U.S. Department of Transportation

National Highway Traffic Safety Administration

NHTSA

DOT HS 812 377 April 2017

Evaluation of Methodology for LPG Fuel System Integrity Tank Test

DISCLAIMER

Suggested APA Format Citation:

Packard, M. H., & Stoltzfus, D. (2017, April). *Evaluation of methodology for LPG fuel system integrity tank test* (Report No. DOT HS xxx xxx). Washington, DC: National Highway Traffic Safety Administration.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT HS 812 337		NA

4. Title and Subtitle
Evaluation of Methodology for LPG Fuel System Integrity Tank Test

5. Report Date
April 2017

6. Performing Organization Code
NHTSA/NSR-130

7. Author(s)
M. H. Packard, National Highway Traffic Safety Administration
D. Stoltzfus, Transportation Research Center Inc.

8. Performing Organization Report No.

9. Performing Organization Name and Address
National Highway Traffic Safety Administration
Vehicle Research and Test Center
P.O. Box B-37
East Liberty OH 43319

10. Work Unit No. (TRAIS)n code
NA

11. Contract of Grant No.
NA

12. Sponsoring Agency Name and Address
National Highway Traffic Safety Administration
1200 New Jersey Avenue SE.
Washington DC 20590

13. Type of Report and Period Covered
Final
June 2014– August 2015

14. Sponsoring Agency C ode

15. Supplementary Notes
NA

16. Abstract

In response to a petition for rulemaking from General Motors Company to adopt new fuel system integrity requirements for liquefied petroleum gas (LPG) vehicles, the National Highway Traffic Safety Administration evaluated the feasibility of assessing fuel leakage from LPG vehicles after a crash test.

The primary challenge for evaluating the fuel system integrity of LPG-fueled vehicles is that LPG exists as both a liquid and a gas in the tank, which is not practical to exactly duplicate during a crash test. However, use of pressurized water and nitrogen was shown to be a reasonable simulation. Loss of "fuel" can be determined by post-crash test measurements of both pressure drop in the tank and volume of liquid lost. Depending on the number of leaks and their locations, a measured post-test pressure drop may be due to a gaseous leak, a liquid leak (pressure drop due to increased gas volume in tank from loss of liquid), or both. Also, the pressure drop due to only a marginal loss of liquid (805 g of water) is relatively small compared to the total tank pressure, particularly for larger LPG tanks.

Results of this project showed promise for using pressure drop and liquid fluid leakage measurements to evaluate the fuel system integrity of LPG-fueled vehicles during crash tests. This study showed that pressure transducers and data acquisition systems are available that can accurately measure the relatively small pressure drop associated with a marginal failure condition, but care must be taken to account for ambient pressure and temperature changes.

17. Key Words
Autogas, CNG, crash, crash test, DOT, FMVSS, fuel system, GM, leak test, LPG, NHTSA, propane

18. Distribution Statement
Available to the public from the National Technical Information System, www.ntis.gov

19. Security Classif. (of this report)	20. Security Classif. (of this page)	No. of Pages	22. Price
Unclassified	Unclassified	58	NA

FORM DOT F1700.7 (8-72) Reproduction of completed page authorized

TABLE OF CONTENTS

EXECUTIVE SUMMARY 1
1.0 – INTRODUCTION 1
2.0 – BACKGROUND 3
3.0 – TEST PROCEDURE 4
3.1 – Test Procedures - General 4
3.2 – Test Setup and System/Component Description 7
3.3 – Test Procedure – Liquid Leak Testing - Details 9
3.4 – Test Procedure – Gaseous Leak Testing 13
4.0 – RESULTS 14
4.1 – Small Tank Leak Testing Results 14
4.11 – Theoretical Calculations 14
4.12 – Drain of 805 g Water in 30 min – One-Hour Test 16
4.13 – Drain 805 g of Water in 30 min – Two-Hour Test 18
4.14 – Drain 1610 g of Water in 60 min 20
4.15 – Gaseous Leak Testing 22
4.2 – Large Tank Leak Testing Results 22
4.21 – Theoretical Calculations 22
4.22 – Drain of 805 g Water in 30 min 23
4.23 – Drain of 1610 g of Water in 60 min 25
5.0 – FINDINGS AND DISCUSSION 27
5.1 – Findings 27
5.2 – Discussion 28
6.0 – ADDITIONAL TESTS 28
Appendix A – General Information A-1
Appendix B – Special Tests B-1
Appendix B1 – Variable Leakage Rate Tests B-2
Appendix B2 – Rapid Pressure Drop Leak Test B-4
Appendix B3 – Evaluation of Tank Fill Procedures B-5
Appendix B4 – Tank Temperature and Ambient Temperature Relationships B-6
Appendix B5 – Large Pressure Drop Volume Evaluations B-7
Appendix B6 – Large Tank Overrun Test B-8
Appendix C – Calculations Details C-1
Appendix C1 – Calculations LPG Equivalent and Energy Content Values C-2
Appendix C2 – Calculations of Gaseous Leak Rates C-3
Appendix D – Tank Technical Data D-1
Appendix E – Other Data Runs E-1

LIST OF TABLES

Table 1 – Theoretical Calculations for Drain of 805 g Water for 30 min – 26.2 Gallon Tank 14
Table 2 – Run 1140 – 26.2 Gallon Tank – Drain 805 g Water in 30 min – One-Hour Test 16
Table 3 – Test 1140 – 26.2 Gallon Tank, Drain of 805 g Water in 30 min, One-Hour Test – Summary 17
Table 4 – Run 1189 – 26.2 Gallon Tank – Drain of 805 g Water in 30 min – Two-Hour Test 18
Table 5 – Test 1189 – 26.2 Gallon Tank, Drain of 805 g in 30 min – Two-Hour Test – Summary 19
Table 6 – Run 1209 – 26.2 Gallon Tank – Drain of 1610 g Water in 60 min – Two-Hour Test 20
Table 7 – Run 1209 – 26.2 Gallon Tank – Drain of 1610 g Water in 60 min – Summary 21
Table 8 – Theoretical Calculations for Drain of 805 g Water in 30 min – 41.4 Gallon Tank 22
Table 9 – Run 1280 – 41.4 Gallon Tank – Drain of 805 g Water in 30 min – Two-Hour Test 23
Table 10 – Run 1280 – 41.4 Gallon Tank – Drain of 805 g Water in 30 min – Summary 24
Table 11 – Run 1287 – 41.4 Gallon Tank – Drain of 1610 g Water in 60 min 25
Table 12 – Run 1287 – 41.4 Gallon Tank – Drain of 1610 g Water in 60 min – Summary Data 26
Table 13 – Acronym List A-2
Table 14 – References Consulted A-3
Table 15 – Equipment and Instrumentation A-4
Table 16 – 26.6 Gallon Tank – Pressure and Temperature Change = f (leakage rate) B-2
Table 17 – Run 1173 – 26.2 Gallon Tank - Drain of 805 g Water in 1.78 min – Input Data B-4
Table 18 – Run 1173 – 26.2 Gallon Tank - Drain of 805 g Water in 1.78 min – Detailed Results B-4
Table 19 – Calculated Drain of Water Small Tank for 15.5 psi Pressure Drop @Exact NT B-7
Table 20 – Calculated Drain of Water Large Tank for 15.5 psi Pressure Drop @Exact NT B-7
Table 21 – 41.4 Gallon Tank - Drain of 1900 g at 26.8 g/min for 70 min – Stop at 120 min B-8
Table 22 – Run 1303 – 41.4 Gallon Tank – Drain of 1901 g Water in 70 min – Summary B-9
Table 23 – Detailed Tank Specifications D-2
Table 24 – Summary of Regular Test Data for Small Tank (26.2 gallon) E-2
Table 25 – Summary of Regular Test Data for Large Tank (41.4 gallon) E-3

LIST OF FIGURES

Figure 1 - Typical 26.2 Gallon LPG Automotive Fuel Tank With Test Components 7
Figure 2 – 41.4 Gallon LPG Tank Test Setup 8
Figure 3 – Data Acquisition System With Ambient Pressure and Temperature Transducers 9
Figure 4 – Operations to Perform a Leak Test on an LPG Tank 11
Figure 5 – Needle Valve Close Up 12
Figure 6 – Pressure Transducers – Close Up 12
Figure 7 – Ambient Pressure Transducer 12
Figure 8 – Ambient Temperature Gauge 12
Figure 9 – Overall Test Setup 13
Figure 10 – Needle Valve on Gas Portion of Tank 13
Figure 11 – Test 1140 – 26.2 Gallon Tank, Drain of 805 g Water in 30 min – Pressure, Temperature = f (time) 17
Figure 12 – Test 1189 – 26.2 Gallon Tank, Drain of 805 g Water in 30 min – Pressure, Temperature = f (time) 19
Figure 13 – Test 1209 – Drain of 1610 g of H_2O in 60 min – Pressure, Temperature = f (time) 21
Figure 14 – Test 1280 – 41.4 Gallon Tank – 30 min Drain of 805 g of Water – Tank Pressure, Temperature = f (time) 24
Figure 15 – Test 1287 – 41.4 Gallon Tank – Drain of 1610 g of H_2O in 60 min, Tank Pressure, Temp. = f (time) 26
Figure 16 – 26.2 Gallon Tank – Initial Pressure and Temperature Drop = f (leakage rate) B-2
Figure 17 – 26.2 Gallon Tank – Recovery of Initial Pressure and Temperature Drop = f (leakage rate) B-3
Figure 18 – Test 1173 – 26.2 Gal Tank – Fast Drain – Tank Pressure and Temperature = f (time) B-4
Figure 19 – 26.2 Gallon Tank – Internal Tank Temperature as a Function of Ambient Temperature B-6
Figure 20 – 41.4 Gallon Tank – Drain of 1900 g Water in 70 min B-9
Figure 21 – 26.2 Gallon Manchester LPG Tank PN 2380417 .... D-3
Figure 22 – 26.2 Gallon Manchester LPG Tank Serial No. Plate D-3
Figure 23 – 41.4 Gallon Manchester LPG Tank PN 20067 .... D-4
Figure 24 – 41.4 Gallon Manchester LPG Tank Serial No. Plate D-4

EXECUTIVE SUMMARY

In response to a petition for rulemaking from General Motors Company [1] to adopt new fuel system integrity requirements for liquefied petroleum gas (LPG) [2] fueled vehicles, the National Highway Traffic Safety Administration evaluated the feasibility of assessing fuel leakage from LPG vehicles after a crash test.

Specifically, the agency examined allowable levels of LPG spillage and pressure drop that was modeled after the theoretical derivation of the allowable compressed natural gas leakage specified in Federal Motor Vehicle Safety Standard (FMVSS) No. 303, "Fuel system integrity of compressed natural gas (CNG) vehicles," and that utilized the equivalent energy content of the allowable gasoline spillage requirement specified in FMVSS No. 301, "Fuel system integrity." Leakage would then be evaluated by examining the calculated amount of liquid propane that escapes from the tank in an equivalent period to gasoline and/or the amount of propane gas escaping from the tank during that same period. The allowable loss of LPG would be equivalent, based on the energy content of the fuel, to the allowable leakage of gasoline in FMVSS 301.

The primary challenge for evaluating the fuel system integrity of LPG-fueled vehicles is that LPG exists as both a liquid and a gas in the tank. However, use of pressurized water and nitrogen was shown to be a reasonable simulation. Loss of 'fuel' can be determined by post-crash test measurements of both pressure drop in the tank and the volume of liquid lost. Depending on the number of leaks and their locations, a measured post-test pressure drop may be due to a gaseous leak, a liquid leak (pressure drop due to increased gas volume in tank from loss of liquid), or both.

Results of this testing showed promise for using pressure drop and liquid fluid leakage measurements to evaluate the fuel system integrity of LPG-fueled vehicles during crash tests. This study showed that pressure transducers and data acquisition systems are available that can accurately measure these pressure drops, but care must be taken to account for ambient pressure and temperature changes.

1.0 – INTRODUCTION

In response to a petition for rulemaking from GM to adopt new fuel system integrity requirements for LPG fueled vehicles, NHTSA evaluated the feasibility of assessing fuel leakage from LPG vehicles after a crash test. Both FMVSS No. 301 for liquid-fueled vehicles and FMVSS No. 303 for CNG fueled vehicles require fuel system integrity in frontal, rear, and lateral barrier crashes for vehicles with a gross vehicle weight rating (GVWR) of 10,000 lb or less and in contoured barrier crash tests for school buses with a GVWR over 10,000 lb.

Propane is a gas at normal atmospheric pressure and temperature.[3] In a vehicle fuel tank, the propane would be in both a liquid and gas phase when under pressure.[4] Because of this, potential fuel leakage cannot be determined by direct measurement of the amount of fuel escaping from the vehicle as done for FMVSS No. 301.[5]

---

[1] Petition for Rulemakings – FMVSS 303 and Liquid Propane, , Date Jan. 3, 2011. Docket No. NHTSA-2011-0002-0001

[2] LPG is commonly known as propane. Propane typically consists of C_3H_8 (majority as propane) and C_4H_{10} (minority as butane). For our calculations we assumed liquid is all propane. Ref: www.afdc.energy.gov/fuels/fuel_properties.php (Retrieved October 9, 2014)

[3] The physical state of propane is a pressured liquid. At normal atmosphere pressure and temperature above -44 °F propane remains in its gas form. At lower temperature and/or higher pressure, propane will become a liquid.

[4] Propane is stored under pressure in the tank. As pressure is reduced/released the liquid propane is vaporizes and turns into gas.

[5] Note: propane is typically delivered to the vehicle engine as a liquid. It goes into a reducer (European term). a device through which the liquid propane is converted to gaseous phase, reducing and adjusting its pressure. The reducer receives heated water from the engine cooling system.

Leakage would then be evaluated by examining the calculated amount of liquid propane that escapes from the tank in an equivalent period to gasoline and/or the amount of propane gas escaping from the tank during that same period. The allowable loss of LPG would be equivalent, based on the energy content of the fuel, to the allowable leakage of gasoline in FMVSS No. 301. Since the LPG tank contains both a liquid and a gas, both leak rates have to be examined. Additionally, since the vehicle may undergo rotation in a fixture, similar to FMVSS No. 301, methods to evaluate and combine both the liquid and gas leakage rates may need to be considered.

NHTSA conducted this project at its Vehicle Research and Test Center (VRTC) to support the agency's future consideration of fuel systems integrity of LPG vehicles, by assessing the practical considerations involved in measuring LPG leakage after a crash test. The pressure drop evaluated during these tests represented only a marginal failure condition, such as a leak due to minor damage to fuel lines, since determination of non-compliance for a large leak is more evident.

This program consisted of the following:

1. Laboratory tests to evaluate the validity of measuring pressure drop as a result of leakage of an equivalent volume of water for small LPG tanks. This also involved evaluating the accuracy of commercially available instrumentation for measuring the relatively small pressure drop associated with a marginal failure condition.
2. Laboratory tests to evaluate the validity of measuring pressure drop as a result of leakage of an equivalent volume of water for large LPG tanks, where the change in pressure would be less than in a small tank, for the same volume of fuel loss.
3. Laboratory tests to evaluate the validity of measuring pressure drop as a result of leakage of a volume of gaseous propane through the identical size orifice that gave the maximum acceptable leak rate for water.

This report contains the results and findings from this study.

2.0 – BACKGROUND

The behavior of a real gas, at sufficiently low density, can be closely approximated by the ideal gas equation of state:

$$PV=nRT$$

Where:

P = absolute pressure Newton/meters^2 (N/m^2)
V = volume (m^3)
n = chemical amount (moles)
R = universal gas constant Joules/mole degree Kelvin[6] (J/mole * K)
T = temperature (K)

A slightly modified version of this equation adds a correction factor to account for the incompressibility of real gases. For nitrogen (the gas used for testing), which closely approximates an ideal gas over a large range of temperatures and pressures, this equation is as follows:

$$PV=ZnRT$$

Where:

Z = Correction Factor specific gas; for Nitrogen: Z is dimensionless with value near 1.[7]

A list of acronyms used in this report is provided in Appendix A1, and a list of references consulted for this research work is provided in Appendix A2.

For a constant volume system, this indicates that pressure drop is directly proportional to the temperature of the gas. For a system with both liquid and gas in a pressurized vessel, loss of liquid will result in an increase in gas volume along with a decrease in pressure. Alternatively, leakage can result in a loss of gas (n, moles of nitrogen). This in turn will affect the pressure and temperature equilibrium states of the gas. Gas temperature is also affected by the ambient temperature, and thus, gas pressure.

A series of bench tests was performed at VRTC to study the practical effects of gas loss on pressure and temperature in an LPG fuel system. The gas used in all of these tests was industrial (welding) grade nitrogen gas. The results and conclusions presented here are based on the results using nitrogen as the working gas. The behavior of propane in the gaseous state is generally considered to be a reasonable approximation of an ideal gas under the ranges of temperature and pressure discussed in these tests.

