

File: @632 outage emission rev5.doc

October 27, 2004

Revised: November 30, 2004

Revised: January 20, 2005

Revised: January 24, 2005

Evaporative Emission Rates from LP Gas Outage Gauges while Refueling

I. Introduction

This report describes ADEPT's initial efforts to quantify evaporative emissions released through outage gauges (also called "fixed liquid level gauges" or "spitter valves") while refueling LP Gas tanks.¹ When refueling, LP Gas is released through outage gauges as a gas, as a liquid, and as a mix of the two phases. This work outlines and compares results from: (1) theoretical emissions calculations, and (2) empirical tests.

These calculations exclude the LP Gas released when the fueling nozzle and/or the vapor return line (if one is installed) are disconnected (relatively minor emissions when compared to outage gauge releases). It was noted that when the fueling process is initiated, a small slug of liquid is often released. This relatively small liquid slug is intentionally also not included in these calculations.

II. Outage Gauge Functions

In many states, outage gauges are used to determine when an LP Gas tank is legally full (i.e. liquid reaches 80% vol. level). Through an outage gauge, a visual signal (i.e. a white cloud) is provided to stop filling for the person doing the refueling.

The outage gauge is a small-bore valve atop a thin hollow tube that drops through the tank wall to the 80% full level of a specific tank at 40 °F.² The small-bore valve is opened before the fueling process begins and is closed once the fueling process ends. The refueling operator must wear gloves to close this valve to avoid cold burns.

On first opening the outage gauge, a small liquid slug may be released, next mostly vapor is emitted, and finally (e.g. when the tank is 80% full), mostly liquid is vented when the liquid LP Gas rises to the bottom of the outage gauge tube.^{3,4}

¹ Detailed information regarding the complete range of outage gauges used in California (e.g. tube length, path geometry, tube material, surface finish, etc.) is not currently available. There is reason to believe that collection of extensive data on outage gauges is not warranted because it will not significantly change these fugitive emission estimates.

² See attached typical outage gauge diagram [courtesy of Mr. Jeff Borton (Sherwood Gas Products)].

³ See attached outage gauge in liquid phase LP Gas release mode photo.

III. Known Facts and Assumption

A. Facts:

- Internal Diameter of Outage Gauge Tube = 0.055" = 0.001397 m.
- Internal Area of Outage Gauge Tube (A) = $1.53 \times 10^{-6} \text{ m}^2$.⁵
- Density (ρ_l) of 100% liquid laboratory grade propane⁶ = $501 \text{ kg/m}^3 = 0.501 \text{ g/cm}^3$. Reference temperature is 68 °F (20 °C) at saturation pressure (107 psig).⁷
- Density (ρ_g) of 100% vapor laboratory grade propane = 17.815 kg/m^3 . Reference temperature is 68 °F (20 °C) at saturation pressure.⁸

B. Assumptions:

- 107 psig was taken to be the average tank internal pressure (P_1).⁹ This assumes a typically filling temperature of 68 °F (20 °C).
- The bore area of the outage gauge bore area that is opened by the operator has a release area that is at least equal to the cross-sectional area of the dip-tube.

IV. Liquid Phase Evaporative Emissions Calculations

To calculate liquid phase emission from an outage gauge, a procedure based on Bernoulli's equation is used. Bernoulli's equation states that the sum of the pressure, velocity and elevation heads is constant. Equation assumptions are: (1) the fluid is incompressible and non-viscous, (2) there is no energy loss due to

⁴ Just because a tank refueler sees liquid emitting from the outage gauge, does not mean that he will stop filling. Reportedly, this undesirable occurrence has been previously a safety enforcement issue (when the vehicle driver/operator is looking to extend his/her operating range).

⁵ Theoretically, this area may be less if operator does not fully open the valve. However, in practice, a half-turn of the valve will expose an area equal to or greater than the calculated area (since the release opening of the spitter valve has a larger diameter than the dip tube).

⁶ For purposes of this paper, it is assumed that only 100% propane (C_3H_8) is present in LP Gas tanks. In real life, LP Gas is known to contain significant amounts of propylene (C_3H_6), ethane (C_2H_6), and butanes (C_4H_{10}). Pure propane is accepted to be a reasonable approximate for these calculations because the lower vapor pressures of butanes (vs. propane) is likely to provide some balance to counter the higher vapor pressures of propylene and/or ethane (also vs. propane).

⁷ Source: Matheson Gas Data Book 6th Edition (see attached).

⁸ Source: Matheson Gas Data Book 6th Edition (see attached).

⁹ The higher the tank internal pressure, the greater the emissions-out flow rate, and the greater the released volume. The internal pressure inside a tank being filled can vary from 100 to 300 psig. (Most LP Gas tanks are equipped with a pressure relief valve that allows fuel to vent to the atmosphere if the pressure reaches 312 psig.) Fill-pump differential pressure ranges from 15 to 200 psi. (The differential pressure is the pressure difference between the discharging pressure of the fueling nozzle and the internal pressure of the vehicle tank.) Typical recommended differential pressure is 80 psid.

friction between the fluid and the wall of the pipe, (3) there is no heat energy transferred across the boundaries of the pipe to the fluid as either a heat gain or loss, and (4) the fluid flow is laminar and steady state.

