the propellant tank. As the example in this appendix shows, the stratified PVT measurement error will likely be greater than an isothermal PVT measurement.

Glenn Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February, 2014

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14. ABSTRACT
Results are presented for pressure-volume-temperature (PVT) gauging of a liquid oxygen/liquid nitrogen tank pressurized with gaseous helium that was supplied by a high-pressure cryogenic tank simulating a cold helium supply bottle on a spacecraft. The fluid inside the test tank was kept isothermal by frequent operation of a liquid circulation pump and spray system, and the propellant tank was suspended from load cells to obtain a high-accuracy reference standard for the gauging measurements. Liquid quantity gauging errors of less than 2 percent of the tank volume were obtained when quasi-steady-state conditions existed in the propellant and helium supply tanks. Accurate gauging required careful attention to, and corrections for, second-order effects of helium solubility in the liquid propellant plus differences in the propellant/helium composition and temperature in the various plumbing lines attached to the tanks. On the basis of results from a helium solubility test, a model was developed to predict the amount of helium dissolved in the liquid as a function of cumulative pump operation time. Use of this model allowed correction of the basic PVT gauging calculations and attainment of the reported gauging accuracy. This helium solubility model is system specific, but it may be adaptable to other hardware systems.

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