---

[6] R = 8.314 4598(48) (J/ mole * K) in SI units http://physics.nist.gov/cgi-bin/cuu/Value?r|search_for=gas+constant (retrieved June 28, 2016) or 8.3144598(48) (L * kPa)/ (mole*K). Standard uncertainty is 0.000 0048 (J / mol * K)

[7] Based on comparing ideal gas calculations to density calculations in our range of interest from Thermophysical Properties of Fluid Systems" in NIST Chemistry Web Book for temperature and pressure We also used (1/1) or one/one to specify a dimensionless value, and (a/n) for an alpha-numeric value.

3.0 – TEST PROCEDURE

The test procedure evaluated in this study was modeled after Canada's test procedure for testing the fuel system integrity of LPG vehicles. This involves filling the cylinder with water equivalent to that of the weight of LPG, pressurizing the remainder of the tank with nitrogen gas, and then conducting the crash test.

3.1 – Test Procedures - General

For the laboratory bench tests in this study, rather than impact the cylinders to induce damage and create a leak that is uncontrolled and unpredictable, the cylinders were retrofitted with regulators so that a controlled leak could be achieved (thus allowing an unlimited number of tests with the same cylinder).

The cylinders came with the necessary valves (fill, service, relief, etc.) as well as gauges (pressure, float, and fixed liquid level). Two commercial cylinders, a small 26.2 gallon (99.2 liters (L)) and a large 41.4 gallon (156.7 L) cylinder were fitted with a flow regulator that could control the amount of liquid output. Specifications of the two tanks used in the testing are provided in Appendix D. The cylinders were filled to 40 percent of capacity with water (weight equivalent substitute for 80% LPG fill). [8] [9] Using the fill valve, the remainder of the cylinder was pressurized with nitrogen to a gauge pressure of 292 pounds per square inch (psig), which was 20 pounds per square inch (psi) below the 312 psig maximum operating pressure of the both tanks as specified by the manufacturer.

The maximum allowable leak of liquid propane was based on the equivalent energy of the maximum allowable gasoline leak specified in FMVSS No. 301 (details provided in Appendix C1). The maximum allowable gasoline leak is 870 grams (g) in 30 minutes after a crash test. The equivalent energy maximum allowable LPG leak is 805 g.[10]

Tests were then conducted to verify the following:

1. That a leak in the liquid (water) portion of each tank through the flow regulator (at various rates up to 805 grams[11] [12] total in 30 minutes) will or will not lead to a detectable pressure drop of nitrogen.
2. That a leak in the gaseous portion of the tank from pressure measurement sensors (at various rates) is detectable. This was then compared to a historical reference of a 5 percent[13] cumulative potential measurement error as measured by the pressure gauges.
3. That the total pressure drop is less than 15.5 psi[14] over 60 minutes.

[8] For filling the tanks, all measurements of water were done by weight so the compressibility of water for initial tank fill and drainage was not considered. Also, compressibility of water was not evaluated in any other calculations. Actual density of water at 68 °F, 14.696 psia is 998.20715 kg/m^3 and at 68 °F, 310.0 psia is 999.13784 kg/m^3. E. W. Lemmon, M. O. McLinden & D. G. Friend, "Thermophysical Properties of Fluid Systems" in NIST Chemistry WebBook, NIST Standard Reference Database Number 69, Eds. P. J. Linstrom and W. G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, http://webbook.nist.gov, (retrieved April 1, 2015).

[9] A standard requirement is that LPG tanks be only filled to 80% volume to allow for liquid expansion. For testing we used water, which is approximately twice as heavy as LPG. Then 40% water will allow the tank system to be at a weight that a test vehicle would see.

[10] See Appendix C1 – Calculations LPG Equivalent and Energy Content Values

[11] Actual shut off of water may vary the amount slightly from the target amount of 805 grams. Actual flow rates will also vary due to changing flow rates as the tank pressure decreases.

[12] The figure of 805 g is total allowable from FMVSS 301.

[13] In FMVSS No. 303, the maximum allowable leak of CNG is the greater of 154 psi and $895*T/V_{F\ kiloPascals.}$ The 154 psi corresponds to 5% pressure drop from a 3,000 psi tank, which was considered as the cumulative error in pressure measurement. See April 25, 1994 Final rule establishing FMVSS No. 303. [59FR19648]

[14] Since 154 psi corresponds to 5% error in pressure measurement for a 3,000 psi tank, 5% error in measurement for a 300 psi tank (typical LPG tank) is 15.5 psi.

4. The accuracy at which current pressure transducers are capable of measuring at the targeted normal working pressure range (200-300 psi).

These tests were done at room temperature. A reference pressure transducer, thermocouples (tank and ambient temperature), a pressure transducer for ambient air pressure, and a digital scale to measure mass of water drained from the cylinder were used. Because the volume of liquid water drained was known (i.e. the volume for 805 g of water is 805 cubic centimeters (cc)), this became an exercise in verifying Boyle's law with initial pressures and all volumes known.

$$P_i V_i = Z_{N2}\, nRT_i$$

and

$$P_f V_f = Z_{N2}\, nRT_f$$

then

$$P_f - P_i = (Z_{N2} nRT_f) / V_f - (Z_{N2}\, nRT_i) / V_i$$

Assuming no change in ambient temperature or ambient pressure we have

$$P_i V_i = P_f V_f$$

Where V_i=0.6V cc, V_f=0.6V+805 cc, P_i=P_{max}=P_{start}

$$\Delta P = P_i - P_f = P_i(1 - \frac{V_i}{V_f})$$

$$\Delta P = (P_{max} - P_{start}) * [1/\{1 + (0.6V/805)\}]$$

Where:

P_{max} = max operating pressure [15] (psig)
P_{start} = test start operating pressure reduction (generally 20 psig)[16]

V = volume of tank
ΔP = change in tank pressure after fluid loss[17]
Z_{N2} = compressibility factor nitrogen
n = number of moles

There was a larger pressure drop initially because of temperature drop (due to expansion of the gas) when the liquid is being drained, which will partially recover as the temperature recovers. For a loss of 805 g of water, the theoretical change (at normal temperature and

[15] All calculations and pressure measurement values are performed using English units and are specified in gauge pressure (psig) unless otherwise noted. For our tanks maximum operating pressure is 312 psig so typical starting test pressure would be 20 psig lower.
[16] The precise test start operating pressure reduction is approximate since it requires multiple pressurizations and incremental pressurizations to achieve the approximate starting operating pressure due to cooling of the tank.
[17] stabilized at ambient temperature (or other defined stabilization condition)

pressure, NTP) [18] in pressure will be -4.1 psia for the small 26.2 gallon tank and -2.6 psia for the large 41.4 gallon tank (once the pressure and temperature have stabilized to ambient conditions).

Additional testing and evaluations notes:

1. Collect temperature and pressure data for different flow rates of liquid water drainage over 30 minutes.
2. Evaluate the pressure drop and energy loss of gas flowing through an orifice size that had been adjusted to allow 805 g of fluid to "leak" in 30 minutes.

[18] STP as commonly used in the Imperial and USA system of units - as air at 60 °F (520 °R) and 14.696 psia (15.6 °C , 1 atm); For these calculations, we used what is technically, NTP or Normal Temperature and Pressure, defined as air at 20 °C (293.15 K, 68 °F) and 1 atm (101.325 kN/m2, 101.325 kPa, 14.7 psia, 0 psig, 30 in Hg, 760 torr). Also note that STP - Standard Temperature and Pressure - is defined by IUPAC (International Union of Pure and Applied Chemistry) as air at 0 °C (273.15 K, 32 °F) and 10^5 Pascal. www.engineeringtoolbox.com/stp-standard-ntp-normal-air-d_772.html (Retrieved October 9, 2014)

3.2 – Test Setup and System/Component Description[19]

The test setup included a high pressure nitrogen tank, multiple pressure transducers, a tank thermocouple to measure nitrogen temperature (at the center of the circumference inside the tank), and a digital scale to measure the mass of water being evacuated from the device under test (DUT). The test setups for the 26.2 gallon and 41.4 gallon LPG tanks are shown in Figures 1 and 2, respectively.[20] The tanks each have a “FILL”[21] port that opens to the top of the tank, a “LIQUID” port which opens at the bottom of the tank, and a “RELIEF” port where pressure transducers were attached.

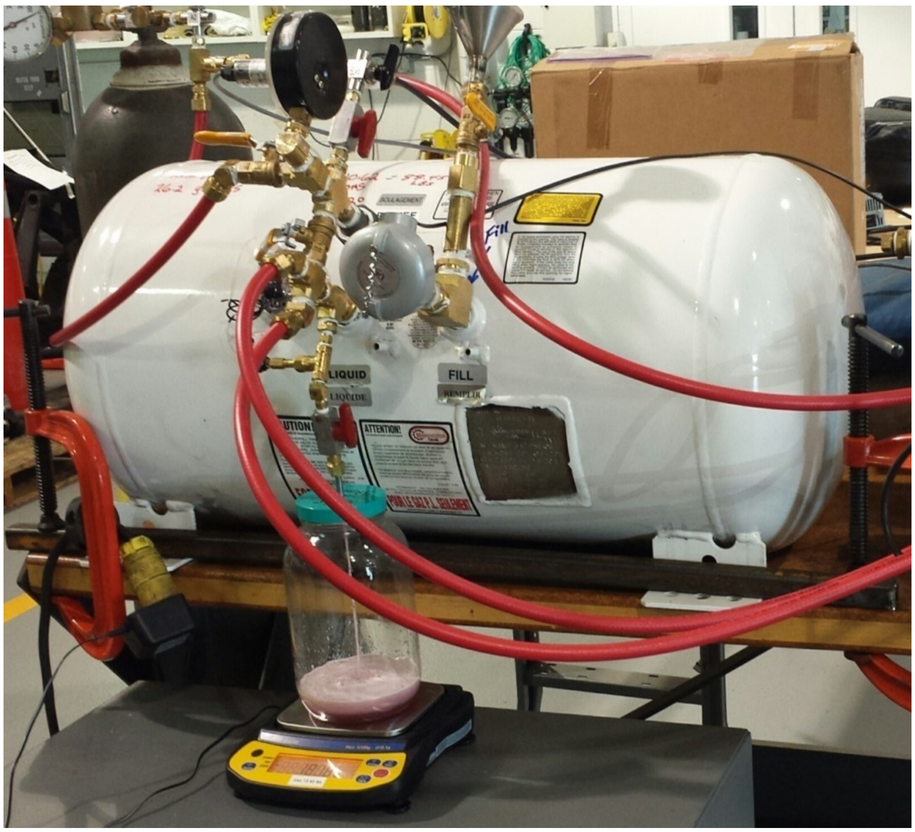


Figure 1 - Typical 26.2 Gallon LPG Automotive Fuel Tank with Test Components

[19] See Appendix A3 – Equipment and Instrumentation, for detailed information on components and instrumentation.

[20] The test tanks are automotive fuel tanks currently in production from Manchester Tank Corporation, 1000 Corporate Centre Drive, Suite 300, Franklin, TN 37067, Autogas tanks, liquid, vapor or dual service options, 80% stop fill device, seal welded stainless steel, with ASME nameplate; 312 PSI maximum allowable working pressure, and meet AASME Section VIII, Division I Code and meet NFPA # 58 standards for engine fuel applications.

[21] As labeled by the tank manufacturer. See Appendix D – Tank Technical Data, for detailed test tank specifications, detailed drawings, serialization specifications and other information.

Figure 2 – 41.4 Gallon LPG Tank Test Setup

A needle valve and a shutoff valve were attached to the liquid port on each tank. The fill port also had a shutoff valve and funnel for reintroducing liquid back into the tank after each test. The data acquisition system consisted of dedicated analog signal conditioners connected to a high speed multiplexer, and the data were processed with VRTC in-house software (see Figure 3).[22] Additionally, an ambient pressure transducer to measure atmospheric pressure and an ambient temperature thermocouple were used to evaluate temperature in the building that might affect results.[23] Details of instrumentation in these tests are provided in Appendix A3.[19]

[22] Signal conditioning of the data was provided by Analog Devices 3B series signal conditioning. Data was converted from analog to digital using a Measurement Computing Inc. PCMCIA DAS16/16 card, controlled by VRTC written software DAS16 version V14B. Data was acquired at a rate of 200 samples per second. Data was then averaged over a 100 sample interval and then subsampled to 2 samples per second. Post processing of the data was accomplished by using VRTC written software program DSAN_Win, version: 14C, version date: Oct-03-2014. Post processing consisted of filtering using a Butterworth 2-pole low pass phaseless filter with a 0.1 Hz cutoff (-3 dB) frequency.

[23] It was decided to run tests in a bay where some temperature changes occur so that it could more realistically evaluate conditions that would be experienced during an actual test. Additionally, ambient air pressure (raw) was evaluated so that gauge pressure readings could be evaluated as absolute pressures as well. Also, the Transportation Research Center Inc., on which VRTC is located, publishes raw ambient pressure readings as well as temperature, humidity and other readings which can assist in verifying any atmospheric conditions which might affect the tests.

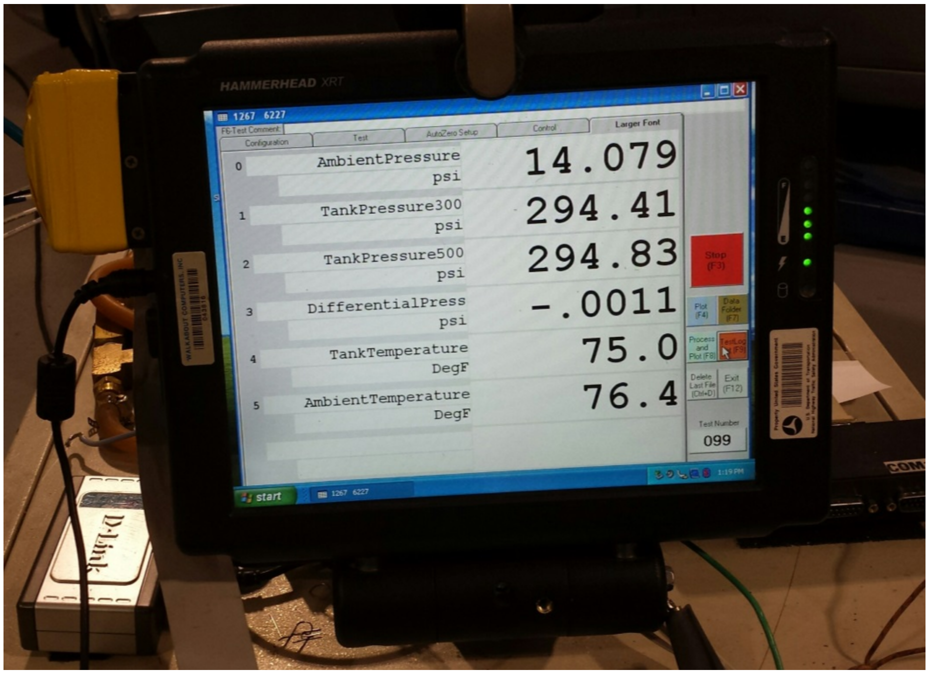


Figure 3 – Data Acquisition System with Ambient Pressure and Temperature Transducers

Tests were typically run with the specified leak rate over a 30-minute or 60-minute period, and data was collected over a 120-minute period to evaluate pressure and temperature stabilization and recovery. Following each test, the tank was depressurized and the water "leaked" from the tank was simply reintroduced into the tank. Then for the next test, the tank was repressurized to the desired level and allowed to stabilized, with additional minor re-pressurizations as needed.

3.3 – Test Procedure – Liquid Leak Testing - Details

1. As mentioned above, the LPG tanks were filled with water to 40 percent of their capacity. The weight of the water added to the small tank was 88.45 lb, and 139.77 lb of water was added to the large tank. We allowed an overnight soak so that the tank skin and water could reach approximate ambient temperature. [24]
2. The LPG tank was then pressurized to approximately 292 psi (actual pressure was temperature corrected) through at least two pressurizations, allowing for pressure and temperature stabilizations after each fill.[25]
3. The LPG tanks were fitted with a highly accurate pressure transducer[26] and a pressure gauge to monitor tank pressure. Tank temperature (in the gaseous portion of the tank), ambient temperature, and ambient pressure were also monitored on a digital data acquisition system.