The below equation converts tank pressure energy to kinetic energy:

$$P_1/\rho_1g + z_1 + V_1^2/2g = P_2/\rho_1g + z_2 + V_2^2/2g \text{ (Bernoulli's equation) equation \#1}$$

$$P_1 = \text{Tank Internal Pressure} = 107 \text{ psig}$$

$$P_2 = \text{Ambient Pressure} = 0 \text{ psig}$$

$$V_1 = \text{Internal Liquid Velocity} = 0$$

$$V_2 = \text{External Liquid Velocity}$$

$$Z_1 = \text{Internal Elevation} = 0$$

$$Z_2 = \text{External Elevation} = 0$$

$$g = \text{Gravitational Acceleration (9.81 m/s}^2\text{)}$$

$$P_1/\rho_1g = V_2^2/2g \quad \Rightarrow \quad V_2 = (2P_1/\rho_1)^{0.5} \quad \text{equation \#2}$$

$$V_2 = [(2 * 107 \text{ psi} * 6,894.8 \text{ N/m}^2/\text{psi}) / 501 \text{ kg/m}^3]^{0.5} = 54.27 \text{ m/s} \quad \text{equation \#3}$$

Uncorrected mass flow rate is:

$$m_{\text{dot}} = \rho_1 V_2 A = (501 \text{ kg/m}^3)(54.27 \text{ m/s})(1.53 * 10^{-6} \text{ m}^2) = 0.04156 \text{ kg/s} = \mathbf{41.6 \text{ g/s}} \quad \text{equation \#4}$$

Corrected mass flow rate is:

$$m_{\text{dot corrected}} = m_{\text{dot}} * C$$

$$\text{where } C = \text{discharge coefficient (dimensionless)} = 0.62^{10}$$

$$m_{\text{dot corrected}} = 44 \text{ g/s} * 0.62 = \mathbf{25.77 \text{ g/s}} \quad \text{equation \#5}$$

The maximum liquid LP Gas release rate via the above theoretical calculation is **25.77 g/s**.

V. Gas Phase Evaporative Emissions Calculations

To calculate gas phase emissions from an outage gauge, a procedure based on the speed of sound in propane is used.

At a given temperature and pressure (i.e. 68 °F and 107 psig), gas flow rate from an LP Gas tank is limited by the speed of sound.

Speed of Sound (c) in Propane:¹¹

$$c = (kRT)^{0.5} \quad \text{equation \#6}$$

$$c = (1.14 * 188.95 * 293.2)^{0.5} = \mathbf{251.29 \text{ m/s}} \quad \text{equation \#7}$$

¹⁰ See attached article re: "Gas/Liquid Discharge from a Pressure Source" from The Chemical Engineers' Resource Page (www.cheresources.com/discharge.shtml).

¹¹ Fundamentals of Engineering Supplied-Reference Handbook 4th Edition, National Council of Examiners for Engineering and Surveying, page 43.

$k = \text{Ratio of Specific Heats } (c_v/c_p) = 1.14^{12}$
 $R = \text{Ideal Gas Constant} = (8.314 \text{ J/kmol} \cdot \text{K}) / (44 \text{ kg/kmol}) = 188.95 \text{ J/kg} \cdot \text{K}$
 $T = \text{Temperature} = 68 \text{ }^\circ\text{F} (293.2 \text{ }^\circ\text{K})$

Uncorrected mass flow rate is:

$m_{\text{dot}} = \rho_g V_2 A$ equation #8
 $m_{\text{dot}} = (17.82 \text{ kg/m}^3)(251.29 \text{ m/s})(1.53 \cdot 10^{-6} \text{ m}^2) = \mathbf{6.85 \text{ g/s}}$ equation #9

Corrected mass flow rate is:

$m_{\text{dot corrected}} = m_{\text{dot}} \cdot C$ equation #10
 where $C = \text{discharge coefficient (dimensionless)} = 0.62^{13}$
 $m_{\text{dot corrected}} = 6.85 \text{ g/s} \cdot 0.62 = \mathbf{4.25 \text{ g/s}}$ equation #11

The maximum limit case for 100% LP Gas vapor emissions via the above equation and calculation is **4.25 g/s**.

This maximum theoretical value of vapor emissions is a conservative estimate of LP Gas releases during cylinder and tank filling as there is reason to believe (based on visual observations of the emissions from the outage gauge) that these emissions are rarely 100% gas (it is thought that typically some liquid is entrained).