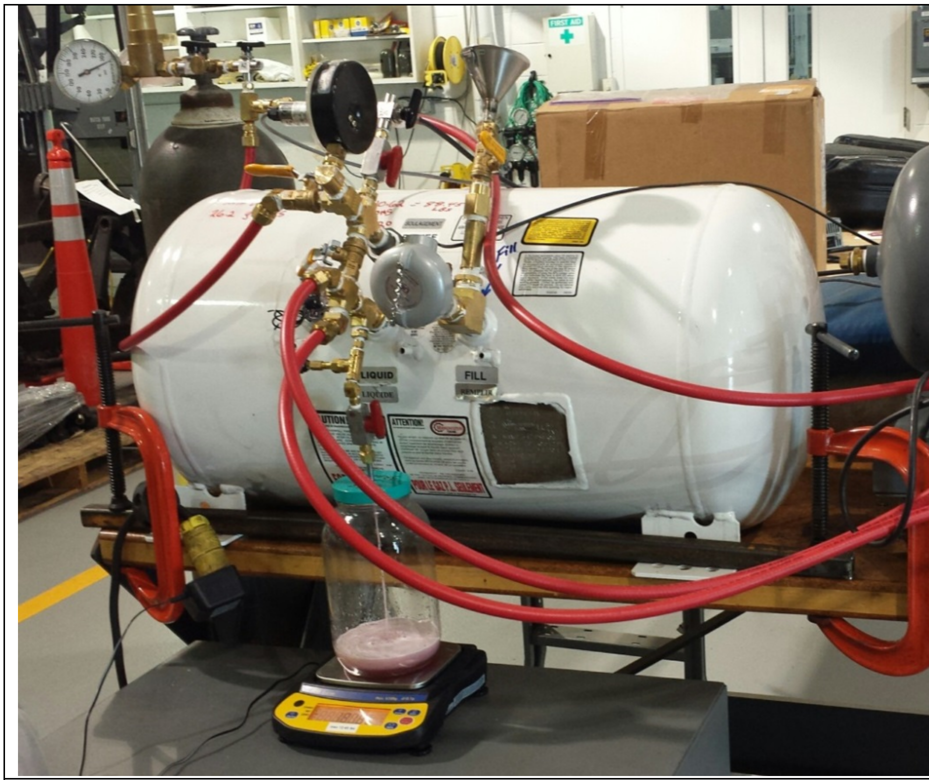
---

[24] See Appendix D — Detailed Tank Specifications for overall tank specifications for both tanks and Tank Technical Data, Table 23 for engineering specifications

[25] Expansion principles that affect the liquid propane volume were factored into what would be a typical delivery to an end use tank (the example here is a tank used for heating). Assume for instance, that a 250 gallon propane tank has 100 gallons of propane at 6 °F. The industry standard 60°F is universally recognized as the base reference point for liquid propane volume correction. A properly functioning float gauge will read 40%. Many propane delivery trucks and vehicle propane filling stations have meters that measure the amount of propane pumped into consumer tanks. These meters include a volume correction device known as an automatic temperature compensator. The temperature compensator takes into account the temperature of the liquid propane running through the meter and automatically adjusts to correctly deliver the amount of propane requested. www.propane101.com/propanevolumecorrection.htm (Retrieved December 12, 2014)

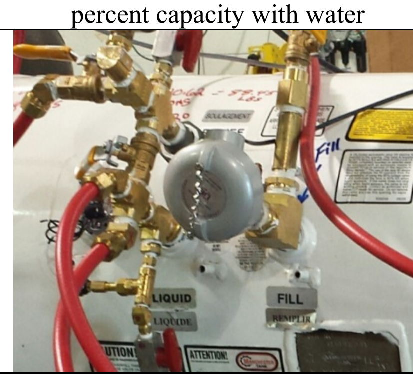
4. Water flow was controlled with a needle valve, and flow rate was measured with a scale to regulate the exact mass of water leaving the tank (at the conclusion of each test, the water was reentered into the tank to maintain the exact required mass of the water) (see Figures 4 through 8).
5. The desired flow rate in grams of water was calculated, and the time for this flow for each 100 g of water was tabulated. Then a stopwatch was used to record the time for each 100 g increment of water to flow out of the tank. In this way, the flow could be adjusted to get a very precise mass flow rate to match the required output.
6. After the required 30-minute period of flow monitoring was done, the LPG tank pressures, as well as other parameters, were monitored for a total of 120 minutes to evaluate the drift and the time to stabilize temperature and pressure from the initial liquid loss.

[26] Since the tank maximum working pressure (MAWP) was specified as gauge pressure and the CNG tank test specifications used gauge pressure, we monitored tank pressure in psig. This would be a more conservative value when compared to absolute pressure. Of course, air pressure (raw) was also monitored to evaluate the effects that using an absolute pressure gauge would have on the outcome of the testing.



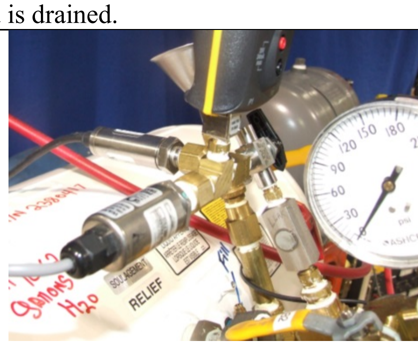
Overview of 26.2 Gallon LPG tank as liquid is drained.

A. The tank is initially filled to 40 percent capacity with water



C. Nitrogen temperature in the tank is monitored.

B. Nitrogen is introduced into the tank



D. Pressures are precisely monitored

F. Water is “leaked” from the tank.

Figure 4 – Operations to Perform a Leak Test on an LPG Tank

Figure 5 – Needle Valve Close Up

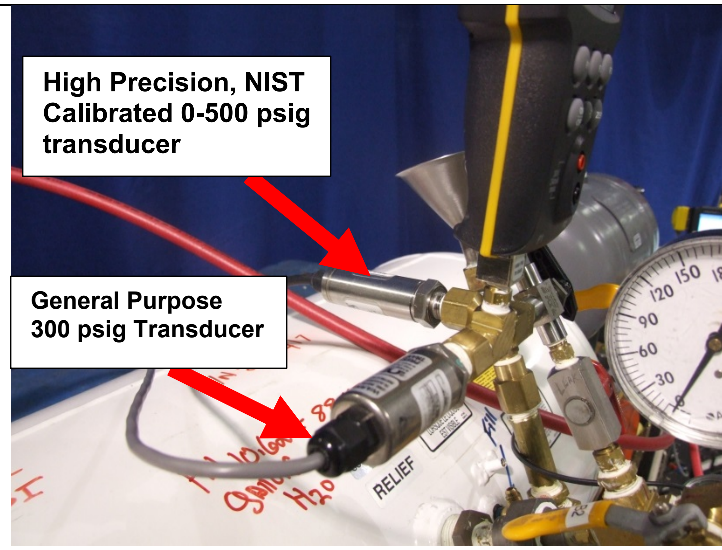


Figure 6 – Pressure Transducers – Close Up

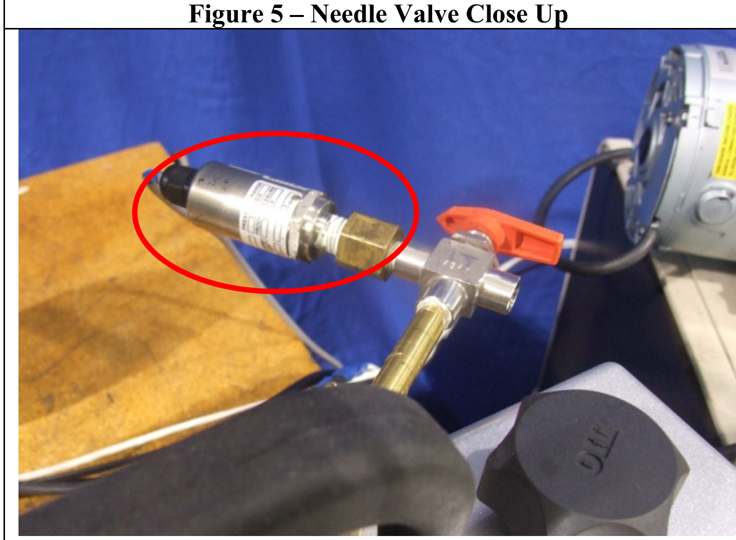


Figure 7 – Ambient Pressure Transducer

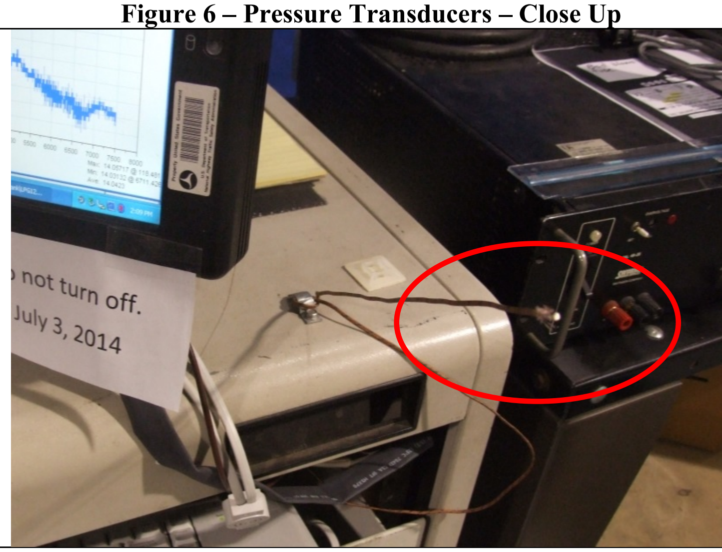


Figure 8 – Ambient Temperature Gauge

3.4 – Test Procedure – Gaseous Leak Testing

Since an LPG fuel system integrity test could also include rotation of the post-crash test vehicle, similar to FMVSS No. 301 testing of a gasoline powered vehicle, we evaluated the effects of an identical size leak with gas escaping instead of liquid escaping. To do this, we set the needle valve that had controlled the water flow rate during the liquid escape tests to the exact orifice size which allowed 805 g of water to leak in 30 minutes. This needle valve setting was secured and the valve (red arrow Figure 10) was moved from the liquid fill connection to a port that connected to the gas portion of the tank (see also Figure 9). The pressure drop through this size orifice over a 30-minute period was monitored and recorded.

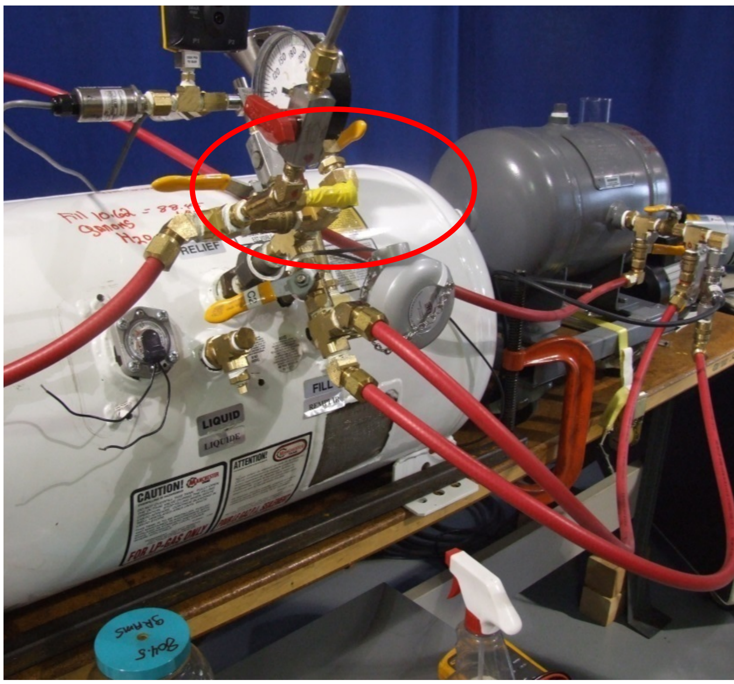


Figure 9 – Overall Test Setup

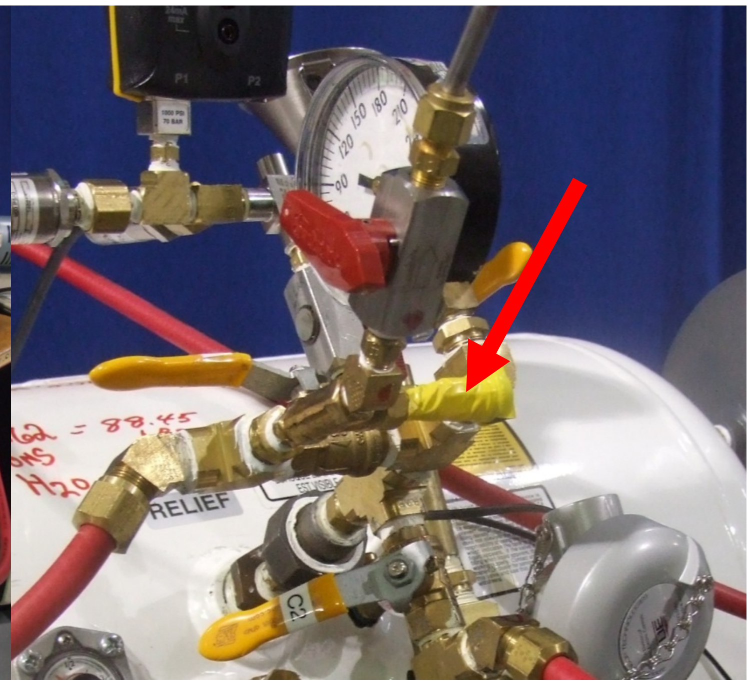


Figure 10 – Needle Valve on Gas Portion of Tank

4.0 – RESULTS

This section contains the theoretical calculations and test results.

4.1 – Small Tank Leak Testing Results

4.11 – Theoretical Calculations

Theoretical calculations for the 26.2 gallon (99.2 L) tank are shown in Table 1. These calculations are for a leak of exactly 805 g of water, at normal temperature and pressure (NTP), assuming no temperature change in the tank or ambient barometric pressure change during the event.

Table 1 – Theoretical Calculations for Drain of 805 g Water for 30 min – 26.2 Gallon Tank

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	Nitrogen Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia	Actual ΔTank Pres. @NTP
a/n	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
TEST CALC	NA	99.18	40.12	59.06	0.0	0.000	292.00	14.70	306.70	68.0	68.0	306.70	
ALL NTP	NA	99.18	39.32	59.86	805.0	-0.805	287.88	14.70	302.57	68.0	68.0	302.57	-4.12

Providing the equations for the above we have:

Calculating the pressure loss for a given volume of water drained

We have the N_2 volume of the tank as

$$V_{(N2i)} = V_{(tank)} - V_{(H2Oi)}$$

The final N2 tank volume after water drainage is

$$V_{(N2f)} = V_{(N2i)} + V_{(H2Of)}$$
$$\Delta V_{(N2)} = V_{(N2f)} - V_{(N2i)}$$

Measuring pressure change and converting to absolute pressure we have:

$$P_{t(N2i)} \text{ absolute} = P_{t(N2i)} \text{ gauge} + P_{a(i)} \text{ ambient air pressure (raw)}$$ [27]
$$P_{t(N2f)} \text{ absolute} = P_{t(N2f)} \text{ gauge} + P_{a(f)} \text{ ambient air pressure (raw)}$$

Correcting temperature to absolute temperature we have:

$$T_{(N2i)}\ K = (T_{(N2i)}\ °F - 32) * (5/9) + 273.15)$$
$$T_{(N2f)}\ K = (T_{(N2f)}\ °F - 32) * (5/9) + 273.15)$$

Calculating pressure correcting for temperature change at normal temperature (NT) we have:

$$P_{t(N2i)} \text{ at NT} = P_{t(N2i)} \text{ absolute} * (293.15\ K / + T_{(N2i)}\ K)$$
$$P_{t(N2f)} \text{ at NT} = P_{t(N2f)} \text{ absolute} * (293.15\ K / + T_{(N2f)}\ K)$$

Finally we have

$$\Delta P_{t(N2)} = P_{t(N2f)} \text{ at NT} - P_{t(N2i)} \text{ at NT}$$

Where

$V_{(N2i)}$ is N_2 volume tank initial
$V_{(N2f)}$ is N_2 volume tank final
$V_{(H2O\ i)}$ is water volume tank initial
$V_{(H2O\ f)}$ is water volume tank final
$V_{(tank)}$ is total volume of tank
$P_{t(N2i)}$ is N_2 pressure tank initial
$P_{t(N2f)}$ is N_2 pressure tank final
$P_{a(i)}$ is atmospheric pressure (raw) initial
$P_{a(f)}$ is atmospheric pressure (raw) final
$T_{(N2i)}$ is N_2 temperature initial
$T_{(N2f)}$ is N_2 temperature final
$\Delta P_{(N2)}$ is change in tank pressure

[27] Raw refers to ambient air pressure (barometric pressure) at a given altitude not corrected to mean sea level.

4.12 – Drain of 805 g Water in 30 min – One-Hour Test

Run 1140 was a typical test with the tank filled with water to 40 percent of its capacity and the pressure in the tank at 292 psig (+/-2%), as corrected to normal temperature.[28] This run produced the following results (see detailed final results in Table 2, summary data in Table 3, and pressure and temperature graphed as a function of time in Figure 11).[29] [30]

Table 2 – Run 1140 – 26.2 Gallon Tank – Drain 805 g Water in 30 min – One-Hour Test[31]

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	N_2 Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pres. @NTP
min	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
RUN 1140	0	99.2	40.1	59.1	0.0	0.000	296.6	14.2	310.8	74.0	76.1	306.0	
30 min DRAIN @ 30 min	30	99.2	39.3	59.9	805.2	-0.805	292.2	14.2	306.4	75.0	75.8	301.9	-4.1
30 min DRAIN @ 60 min	60	99.2	39.3	59.9	805.2	-0.805	292.4	14.2	306.6	75.0	76.0	302.0	-4.1

[28] See Appendix E – Other Data Runs, for detailed test tank of regular leak rate results on the small tank (corrected for ambient pressure change and tank temperature). Additional runs for practice and for fast and slow leak rates were also made.

[29] The target total drain was 805 g water in 30 minutes. For testing, the rate was calculated based on a predetermined time for each 100g of water (100g in 212 seconds). The cumulative and interval time were then compared to this precalculated time and fine adjustments were made as needed. No attempt to vary the initial allowed loss" first 5-minute amounts was made. Total time may be slightly higher than 30 minutes.

[30] The target amount to drain in the GM Petition presentation was target of 804.2 g. We rounded up for clarity. Also note that there was a typical overrun of water drained. For this run, the total of 805.2 g water was drained in 29 minutes, 46.9 sec.

[31] Under the column "Run No.", "30 min DRAIN @30 min" means we drained water for 30 minutes and read all data at 30 minutes. Also "30 min DRAIN @60 min" means we drained for a total of 30 minutes and took data at 60 minutes allowing for temperature and pressure stabilization time.

Table 3 – Test 1140 – 26.2 Gallon Tank, Drain of 805 g Water in 30 min, One-Hour Test – Summary[32]

Time	Ambient Pressure	Tank Pressure	Tank Temperature	Ambient Temperature	Cumulative Water Leakage
min	psia (raw)	Psig	°F	°F	g
0	14.2	296.6	76.1	75.3	0
10	14.2	295.1	76.0	75.3	262
20	14.2	293.7	75.9	75.5	536
30	14.2	292.2	75.8	75.7	805
40	14.2	292.4	76.0	75.9	805
50	14.2	292.4	76.0	75.9	805
60	14.2	292.4	76.0	76.4	805

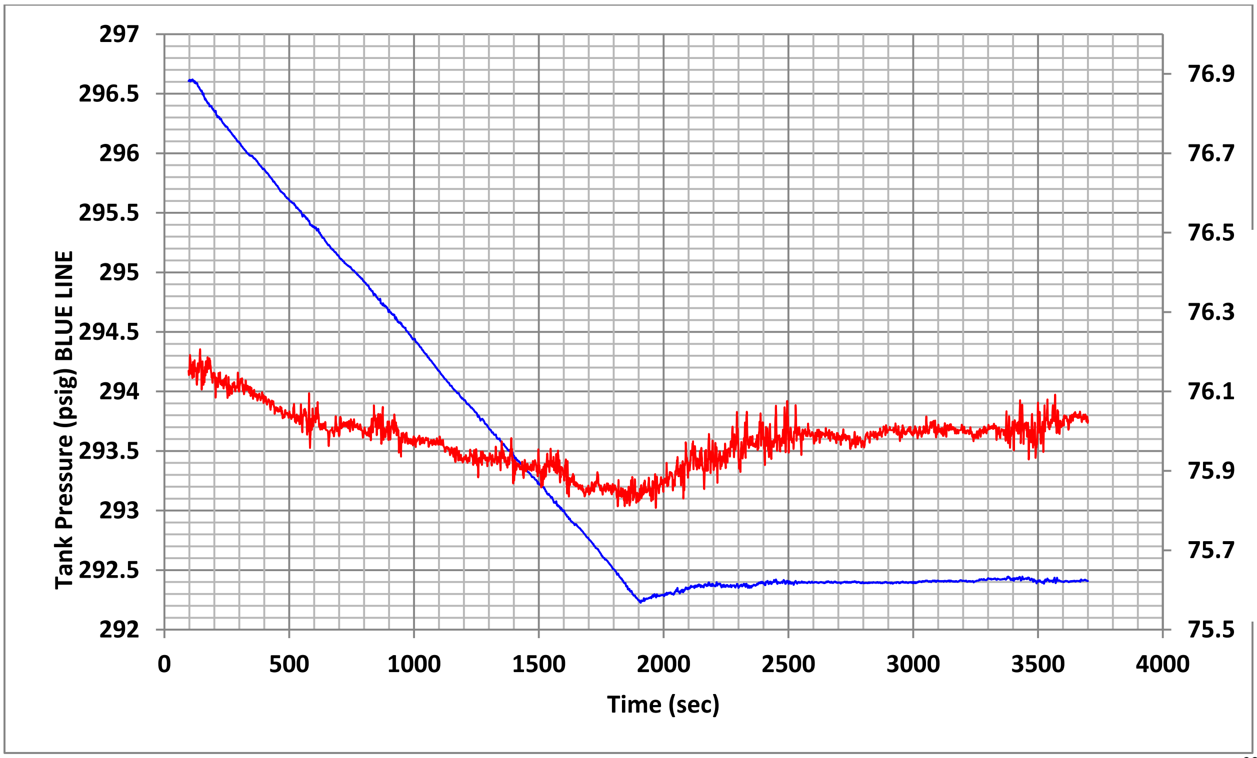


Figure 11 – Test 1140 – 26.2 Gallon Tank, Drain of 805 g Water in 30 min – Pressure, Temperature = f (time)[33]

[32] Note that slight variations in "leak" rate occurred due to fine adjustment of needle valve controlling flow and changes in leak rate as pressure diminished in tank. This is also evident in the initial leak rate as shown in the graph. Actual target rate was 805 g in 30 minutes.

[33] For all graphs blue represents pressure and red is temperature. Drain time for all tests start at 100 seconds.

4.13 – Drain 805 g of Water in 30 min – Two-Hour Test

Another run with identical flow rate with a longer stabilization time was performed to compare results. Here the tank again was filled with water to 40 percent of its capacity and the pressure in the tank set at 292 psig (+/-2%), as corrected to normal temperature. After the 30-minute drain, we continued to record tank pressure and temperature for a 2- hour period to evaluate how the pressure stabilized over this longer period of time. This run produced the following results (see detailed final results in Table 4, and summary data in Table 5, and pressure and temperature graphed as a function of time in Figure 12).

Table 4 – Run 1189 – 26.2 Gallon Tank – Drain of 805 g Water in 30 min – Two-Hour Test

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	N_2 Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pres. @NT
min	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
RUN 1189	0	99.2	40.1	59.1	0.0	0.000	296.0	14.1	310.1	74.0	75.9	305.6	
30 min DRAIN@ 30 min	30	99.2	39.3	59.9	804.3	-0.804	291.7	14.1	305.8	75.0	75.5	301.5	-4.1
30 min DRAIN@ 60 min	60	99.2	39.3	59.9	804.3	-0.804	291.8	14.1	305.9	75.0	75.6	301.6	-4.0
30 min DRAIN@ 120 min	120	99.2	39.3	59.9	804.3	-0.804	291.7	14.1	305.8	75.0	75.5	301.5	-4.1

Table 5 – Test 1189 – 26.2 Gallon Tank, Drain of 805 g in 30 min – Two-Hour Test – Summary

Time	Ambient Pressure	Tank Pressure	Tank Temperature	Ambient Temperature	Cumulative Leak
min	Psi (raw)	psi	°F	°F	g
0	14.1	296.0	75.9	75.7	0.0
10	14.1	294.4	75.6	76.2	266
20	14.1	293.0	75.6	76.4	548
30	14.1	291.7	75.5	75.7	782
40	14.1	291.8	75.6	76.8	804.3
50	14.1	291.8	75.7	76.3	804.3
60	14.1	291.8	75.6	76.6	804.3
70	14.1	291.8	75.6	77.1	804.3
80	14.1	291.7	75.6	75.8	804.3
90	14.1	291.7	75.6	76.2	804.3
100	14.1	291.7	75.5	76.9	804.3
110	14.1	291.7	75.5	76.8	804.3
120	14.1	291.7	75.5	76.7	804.3

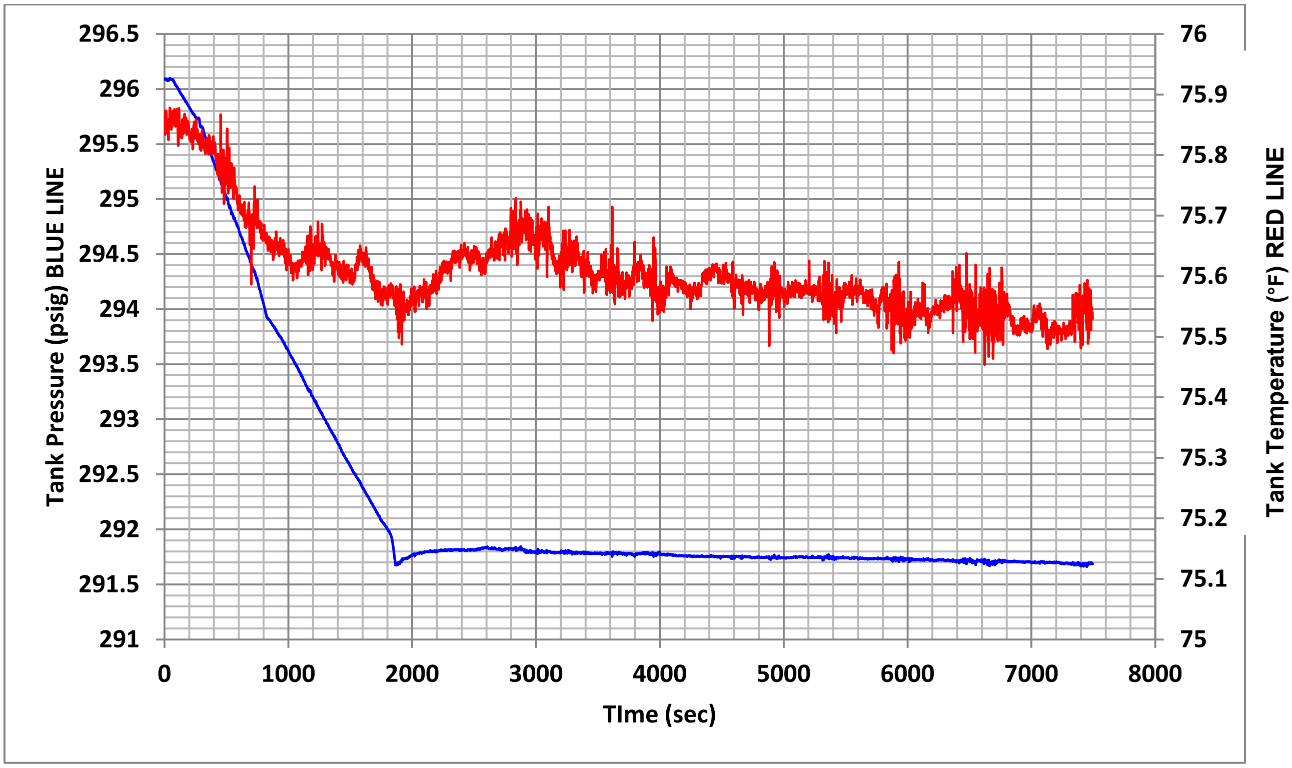


Figure 12 – Test 1189 – 26.2 Gallon Tank, Drain of 805 g Water in 30 min – Pressure, Temperature = f (time)

4.14 – Drain 1610 g of Water in 60 min

Run 1209 was a test with the tank filled with water to 40 percent of its capacity and the pressure in the tank set at 292 psig (+/-2%), as corrected to normal temperature. The leak was stopped after 60 minutes, but data was collected for 120 minutes to assess pressure stabilization. This run produced the following results (see detailed final results in Table 6, summary data in Table 7, and pressure and temperature graphed as a function of time in Figure 13).

Table 6 – Run 1209 – 26.2 Gallon Tank – Drain of 1610 g Water in 60 min – Two-Hour Test

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	N_2 Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pres. @NT
min	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
RUN 1209	0	99.2	40.1	59.1	0.0	0.000	298.6	14.1	312.7	74.0	72.0	310.3	
60 min DRAIN@ 30 min	30	99.2	39.3	59.9	804.5	-0.805	294.3	14.0	308.3	75.0	72.0	306.0	-4.3
60 min DRAIN@ 60 min	60	99.2	38.5	60.7	1608.6	-1.609	290.2	14.0	304.3	75.0	72.0	302.0	-8.3
60 min DRAIN@ 120 min	120	99.2	38.5	60.7	1608.6	-1.609	290.5	14.0	304.5	75.0	72.3	302.1	-8.2

Table 7 – Run 1209 – 26.2 Gallon Tank – Drain of 1610 g Water in 60 min – Summary

Time	Ambient Pressure	Tank Pressure	Tank Temperature	Ambient Temperature	Cumulative Water Drain
min	psia (raw)	psig	°F	°F	g
0	14.1	298.6	72.0	73.7	0
10	14.1	297.0	71.9	74.1	268
20	14.1	295.6	72.0	73.9	536
30	14.0	294.3	72.0	73.3	755
40	14.0	292.9	71.9	73.3	1074
50	14.0	291.5	71.9	73.9	1344
60	14.0	290.2	72.0	74.3	1606
70	14.0	290.4	72.1	73.8	1608
80	14.0	290.4	72.2	74.4	1608
90	14.0	290.5	72.2	74.4	1608
100	14.0	290.5	72.3	74.5	1608
110	14.0	290.5	72.3	74.2	1608
120	14.0	290.5	72.3	74.5	1608

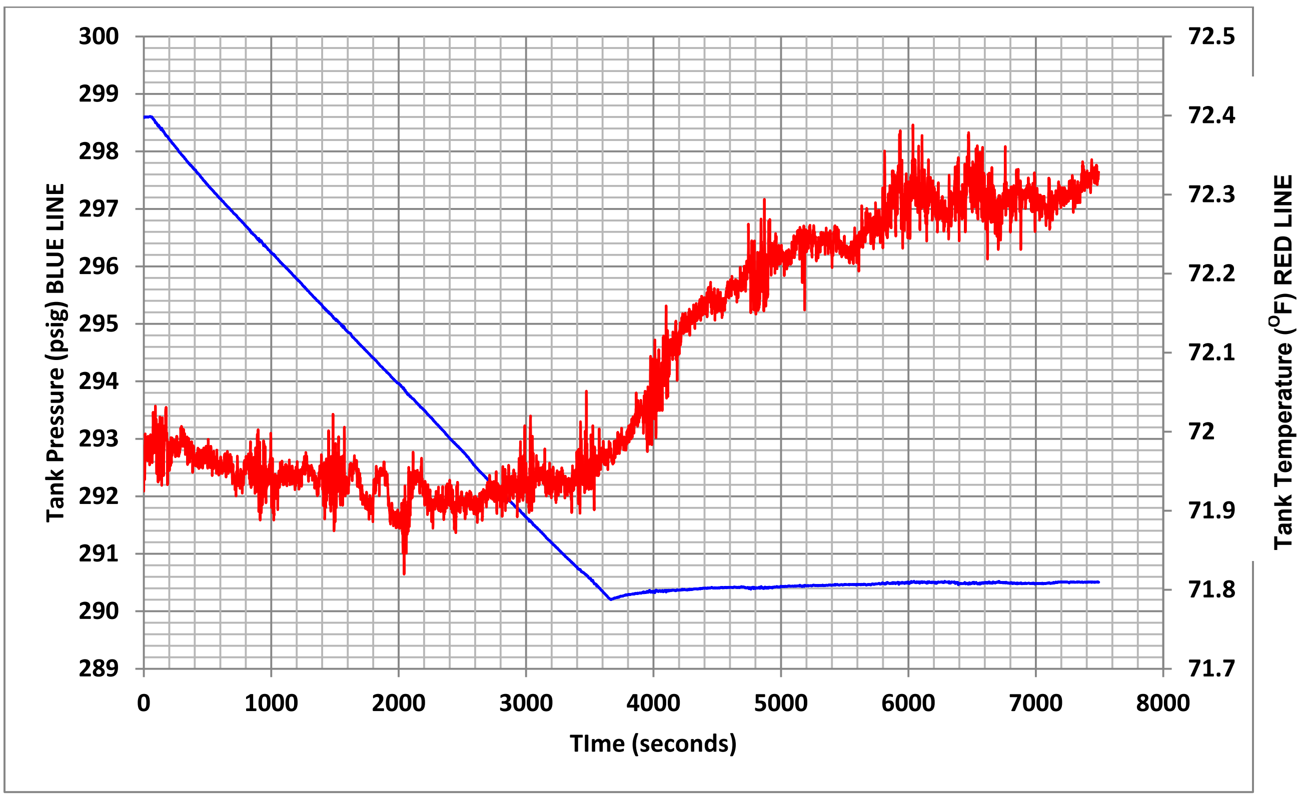


Figure 13 – Test 1209 – Drain of 1610 g of H_2O in 60 min – Pressure, Temperature = f (time)

4.15 – Gaseous Leak Testing

The gaseous leak test was conducted to evaluate the energy loss from gaseous LPG compared to liquid LPG escaping through the same size opening. For the gaseous leak test, we set the needle valve regulating liquid flow to the exact orifice opening that would allow a flow rate of 805 g of water in 30 minutes. This valve and a shutoff valve were then transferred to a tank opening that accessed the gaseous portion of the tank (see Figures 9 and 10).

The tank was filled with 40 percent water and pressurized with nitrogen to 297 psig +/-2 percent, as corrected to normal temperature. After pressure stabilization, the shutoff valve was opened for 30 minutes. Initial tank pressure was 297.4 psig and the final tank pressure was 268.3 psig. This represents a loss of 5.2 mol of nitrogen. Assuming a leak of approximately an equivalent number of moles of propane (C_3H_8), this gaseous propane leak would then have 28 percent of the “heat content” of 805 g of liquid propane.[34]

4.2 – Large Tank Leak Testing Results

4.21 – Theoretical Calculations

As mentioned, the test setup was identical to that of the small tank testing, except instead of a 26.2 gallon tank, we evaluated a 41.4 gallon (156.7 L) tank. This tank had the same diameter (16 inch OD) as the 26.2 gallon tank, except its overall length was 52 inches instead of 34 inches.

The theoretical calculation results for the 41.4 gallon tank are presented in Table 8. These calculations are for a leak of 805 g of water, at normal temperature and pressure (68.0 °F and 14.70 psia ambient air pressure), assuming no temperature change in the tank or ambient barometric pressure change during the event.

Table 8 – Theoretical Calculations for Drain of 805 g Water in 30 min – 41.4 Gallon Tank

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	N_2 Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pres. @NT
a/n	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
TEST CALC	NA	156.72	63.4	93.32	0.0	0.000	292.00	14.70	306.70	68.0	68.0	306.70	
ALL NT	NA	156.72	62.59	94.12	804.5	-0.805	289.38	14.70	304.07	68.0	68.0	304.07	-2.62

[34] See Appendix C2 – Gaseous Leak Rates, for details.

4.22 – Drain of 805 g Water in 30 min

Run 1280 was a test with the tank filled with water to 40 percent of its capacity and the pressure in the tank set at 292 psig (+/-2%) as corrected to normal temperature.[35] The leak was stopped after 30 minutes, but data was collected for 120 minutes to assess pressure stabilization. This run produced the following results (see detailed final results in Table 9, summary data in Table 10, and pressure and temperature graphed as a function of time in Figure 14).

Table 9 – Run 1280 – 41.4 Gallon Tank – Drain of 805 g Water in 30 min – Two-Hour Test

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	N_2 Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pres. @NT
a/n	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
RUN 1280	0	156.7	63.4	93.3	0.0	0.000	295.5	14.2	309.7	74.0	71.7	307.6	
30 min DRAIN@ 30 min	30	156.7	62.6	94.1	805.2	-0.805	292.7	14.2	306.9	75.0	71.4	304.9	-2.6
30 min DRAIN@ 60 min	60	156.7	62.6	94.1	805.2	-0.805	292.9	14.2	307.1	75.0	71.8	304.9	-2.6
30 min DRAIN@ 120 min	120	156.7	62.6	94.1	805.2	-0.805	293.1	14.2	307.3	75.0	72.2	304.9	-2.7

[35] See Appendix E – Other Data Runs, for detailed test tank of regular leak rate results on the large tank (corrected for ambient pressure change and tank temperature). Additional runs for practice and for fast and slow leak rates were also made.

Table 10 – Run 1280 – 41.4 Gallon Tank – Drain of 805 g Water in 30 min – Summary

Time	Ambient Pressure	Tank Pressure	Tank Temperature	Ambient Temperature	Cumulative Water Drain
min	psia (raw)	psig	°F	°F	g
0	14.2	295.5	71.7	71.1	0
10	14.2	294.5	71.5	71.5	246
20	14.2	293.7	71.5	71.3	501
30	14.2	292.7	71.4	71.4	805
30	14.2	292.7	71.4	71.4	805
40	14.2	292.8	71.6	71.7	805
50	14.2	292.9	71.7	71.7	805
60	14.2	292.9	71.8	71.9	805
70	14.2	292.9	71.8	72.0	805
80	14.2	293.0	71.9	71.9	805
90	14.2	293.0	72.0	72.1	805
100	14.2	293.0	72.0	72.2	805
110	14.2	293.1	72.1	72.3	805
120	14.2	293.1	72.2	72.5	805

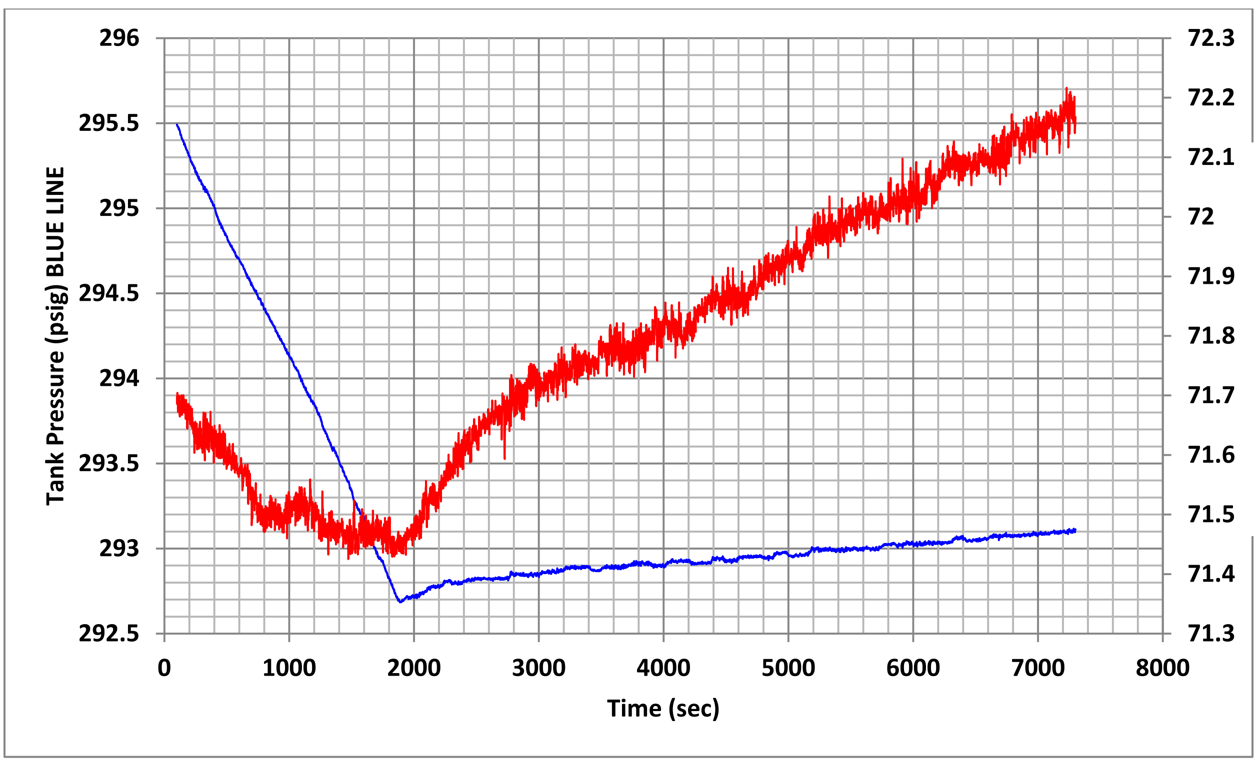


Figure 14 – Test 1280 – 41.4 Gallon Tank – 30 min Drain of 805 g of Water – Tank Pressure, Temperature = f (time)

4.23 – Drain of 1610 g of Water in 60 min

Run 1287 was a typical test with the tank filled with water to 40 percent of its capacity and the pressure in the tank at 292 psig (+/-2%), as corrected to normal temperature. The leak was stopped after 60 minutes, but data was collected for 120 minutes to assess pressure stabilization. This run produced the following results (see detailed final results in Table 11, summary data in Table 12, and pressure and temperature as a function of time in Figure 15).

Table 11 – Run 1287 – 41.4 Gallon Tank – Drain of 1610 g Water in 60 min

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	N_2 Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pres. @NT
a/n	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
RUN 1287	0	156.7	63.4	93.3	0.0	0.000	293.7	14.2	307.9	74.0	71.0	306.1	
60 min DRAIN@ 30 min	30	156.7	62.6	94.1	804.5	-0.805	291.2	14.2	305.4	75.0	71.3	303.5	-2.6
60 min DRAIN@ 60 min	60	156.7	62.6	94.1	1609.5	-1.610	288.7	14.2	302.9	75.0	71.4	300.9	-5.2
60 min DRAIN@ 120 min	120	156.7	62.6	94.1	1609.5	-1.610	288.8	14.2	303.0	75.0	71.4	301.0	-5.1

Table 12 – Run 1287 – 41.4 Gallon Tank – Drain of 1610 g Water in 60 min – Summary Data

Time	Ambient Pressure	Tank Pressure	Tank Temperature	Ambient Temperature	Cumulative Water Drain
min	psia (raw)	psig	°F	°F	g
0	14.2	293.7	71.0	70.6	0
10	14.2	292.8	71.1	71.2	286
20	14.2	292.0	71.2	71.5	517
30	14.2	291.2	71.3	71.6	790
40	14.2	290.4	71.4	72.0	1055
50	14.2	289.5	71.4	71.8	1317
60	14.2	288.7	71.4	72.0	1579
70	14.2	288.8	71.6	71.7	1609
80	14.2	288.8	71.7	71.7	1609
90	14.2	288.8	71.7	71.9	1609
100	14.2	288.8	71.8	71.9	1609
110	14.2	288.8	71.8	72.1	1609
120	14.2	288.8	71.9	71.9	1609

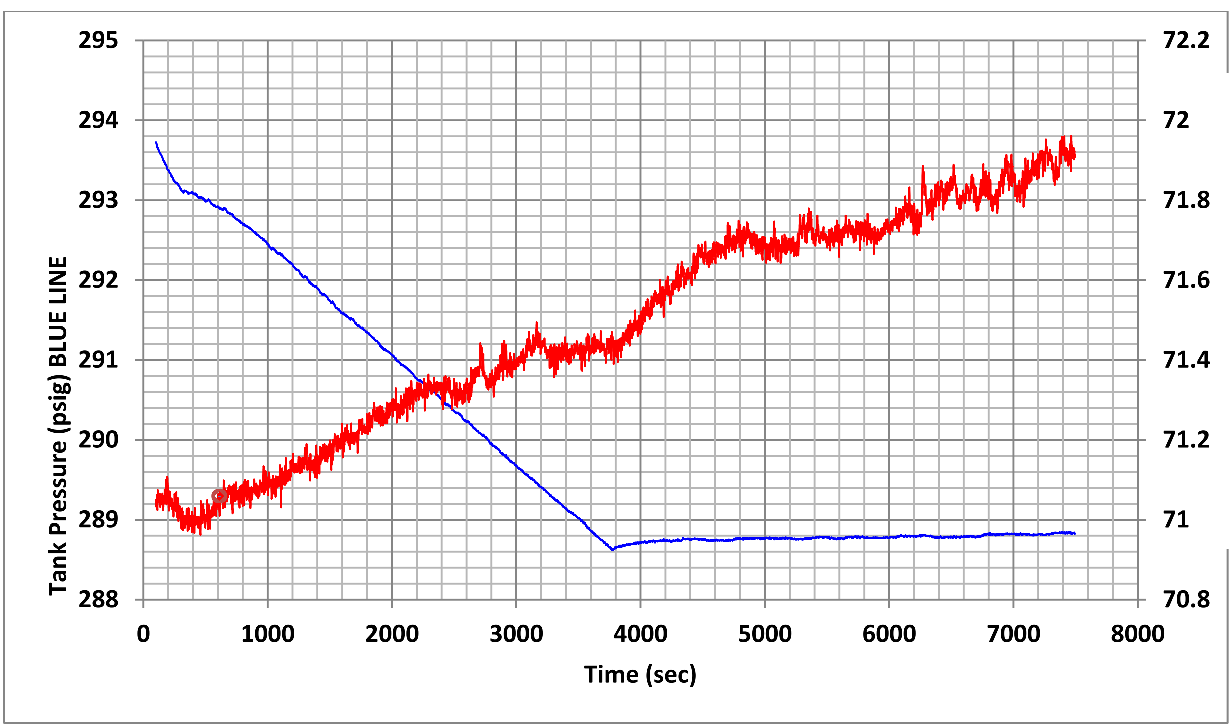


Figure 15 – Test 1287 – 41.4 Gallon Tank – Drain of 1610 g of H_2O in 60 min, Tank Pressure, Temp. = f (time)

Data from other test runs to assess the repeatability and consistency of the tests are presented in Appendix E.

5.0 – FINDINGS AND DISCUSSION

5.1 – Findings

- Finding 1: For smaller tanks, measuring pressure drop to calculate fluid leakage is within the accuracy of the measurement system. As tanks get larger, the pressure drop caused by the loss of 805 g of fluid diminishes. Thus recording the pressure drop over a longer period of time, such as 60 minutes, would measure any leak rate more accurately.
- Finding 2: The temperature of the gaseous portion of the tank should be recorded so that the measured tank pressure can be corrected for temperature change. The Canadian standard specifies temperature corrected pressure.
- Finding 3: Gaseous LPG that leaked over a 30-minute period has 28 percent of the "energy content of liquid LPG leaked" through the same size hole (damage) for the same period of time. The Canadian specification of fluid loss and/or reduction in tank pressure does not include rolling the vehicle.
- Finding 4: During the laboratory bench testing, the leak was "shut off" then the tank pressure and tank temperature were allowed to stabilize. This cannot be done during a crash test since a leak will continue as long as the system is pressurized. Detailed time stamps are necessary to evaluate the finishing pressure after a "30-minute leak" or a "60-minute leak" since the system will continue to lose pressure. Then, based on temperature change, actual pressure loss at NTP, etc. must be estimated. [36]
- Finding 5: Absolute pressure can be measured instead of gauge pressure to eliminate the effects of atmospheric pressure changes during testing.
- Finding 5A: A high stability, high reliability, broad temperature compensation range pressure transducer with NIST traceable calibration helps to minimize potential drift in output values.[37]
- Finding 6: Pressure transducers can be insulated to reduce the effects of temperature changes on the reading.

[36] The Canadian standard of either/or a 5% drop in pressure temperature corrected pressure or 142 g of fuel loss. Reference Transport Canada, Standards and Regulations Division, Test Method 301.1, LPG Fuel System Integrity, Revised: February 8, 2001, with update to SOR/2008, 104 April 16, 2008, 301.1 Section (2) (a) and (b).

[37] Transducers are available with up to +/- 0.05% FS. Also consider a 5 volt or 10 volt full scale output in lieu of mv/V output.

5.2 – Discussion

The primary challenge for evaluating the fuel system integrity of LPG-fueled vehicles is that LPG exists as both a liquid and a gas in the tank, which is not practical to exactly duplicate during a crash test. However, use of pressurized water and nitrogen was shown to be a reasonable simulation. Loss of ‘fuel’ can be determined by post-crash test measurements of both pressure drop in the tank and volume of liquid lost. Depending on the number of leaks and their locations, a measured post-test pressure drop may be due to a gaseous leak, a liquid leak (pressure drop due to increased gas volume in tank from loss of liquid), or both.

By measuring both pressure drop and volume of liquid lost, the portion of the pressure drop (if any) due solely to a liquid loss can be calculated and thereby separated from the portion of pressure drop (if any) due to a gaseous leak. Since the energy content of liquid and gaseous propane escaping though the same size hole over the same period of time are not equal, equivalent energy should be calculated separately to determine the energy content of a gaseous leak and a liquid leak. The combination of these is the total energy content lost.

The pressure drop due to only a marginal loss of liquid (805 g of water) is relatively small compared to the total tank pressure, particularly for larger LPG tanks. This study showed that pressure transducers and data acquisition systems are available that can accurately measure these pressure drops, but care must be taken to account for ambient pressure and temperature changes.

6.0 – ADDITIONAL TESTS

Specialized test results can be found in Appendix B including Appendix B1, variable leakage rate tests, Appendix B2, a rapid pressure drop leak test, Appendix B3 - evaluation of tank fill and stabilization procedures, Appendix B4, tank temperature and ambient temperature relationships, Appendix B5, large pressure drop volume evaluations, and Appendix B6, large tank overrun tests.

Appendix A – General Information

Appendix A1 – Acronym List

Table 13 – Acronym List

Acronym	Description
Btu	British thermal unit
CFR	Code of Federal Regulations
DOT	Department of Transportation
DUT	device under test
FMVSS	Federal Motor Vehicle Safety Standard
FOM	figure of merit
FS	full scale
GM	General Motors Company
HHV	high heating value
ISSN	International Standard Serial Number
IUPAC	International Union of Pure and Applied Chemistry
LHV	low heating value
LPG	liquefied petroleum gas
MAWP	Maximum working pressure
na	not apply/not applicable
NHTSA	National Highway Traffic Safety Administration
NIST	National Institute of Standards and Technology
nr	not recorded
NTP	normal temperature and pressure
NVS	NHTSA Vehicle Safety
OE	original equipment
OEM	original equipment manufacturer
psia	pounds per square inch absolute
psig	pounds per square inch gauge (gauge pressure)
RMS	root of the mean squared
RSS	root of the sum squared
STP	standard temperature and pressure
TBD	to be determined
TC	Transport Canada
TP	test plan
TRC	Transportation Research Center
VRTC	Vehicle Research and Test Center

Appendix A2 – References Consulted

Table 14 – References Consulted

Number	Report Name
0894-1777/88	Describing the Uncertainties in Experimental Results, Robert J. Moffat, Professor of Mechanical Engineering, Stanford University, Stanford, California, Experimental Thermal and Fluid Science 1988; 1:3-17, 1988 by Elsevier Science Publishing Co., Inc. New York, NY 10017
49 CFR Part 571, Sec. 301	Subpart B—Federal Motor Vehicle Safety Standards: Standard No. 301; Fuel system integrity.
49 CFR Part 571, Sec. 303	Subpart B—Federal Motor Vehicle Safety Standards: Standard No. 303; Fuel system integrity of compressed natural gas vehicles (571.303)
CEC-600-2007-002-D	FULL FUEL CYCLE ASSESSMENT WELL TO Tank ENERGY INPUTS, EMISSIONS, AND WATER IMPACTS, Prepared For: California Energy Commission, February 2007
ISSN 1368-655	A Beginner's Guide to Uncertainty of Measurement, Measurement Good Practice Guide No. 11 (Issue 2), Stephanie Bell, Centre for Basic, Thermal and Length Metrology, National Physical Laboratory, August 1999, Issue 2 with amendments March 2001
ISSN 1368-6550	Estimating Uncertainties in Testing, An Intermediate Guide to Estimating and Reporting Uncertainty of Measurement in Testing, Measurement Good Practice Guide No. 36, Keith Birch, British Measurement and Testing Association, Crown Copyright 2001
GM Petition	GM Petition FMVSS No. 303 Upgrade Briefing, NHTSA, MRT Briefing, September 18, 2012
NIST Technical Note 1297	Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, Barry N. Taylor and Chris E. Kuyatt, United States Department of Commerce Technology Administration, National Institute of Standards and Technology, September 1994
NIST Standard Reference Database Number 69	E. W. Lemmon, M. O. McLinden and D. G. Friend, "Thermophysical Properties of Fluid Systems" in NIST Chemistry WebBook, NIST Standard Reference Database Number 69, Eds. P. J. Linstrom and W. G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, http://webbook.nist.gov
TC 301.1	Reference Transport Canada, Standards and Regulations Division, Test Method 301.1, LPG Fuel System Integrity, Revised: February 8, 2001, with update to SOR/2008, 104 April 16, 2008, 301.1 Section (2) (a) and (b).
TP-301-04, (Jan 17, 2007)	U. S. DEPARTMENT OF TRANSPORTATION, NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION, LABORATORY TEST PROCEDURE FOR FMVSS 212 Windshield Mounting FMVSS 219 Windshield Zone Intrusion FMVSS 301 Fuel System Integrity
TP-303.00 (June 30, 1995)	U. S. DEPARTMENT OF TRANSPORTATION, NATIONAL HIGHWAY TRAFFIC SAFETY AD*MIN*ISTRATION, LABORATORY TEST PROCEDURE FOR FMVSS 212 Windshield Mounting, FMVSS 219 Windshield Zone Intrusion, FMVSS 303 Fuel System Integrity of Compressed Natural Gas (CNG) Vehicles
VRTC-83-0307 (July 1994)	VRTC Event Report: Compressed Natural Gas Fuel System Integrity

Appendix A3 – Equipment and Instrumentation

Table 15 – Equipment and Instrumentation

No.	Description	Make	Model	Serial No.	Size	Application
1	LPG Tank	Manchester	P/N 2380417	1737315	26.2 gal	Test Article
1a	LPG Tank	Manchester	P/N 20067	1735147	41.4 gal	Test Article
2	LPG Fill Water	Tank Full	na	na	88.45 lbm	LPG equivalent
3	Pressure Transducer	Omega	PX409-500G5V	442527	0-500 psig	Tank pressure
4	Pressure Transducer	Omega	PX302-300GV	140210	0-300 psig	Tank pressure
4a	Pressure Transducer	Omega	PX302-015AV	121213	0-15 psia	Ambient Air Pressure
5	Thermocouple	Applied Sensor Technologies	Analog Devices 3B47 J-type	na	na	Tank Temperature
6	Needle Valve	na	na	na	~ 0-500 g/min	Flow Control
7	Thermocouple	J-type thermocouple wire	Analog Devices 3B47 J-type	na	na	Ambient Temperature
8	Digital Scale	AND	EJ-6100	5A2833373	6100 g	Water mass flow rate
9	Mass Flow Meter	Omega	FMA1827A	360936-3	0-40 L/min	Gas flow rate
10	Pressure Calibrator	Omega	PCL341	9306073	0-1000 psi	Tank Pressure

Appendix B – Special Tests

Appendix B1 – Variable Leakage Rate Tests

For selected test runs, the leakage rate was varied from 23.5 g/min to 456.5 g/min. Changes in pressure and temperature were evaluated as a function of leakage rate. After the leaks were stopped, the pressure and temperature recovered from their initial drops to "stable" values were also evaluated.[38] See Table 16 for a tabulation of leakage and recovery values and Figures 16 and 17 for plotting of the results.

Table 16 – 26.6 Gallon Tank – Pressure and Temperature Change = f (leakage rate)

Test Run	Slow/Regular/Fast	Rate	Max Pressure Change	Max Temp Change	Pressure Recover	Temp Recover
a/n	a/n	g/min	psig	°F	psig	°F
1210	Fast	51.27	-4.39	-0.23	0.21	0.15
1173	Fast	456.54	-5.32	-0.75	0.81	0.27
1169	Slow	23.52	-4.19	-0.09	0.13	0.19
1172	Regular	26.62	-4.27	-0.21	0.13	0.05
1201	Regular	26.64	-5.12	-0.14	0.17	0.20

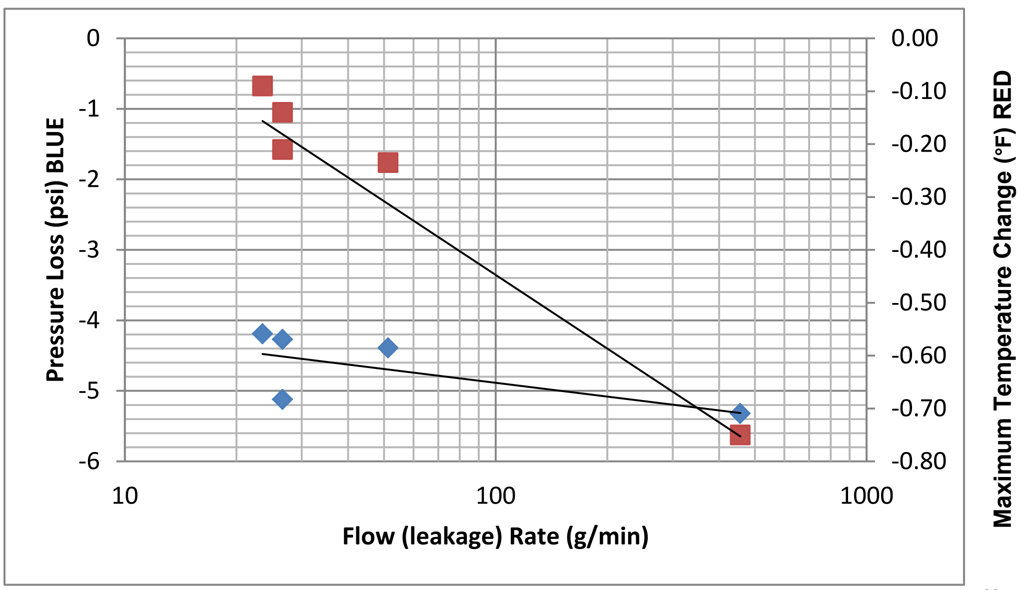


Figure 16 – 26.2 Gallon Tank – Initial Pressure and Temperature Drop = f (leakage rate)[39]

[38] If leakage rate is used in actual testing, since flow out of the tank will not stop after completion of the test, recovery estimates would have to be made to evaluate the true pressure drop to evaluate total energy loss.

[39] For Figure 16 and 17, and graphs of temperature and pressure, red = temperature in degrees Fahrenheit and blue = pressure in psig.

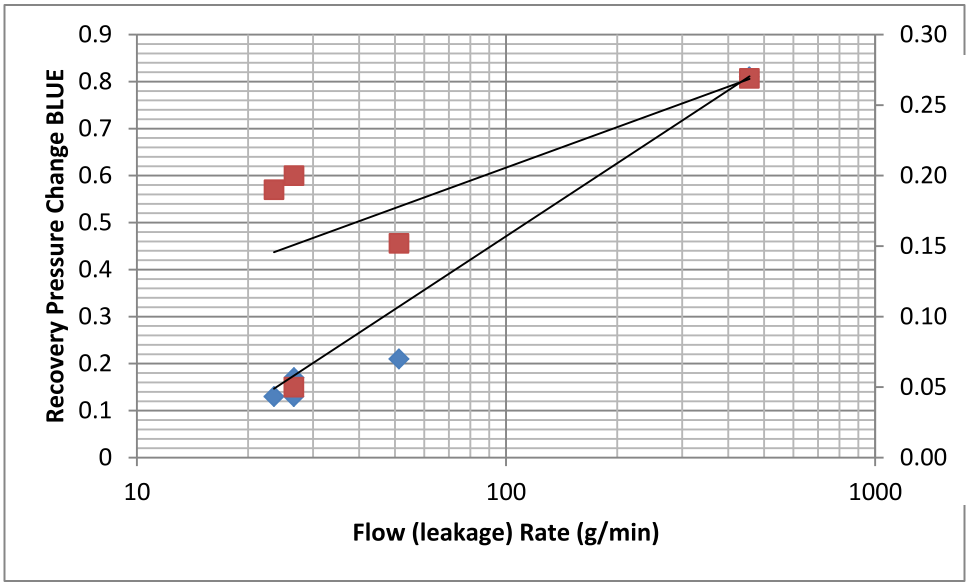


Figure 17 – 26.2 Gallon Tank – Recovery of Initial Pressure and Temperature Drop = f (leakage rate)

Appendix B2 – Rapid Pressure Drop Leak Test

The needle valve on the fluid drain was opened to the maximum extent possible. While the resultant gauge pressure was affected to some extent, the temperature-corrected absolute pressure after stabilization was close to the theoretical value (see Table 17 for input data, Table 18 for detailed final results, and Figure 18 for a graph of pressure and temperature as a function of time).

Table 17 – Run 1173 – 26.2 Gallon Tank - Drain of 805 g Water in 1.78 min – Input Data

Run	cum. time	Action	Tank Total Volume	Water Volume in Tank	Nitrogen Volume in Tank	Weight Water Drain	Change Water Volume	Change Nitrogen Volume in Tank	Tank Pres.
min	min	a/n	L	L	L	g	L	L	psig
RUN1173	0	START: STABILIZE; TEMPERATURE CORRECTED +/- 2%	99.2	40.1	59.1	0.0	0.000	0.000	296.3
FAST DRAIN	1.78	FAST Drain Water; Drained 816.6 g Water in 1:47.02 (1.78 min)	99.2	39.3	59.9	816.6	-0.817	0.817	291.5

Table 18 – Run 1173 – 26.2 Gallon Tank - Drain of 805 g Water in 1.78 min – Detailed Results

Run	cum. time	Ambient Temp	Ambient Pres.	Tank Temp (gas)	Actual Pressure @68 °F NT	Actual ΔTank Pres. @NT	ΔTank Raw Gauge Pres.
min	min	°F	psia	°F	psia	psia	psig
RUN1173	0	74.0	14.3	76.6	305.6		
FAST DRAIN	1.78	75.0	14.3	75.6	301.5	-4.2	-4.8

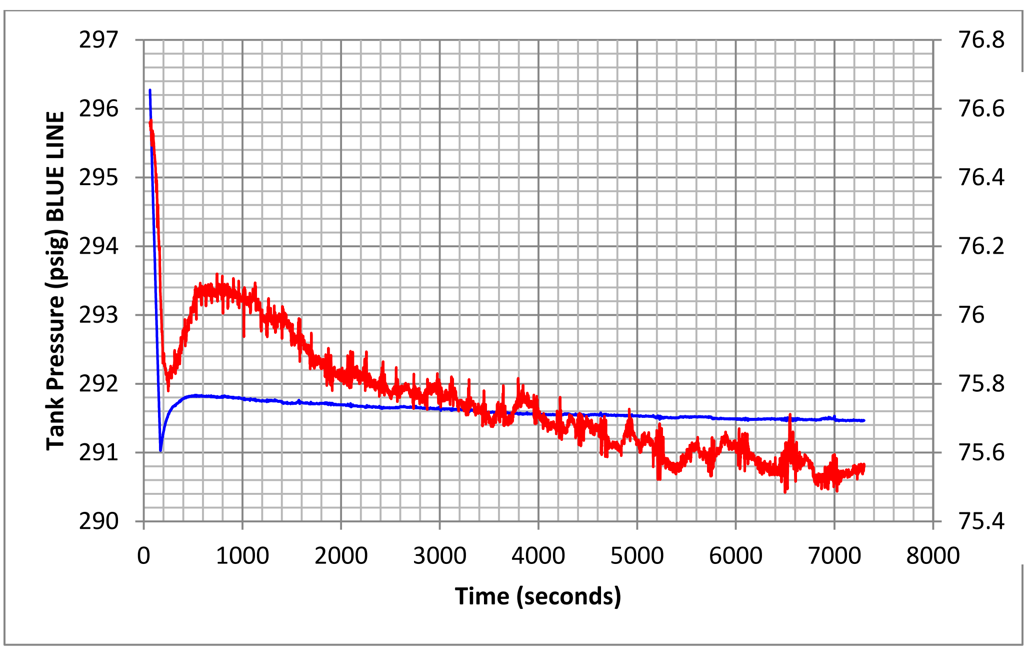


Figure 18 – Test 1173 – 26.2 Gal Tank – Fast Drain – Tank Pressure and Temperature = f (time)

Appendix B3 – Evaluation of Tank Fill Procedures

In order to develop an optimum fill procedure for the tanks, a number of tests were run to evaluate final pretest fill temperature and pressure as a function of initial fill pressure prior to cool down. Based in part on the methodologies of the CNG tank fill procedure, we found that to achieve a desired starting pressure of 292 psig,[40] filling the tank to 310 psig, allowing it to stabilize for one hour, refilling it to 300 psig, and then allowing it to stabilize for an additional hour was sufficient to achieve the desired starting pressure.[41]

[40] For example, the MAWP (or as specified by the tank manufacturer, the service pressure in psig), is 312 psig so 20 psig less would be 292 psig. Correcting for tank temperature (see appendix for allowable tank pressures), and using the maximum and minimum temperature range as specified by the CNG test as well as +/-2% accuracy gives us the desired pressure to be used at test initiation.

[41] It should be noted, that unlike CNG testing, with initiating pressure of 3000 psig or higher, we are only using 300 psig, so the temperature and pressure changes during the filling operation are not as high.

Appendix B4 – Tank Temperature and Ambient Temperature Relationships

In order to develop an understanding of how changes in ambient temperature might affect changes in tank temperature during an actual FMVSS test set up and execution, data was taken over an extended period of time during which ambient temperature fluctuated due to normal daily heating and cooling. These temperatures are measured in a test bay. As can be seen in Figure 19, changes in tank temperature typically lagged the changes in ambient temperature, and the tank temperature was typically below ambient temperature (0.94° F maximum). [42]

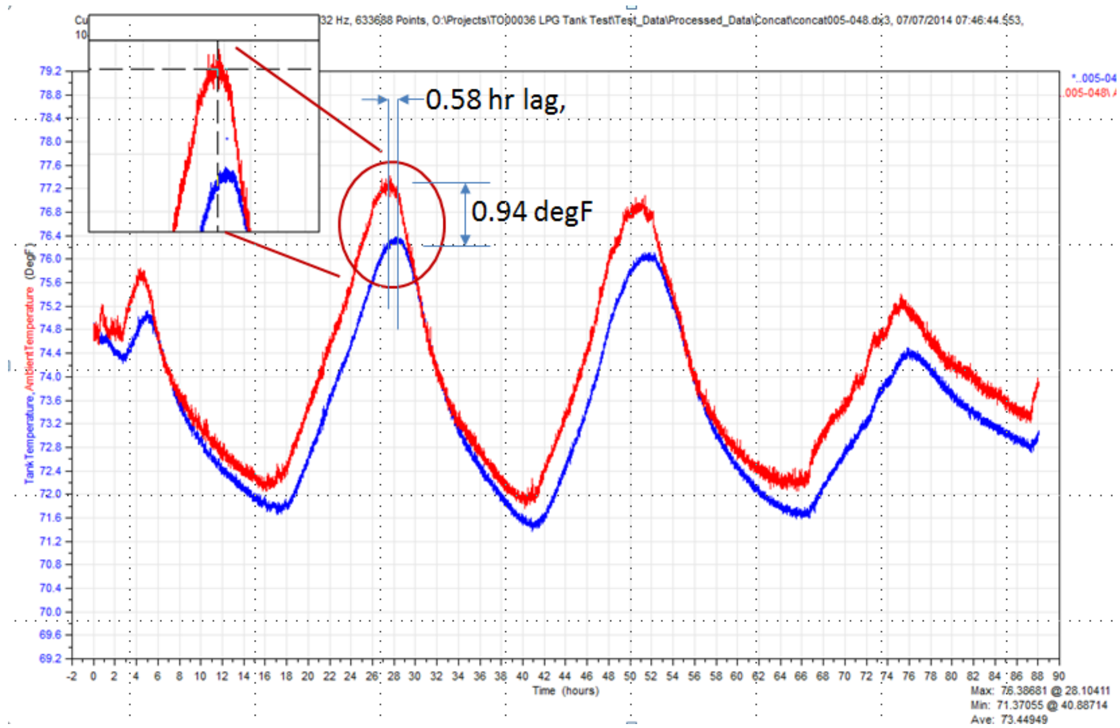


Figure 19 – 26.2 Gallon Tank – Internal Tank Temperature as a Function of Ambient Temperature

[42] We are not trying to develop a heat transfer function, but merely want to show change in tank temperature in a typical test environment.

Appendix B5 – Large Pressure Drop Volume Evaluations

Additional calculations were conducted to determine what amount of liquid (water) would have to be drained (in 30 min) to achieve pressure drop of 15.5 psi over 60 minutes. We used the normal temperature and pressure leak rate calculations to evaluate the approximate amount of change in water volume that would cause a 15.5 psia pressure drop. See Table 19 and Table 20 for details on the 26.2 gallon and the 41.4 gallon tank, respectively.

Table 19 – Calculated Drain of Water Small Tank for 15.5 psi Pressure Drop @Exact NT[43]

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	Nitrogen Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	New Pressure @68 °F NT	Actual ΔTank Pres. @NT
min	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
TEST CALC	NA	99.2	40.1	59.1	0.0	0.000	292.0	14.7	306.7	68.0	68.0	306.7	
ALL NT	NA	99.2	37.0	62.2	3145.0	**-3.145**	276.5	14.7	291.2	68.0	68.0	291.2	**-15.5**

Table 20 – Calculated Drain of Water Large Tank for 15.5 psi Pressure Drop @Exact NT

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	Nitrogen Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	New Pressure @68 °F NT	Actual ΔTank Pres. @NT
a/n	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
TEST CALC	NA	156.7	63.4	93.3	0.0	0.000	292.0	14.7	306.7	68.0	68.0	306.7	
ALL NT	NA	156.7	58.4	98.3	4967.0	**-4.967**	276.5	14.7	291.2	68.0	68.0	291.2	**-15.5**

Assuming standard temperature and absolute pressure,[44] a drain of 3.145 L (0.83 gal) from the 26.2 gallon tank would produce a pressure drop of 15.5 psig. Similarly for the 41.4 gallon tank, a drain of 4.967 L (1.31 gal) would produce a pressure drop of 15.5 psi.[45]

---

[43] Numbers do not necessarily represent the uncertainty of a value based on the number of significant figures but rather the number of active digits is presented for understanding of the measurement or change in the figure of merit being used.

[44] Those would be similar to changing to absolute pressure and then correcting to normal temperature.

[45] The intent of this analysis was to evaluate a pressure drop that according to some calculations would be required to correlate to a verifiable measured amount. This amount would have been the minimum amount according to a value based on the accuracy of a pressure measurement that has been shown in other presentations to be unreasonably large (e.g. using sum instead of RSS cancelations to aggregate uncertainties, etc.).

Appendix B6 – Large Tank Overrun Test

Since in an actual LPG vehicle system test, the leak will not stop at a specific time, we must determine how stable measurements are at a specific time if the tank or fuel system breach continues to occur beyond that time. For this test, we used a leak rate of approximately 26.8 g/min and took measurements at 60 minutes, but we allowed the leak to continue after 60 minutes. We picked 60 minutes because at least for larger tanks, a 30-minute leak of 2.6 psia may be difficult to measure (see Table 21 for detailed final results, Table 22 for summary data, and Figure 20 for a graph of pressure and temperature as a function of time).

Table 21 – 41.4 Gallon Tank - Drain of 1900 g at 26.8 g/min for 70 min – Stop at 120 min

RUN No.	cum. time	Tank Total Volume	Water Volume in Tank	Nitrogen Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pres. @NT
a/n	min	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
RUN 1303	0	156.7	63.4	93.3	0.0	0.000	293.9	14.2	308.1	74.0	78.6	302.0	
70 min Drain @ 30 min	30	156.7	62.6	94.1	804.5	-0.805	291.3	14.2	305.5	75.0	78.7	299.5	-2.6
70 min Drain @ 60 min	60	156.7	61.8	94.9	1608.6	-1.609	288.8	14.2	303.0	75.0	79.0	296.8	-5.2
70 min Drain @ 70 min	60	156.7	61.5	95.2	1900.8	-1.901	288.0	14.2	302.2	75.0	79.2	295.9	-6.1
70 min Drain @ 120 min	60	156.7	61.5	95.2	1900.8	-1.901	288.5	14.2	302.7	75.0	80.0	295.9	-6.1

Table 22 – Run 1303 – 41.4 Gallon Tank – Drain of 1901 g Water in 70 min – Summary

Time	Ambient Pressure	Tank Pressure	Tank Temperature	Ambient Temperature	Cumulative Water Drain
min	psia (raw)	psig	°F	°F	g
0	14.2	293.9	78.6	82.2	0
10	14.2	293.0	78.6	82.5	264
20	14.2	292.1	78.6	82.9	518
30	14.2	291.3	78.7	83.2	794
40	14.2	290.5	78.8	83.9	1088
50	14.2	289.6	78.9	84.1	1347
60	14.2	288.8	79.0	84.1	1608
70	14.2	288.1	79.2	84.1	1901
80	14.2	288.0	79.2	84.0	1901
90	14.2	288.2	79.5	84.5	1901
100	14.2	288.4	79.8	84.3	1901
110	14.2	288.4	79.9	85.0	1901
120	14.2	288.5	80.0	84.3	1901

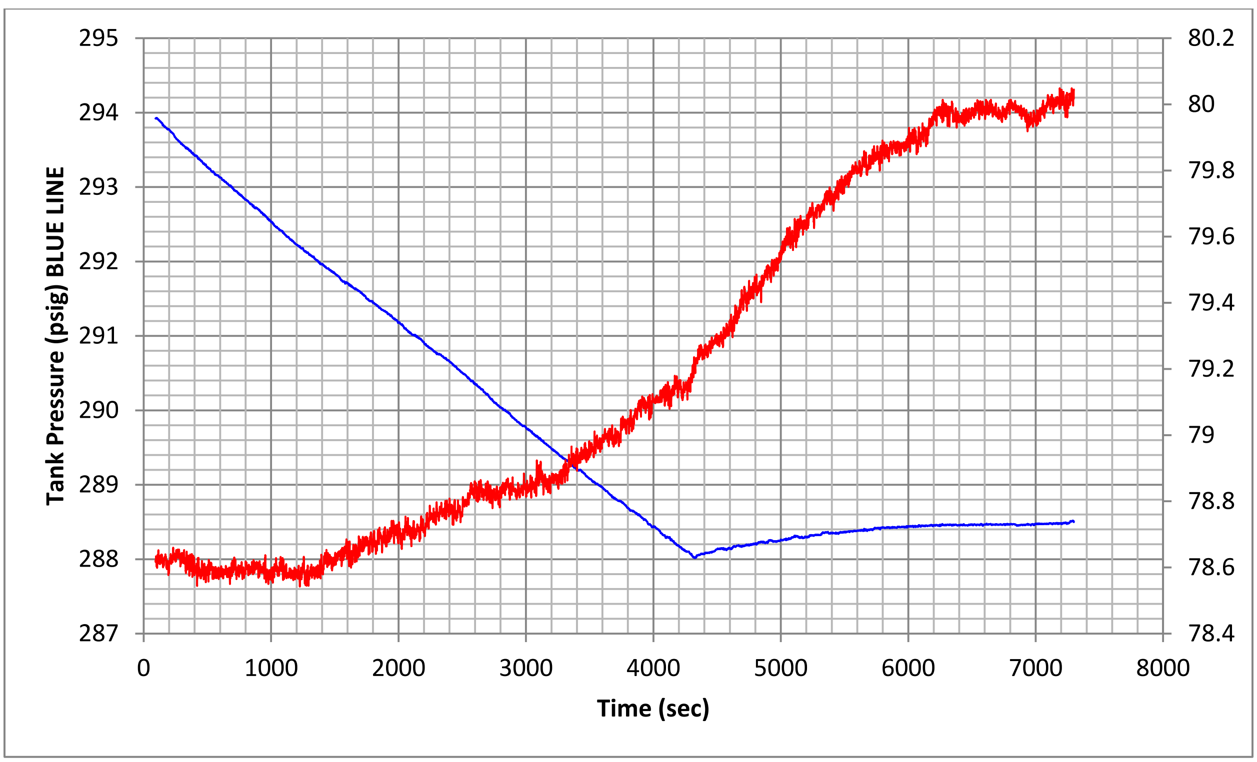


Figure 20 – 41.4 Gallon Tank – Drain of 1900 g Water in 70 min

Appendix C – Calculations Details

Appendix C1 – Calculations LPG Equivalent and Energy Content Values

Gasoline gallon equivalent of LPG to duplicate total energy fuel leakage is as follows:

Fuel Leakage				§571.301 Standard No. 301; Fuel system integrity states:
Gasoline	=	28	g	Initial fuel loss
Gasoline	=	142	g	5 min fuel loss
Gasoline	=	700	g	28g min fuel loss
Gasoline	=	870	g	Total fuel loss
		Energy Content of Various Fuels	Per lbm	
Gasoline	=	20800	Btu/lbm	HHV CEC-600-2007-002-D, CA Energy Commission (6.00 lbm/gal)
Gasoline	=	19200	Btu/lbm	LHV CEC-600-2007-002-D, CA Energy Commission (6.00 lbm/gal)
Methane	=	23900	Btu/lbm	HHV CEC-600-2007-002-D, CA Energy Commission (4.31 lb/100 scf)
Methane	=	21500	Btu/lbm	LHV CEC-600-2007-002-D, CA Energy Commission (4.31 lb/100 scf)
Propane	=	21669	Btu/lbm	HHV CEC-600-2007-002-D, CA Energy Commission (4.26 lbm/gal)
Propane	=	19950	Btu/lbm	LHV CEC-600-2007-002-D, CA Energy Commission (4.26 lbm/gal)
Propane	=	21548	Btu/lbm	NFPA 58, Liquefied Petroleum Gas Code, 1998 Ed., Table B-1.2
Propane	=	21591	Btu/lbm	http://www.propane101.com/aboutpropane.htm [10/09/2014 12:48]
		Energy Content of Various Fuels	Per gram	
Gasoline	=	45.86	Btu/g	HHV CEC-600-2007-002-D, CA Energy Commission (6.00 lbm/gal)
Gasoline	=	42.33	Btu/g	LHV CEC-600-2007-002-D, CA Energy Commission (6.00 lbm/gal)
Methane	=	52.69	Btu/g	HHV CEC-600-2007-002-D, CA Energy Commission (4.31 lb/100 scf)
Methane	=	47.39	Btu/g	LHV CEC-600-2007-002-D, CA Energy Commission (4.31 lb/100 scf)
Propane	=	47.77	Btu/g	HHV CEC-600-2007-002-D, CA Energy Commission (4.26 lbm/gal)
Propane	=	43.98	Btu/g	LHV CEC-600-2007-002-D, CA Energy Commission (4.26 lbm/gal)
Propane	=	47.50	Btu/g	NFPA 58, Liquefied Petroleum Gas Code, 1998 Ed., Table B-1.2
Propane	=	47.60	Btu/g	http://www.propane101.com/aboutpropane.htm [10/09/2014 12:48]
Methane	=	46.36	Btu/g	*from GM Petition Chart*
Gasoline	=	44.09	Btu/g	*from GM Petition Chart*
Propane	=	47.70	Btu/g	*from GM Petition Chart*
		Energy Leak Rate of LPG liquid	equivalent to Gasoline Leak Rate	
LPG	=	25.9	g	Initial
LPG	=	131.3	g	5 min
LPG	=	647.0	g	25.9g/min for 25 min
LPG	=	804.2	g	TOTAL Using GM Petition Chart values

Appendix C2 – Calculations of Gaseous Leak Rates

Calculation results are as follows. We have:

$$P * V = Z * n * R * T$$

$$(P_{t(N2i)} * V_{t(N2i)} / (Z_{(N2)} * R * T_{(N2i)})) = n_{(N2i)} \text{ moles}$$

$$(P_{t(N2f)} * V_{t(N2f)} / (Z_{(N2)} * R * T_{(N2f)}) = n_{(N2f)} \text{ moles}$$

where:

$P_{t(N2i)}$	is	N_2 pressure tank initial	in	kPa absolute
$P_{t(N2f)}$	is	N_2 pressure tank final	in	kPa absolute
$V_{t(N2i)}$	is	N_2 volume tank initial	in	liters
$V_{t(N2f)}$	is	N_2 volume tank final	in	liters
$T_{(N2i)}$	is	N_2 temperature initial	in	K
$T_{(N2f)}$	is	N_2 temperature final	in	K
$N_{(N2i)}$	is	N_2 number of moles initial	in	mol
$N_{(N2f)}$	is	N_2 number of moles final	in	mol
$Z_{(N2)}$	is	Nitrogen compressibility factor	in	1/1 or dimensionless[46]
R	is	molar gas constant	in	(L*kPa) / (mol*K)

Where measured values and units are as follows:

$P_{t(N2i)}$	is	N_2 gauge pressure tank initial	=	297.4	psig
$P_{t(N2f)}$	is	N_2 gauge pressure tank final	=	268.3	psig
$V_{(N2i)}$	is	N_2 volume tank initial	=	59.0	liter
$V_{(N2f)}$	is	N_2 volume tank final	=	59.0	liter
$P_{a(i)}$	is	atmospheric pressure (raw) initial	=	14.1	psia (raw)
$P_{a(f)}$	is	atmospheric pressure (raw) final	=	14.1	psia (raw)
$P_{t(N2i)}$	is	N_2 absolute pressure tank initial	=	311.5	psia
$P_{t(N2f)}$	is	N_2 absolute pressure tank final	=	282.3	psia
kPa/psi		conversion	=	6.8948	kPa/psi
$P_{t(N2i)}$	is	N_2 absolute pressure tank initial	=	2147.5	kPa absolute
$P_{t(N2f)}$	is	N_2 absolute pressure tank final	=	1946.7	kPa absolute
$T_{(N2i)}$	is	N_2 temperature initial in Fahrenheit	=	69.8	°F
$T_{(N2f)}$	is	N_2 temperature final in Fahrenheit	=	73.7	°F
$T_{(N2i)}$	is	N_2 temperature initial in degrees Kelvin	=	294.2	K
$T_{(N2f)}$	is	N_2 temperature final in degrees Kelvin	=	296.3	K
R	is	molar gas constant	=	8.314	(L*kPa) / (mol*degK)

Therefore:

$n_{(N2i)}$	is	number of N_2 moles initial	=	51.8	mol
$n_{(N2f)}$	is	number of N_2 moles final	=	46.6	mol
$\Delta n_{(N2)}$	is	change moles N_2 in tank	=	5.2	mol

For an approximate estimate assume same number of moles of C_3H_8 as moles N_2 passing through orifice: [47]

$U_{(C3H8)/g}$	is	LPG energy/unit weight	=	47.7	BTU/g
$MW_{(C3H8)}$	is	LPG Molecular Weight	=	44.1	g/mol
$C_3H_{8\,(loss)}$	is	C_3H_8 for gas leak	=	228.3	g
$U_{(C3H8)}$	is	Heat C_3H_8 gas leak	=	10891.4	BTU
$C_3H_{8\,(loss)}$	is	C_3H_8 allowable	=	805	g
Gas vs. Liquid %		"Ratio gas vs liquid leak rate–same orifice"	=	28	percent

[46] We also assume a compressibility factor for nitrogen, Z of unity. Actual compressibility factor based on "Thermophysical Properties of Fluid Systems" in NIST Chemistry WebBook is approximately 0.9976 to 0.9979.

[47] We merely wish to illustrate a variation in leak rate if gas is escaping instead of a liquid. We are of course not taking into account the fact that with propane (instead of nitrogen), as the pressure in the tank would decrease additional propane would go from a liquid phase to a gaseous phase thus increasing the pressure to some extent. Also as liquid propane comes out it could flash and freeze and that could change the pressures and the amount of available fuel. Additionally, the issue with using nitrogen for propane is the viscosities of the two gases are different. For the same pressure of nitrogen gas and propane the velocity of nitrogen is about 1.5 times faster. Pressure would remain higher if more propane entered the gaseous phase increasing loss, while freezing and taking into account different velocities lower the actual ratio.

Appendix D – Tank Technical Data

Specifications and other technical data for the LPG tanks used in this study are found in Table 23 and in Figures 21 through 24.[48] [49] [50] [51] [52] The Manchester autogas tanks used in these tests were manufactured to ASME Section VIII, Division I Code and meet NFPA # 58 standards for engine fuel applications. Liquid, vapor, or dual service (liquid and vapor) type tanks are options for autogas tanks. Standard features include 80 percent stop fill device and seal welded stainless steel ASME nameplate. Direct or remote fill options and engineered strap brackets or custom designs are available. All tanks are designed for 312 psi maximum allowable working pressure. The tanks have undergone multiple testing procedures, including being pneumatically tested with dry air to eliminate water and corrosion which might plug water drain ports, etc.

The small 26.2 gallon tank, P/N 2380417, is used for mounting in car trunks. It weighs 98 lb and fits into Ford Taurus, Chevrolet Impala, Chevrolet Caprice, and Dodge Charger vehicles for most model years (see Figures 21 and 22). The larger 41.4 gallon tank, P/N 20067, is used as a large capacity under cap or cover mount tank for small pick-up trucks. It weighs 152 lb (see Figures 23 and 24).[53]

Table 23 – Detailed Tank Specifications

MANCHESTER PART #	DIA.	Length	Total Volume	Total Volume	MAWP	MAWP Temp Spec.	C_3H_8 Cap. 80%	Weight C_3H_8	Weight C_3H_8	Water Require	Water Require 20 °C	Free Vol in Tank
P/N	inch	inch	gal	L	psi	°F	gal	lbm	kg	kg	L	L
2380417	16	34	26.2	99.18	312	650	20.96	88.45	40.12	40.12	40.19	58.98
20067	16	52	41.4	156.72	312	650	33.12	139.77	63.40	63.40	63.51	93.20

[48] Labels on the tanks as received are as follows: SG = sight gauge. A float gauge indicates the liquid level inside the tank. V6= Fill valve with an overfill prevention device. V4= fixed maximum liquid level gauge. V3= vapor opening. Plugged: ¾ NPT. V2= relief valve with a 312 psi start to discharge setting. V1= service valve opening with 12 volt solenoid operated valve with a 3/8" SAE outlet. The labels under V6 indicate the function of the fill valve in both English and French. The service openings are labeled as to their communication with either the vapor or liquid space of the container in both English and French.

[49] Note the "weight" of propane is an approximation. The density of propane is actually a function of temperature since it can exist in a liquid/gas phase at temperatures over the boiling point. Liquid density propane (1.013 bar at boiling point) : 580.88 kg/m3 Liquid/gas equivalent (1.013 bar and 15 °C (59 °F))
Ref: http://encyclopedia.airliquide.com/Encyclopedia.asp?GasID=53#LiquidGasConversion (Retrieved March 22,2016 revised)

[50] For this chart and tests for consistency we used 4.22 lbm/gal as presented in the chart Converting Gasoline Energy to Equivalent CNG/LPG Pressure Drop from "GM Petition, FMVSS No. 303 Upgrade, NHTSA, MRT Briefing," September 18, 2012. This gives a value of 505.6 kg/m^3.

[51] Note that Industry Canada/Measurements Canada specifies 510 kg/m^3 C_3H_8 @15 °C (or 4.256 lbm/gal C_3H_8 @15 °C or ~60 °F). Measurements Canada https://www.ic.gc.ca/eic/site/mc-mc.nsf/eng/lm00136.html (Retrieved 01/05/2014:1018). We used the 4.22 lbm/gal value for our calculation of weight and volume. However all temperature and pressure calculations were corrected to NIST NTP as previously noted.

[52] Also "the industry standard 60°F is universally recognized as the base reference point for liquid propane volume correction." www.propane101.com/propanevolumecorrection.htm (Retrieved January 5, 2015)

[53] Reference Guide For Stock Autogas Tanks, www.mantank.com/pdf/AutogasTankGuide.pdf (Retrieved March 15, 2015)

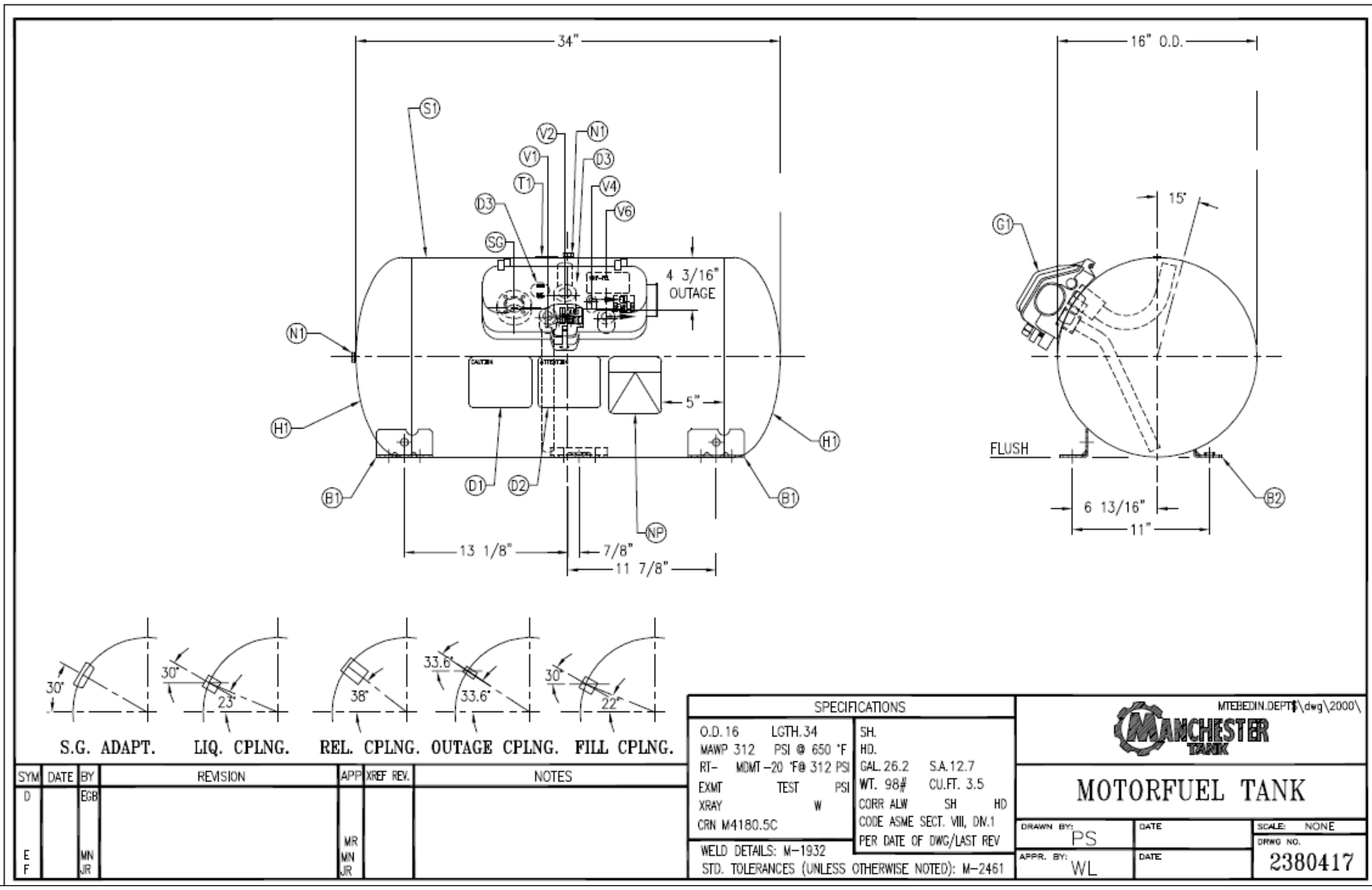


Figure 21 – 26.2 Gallon Manchester LPG Tank PN 2380417

Figure 22 – 26.2 Gallon Manchester LPG Tank Serial No. Plate

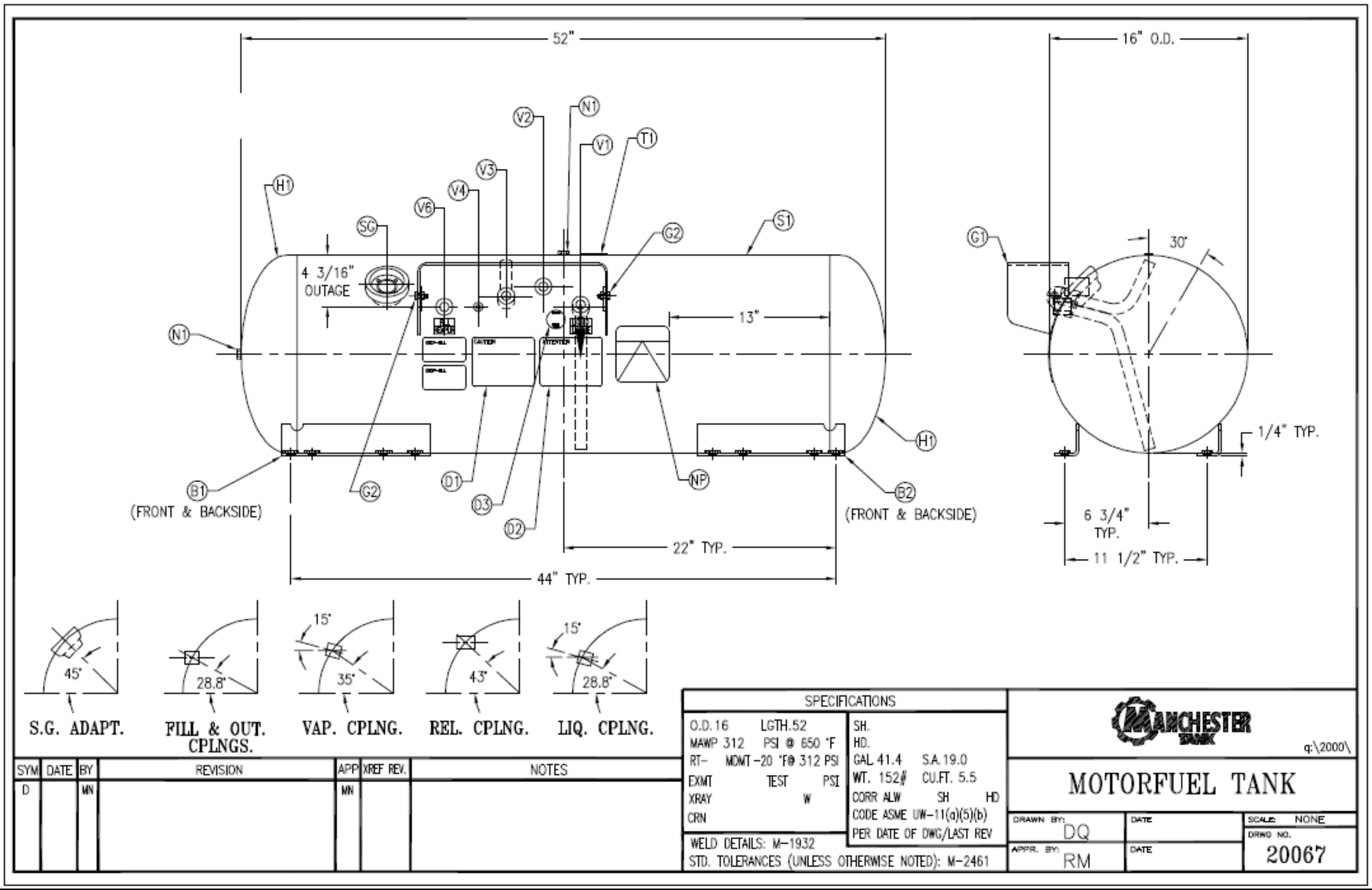


Figure 23 – 41.4 Gallon Manchester LPG Tank PN 20067

Figure 24 – 41.4 Gallon Manchester LPG Tank Serial No. Plate

Appendix E – Other Data Runs

Other test runs to assess repeatability and consistency when correcting results to normal temperature and pressure are as follows:

Table 24 – Summary of Regular Test Data for Small Tank (26.2 gallon)[54]

Test Run/Action	Tank Total Volume	Water Volume in Tank	N_2 Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pressure @NT
a/n	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
RUN 1114 DRAIN 30 min TOTAL DRAIN, DATA @60 min	99.2	39.3	59.9	804.7	-0.805	289.9	14.1	304.0	75.0	72.8	301.3	-4.0
RUN 1125 DRAIN 60 min TOTAL DRAIN, DATA @30 min	99.2	40.1	59.9	806.5	0.000	292.8	14.2	307.0	75.0	72.5	304.4	-4.2
RUN 1140 DRAIN 30 min TOTAL DRAIN, DATA @60 min	99.2	39.3	59.9	805.2	-0.805	292.4	14.2	306.6	75.0	76.0	302.0	-4.1
RUN 1142 DRAIN 30 min TOTAL DRAIN, DATA @60 min	99.2	40.1	59.1	805.1	0.000	291.4	14.2	305.6	76.7	74.8	301.7	-3.9
RUN 1146 DRAIN 30 min TOTAL DRAIN, DATA @60 min	99.2	39.3	59.9	805.0	-0.805	292.9	14.1	306.9	76.7	77.0	301.7	-4.2
RUN 1158 DRAIN 30 min TOTAL DRAIN, DATA @60 min	99.2	39.3	59.9	805.0	-0.805	292.9	14.2	307.1	76.7	73.0	304.2	-4.1
RUN 1160 DRAIN 60 min TOTAL DRAIN, DATA @30 min	99.2	39.3	59.9	804.5	-0.805	294.6	14.1	308.7	76.7	76.0	304.0	-4.1
RUN 1172 DRAIN 30 min TOTAL DRAIN, DATA @60 min	99.2	39.3	59.9	805.3	-0.805	293.4	14.3	307.6	76.7	73.7	304.3	-3.8
RUN 1178 DRAIN 30 min TOTAL DRAIN, DATA @60 min	99.2	39.3	59.9	804.5	-0.805	291.5	14.1	305.6	76.3	76.3	300.9	-4.4
RUN 1189 30 min TOTAL DRAIN, DATA @ 60 min	99.2	39.3	59.9	804.3	-0.804	291.8	14.1	305.9	75.0	75.6	301.6	-4.0
RUN 1201 30 min TOTAL DRAIN, DATA @ 60 min	99.2	39.3	59.9	804.3	-0.804	288.1	14.2	302.3	75.0	73.7	299.0	-3.9
RUN 1209 60 min TOTAL DRAIN, DATA @ 30 min	99.2	39.3	59.9	804.5	-0.805	294.3	14.0	308.3	75.0	72.0	306.0	-4.3

[54] "RUN1178 DRAIN 30 min TOTAL DRAIN, DATA @60 min" means we drained water for 30 minutes and then let conditions stabilize and read all data at 60 minutes. "RUN 1125 DRAIN 60 min TOTAL DRAIN, DATA @30 min" means we drained for a total of 60 minutes and took data at 30 minutes, which means that there was no stabilization time. Other runs were tests to verify set up and fast and slow drain rates.

Table 25 – Summary of Regular Test Data for Large Tank (41.4 gallon)

Test Run/Action	Tank Total Volume	Water Volume in Tank	N_2 Volume in Tank	Weight Water Drain	Change Water Volume	Tank Pres.	Ambient Pres.	Tank Pres.	Ambient Temp	Tank Temp (gas)	Pressure 68 °F 14.7 psia ambient	Actual ΔTank Pressure @NT
a/n	L	L	L	g	L	psig	psia	psia	°F	°F	psia	psia
RUN 1267 30 min TOTAL DRAIN, DATA @60 min; Start Pres 299.1 psig	156.7	62.6	94.1	805.7	-0.8	296.5	14.4	310.9	74.1	71.6	308.8	-2.6
RUN 1273 30 min TOTAL DRAIN, DATA @60 min	156.7	62.6	94.1	804.7	-0.8	291.6	14.1	297.2	75.0	71.5	295.3	-2.8
RUN 1277 30 min TOTAL DRAIN, DATA @60 min	156.7	62.6	94.1	805.2	-0.8	295.0	14.2	309.2	75.0	72.0	306.9	-2.7
RUN 1280 30 min TOTAL DRAIN, DATA @60 min	156.7	62.6	94.1	805.2	-0.8	292.9	14.2	307.1	75.0	71.8	304.9	-2.6
RUN 1287 60 min TOTAL DRAIN, DATA @30 min	156.7	62.6	94.1	804.5	-0.8	291.2	14.2	305.4	75.0	71.3	303.5	-2.6
RUN 1303 70 min TOTAL DRAIN, DATA @30 min	156.7	62.6	94.1	804.5	-0.8	291.3	14.2	305.5	75.0	78.7	299.5	-2.6

DOT HS 812 377
April 2017

U.S. Department
of Transportation

National Highway
Traffic Safety
Administration

NHTSA

12970-040517-v3