VI. Summary of Calculated Gas and Liquid Phases Emission Rates

Theoretical LP Gas Release Rates Calculations		
	Liquid Phase (g/s)	Gas Phase (g/s)
Bernoulli (liquid) / Speed of Sound (gas) Method	25.77	4.25

VII. Theoretical Calculations for Other Ambient Temperatures

The above calculations are repeated below for a range of temperatures (see Figures 1 and 2). These show that emissions will increase with higher ambient temperatures.

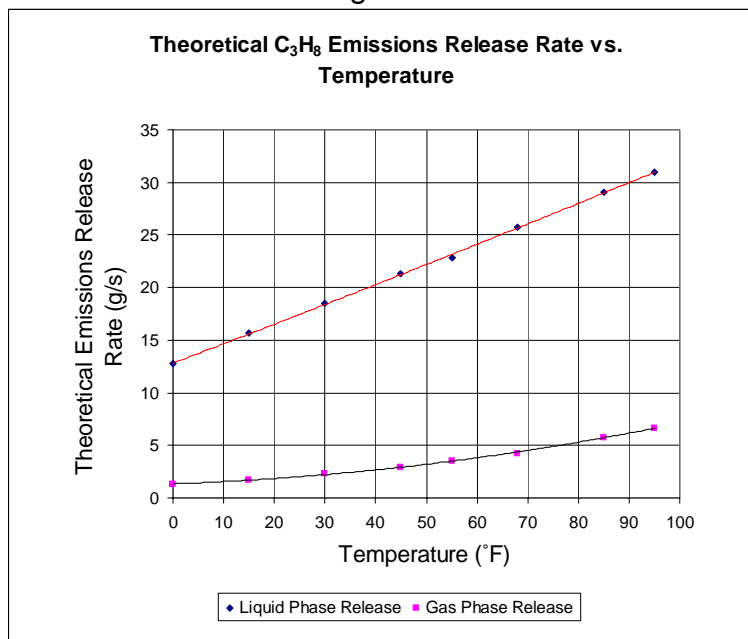
¹² Source is Matheson Gas Data Book 6th Edition (see attached). Reference temperature and pressure is 80.24 °F and 1 atm.

¹³ For reasons of conservative estimation, the gas phase discharge coefficient is taken to be the same as the liquid phase discharge coefficient (0.62).

Figure 1: Theoretical Outage Gauge Emissions

Temp.	Temp.	Average Internal Pressure	Density Liquid	Density Gas	Liquid Phase Exit Velocity	Uncorrected Liquid Flow Rate	Corrected Liquid Flow Rate	Speed of Sound	Uncorrected Gas Flow Rate	Corrected Gas Flow Rate
(°F)	(°K)	(psig)	(kg/m ³)	(g/m ³)	(m/s)	(g/s)	(g/s)	(m/s)	(g/s)	(g/s)
0	255.4	23.7	553.90	5.900	24.30	20.59	12.77	234.54	2.12	1.31
15	263.7	36.3	543.18	7.624	30.36	25.23	15.64	238.33	2.78	1.72
30	272.0	51.8	531.20	9.869	36.67	29.80	18.48	242.07	3.66	2.27
45	280.4	70.6	520.12	12.714	43.27	34.44	21.35	245.75	4.78	2.96
55	285.9	82.2	511.85	14.973	47.07	36.86	22.85	248.17	5.69	3.52
68	293.2	106.9	500.57	17.815	54.27	41.56	25.77	251.29	6.85	4.25
85	302.6	140.2	484.83	23.681	63.15	46.84	29.04	255.30	9.25	5.74
95	308.2	162.7	474.99	27.318	68.72	49.94	30.96	257.64	10.77	6.68

Figure 2:



VIII. Experimental Results For Evaporative Emissions Release Rates

Three (3) tests were conducted to gauge mass flow releases through a #54 drill size (0.055") outage gauge from an LP Gas barbeque (BBQ) bottle. The results conservatively estimate gas phase flow rates from a vehicle's outage valve as the BBQ tank was not being re-filled during this test. Under normal tank filling or automotive refueling conditions (where LP Gas is pumped into the tank while the outage valve is opened) there is little if any pressure drop inside the tank.

It is also of note that the duration of the below tests (50 min., 20 min., and 10 min.) is much greater than typical BBQ tank refilling times.¹⁴ Venting the tank for such extended periods caused the BBQ tank to rapidly cool and the internal pressure to significantly drop. It has been previously shown that a drop in

¹⁴ This was necessary in order to obtain a measurable amount of LP Gas loss with the available equipment.

temperature will lower mass flow releases. Also, for this reason, the experimental emissions results are thought to be conservative vs. real-life in-the-field refueling emissions.

IX. Procedure

- (1) 5-gallon BBQ tank equipped with a 0.055" drilled size outage valve is filled to legal capacity (~4 gallons = 80% full).
- (2) Tank is weighed on an electronic veterinarian scale (0.1 lbs. accuracy).¹⁵
- (3) Tank temperature is measured with a low temperature cooking thermometer.
- (4) Outage valve is fully opened to ambient for the timed periods.
- (5) Tank is weighed on the same scale after outage valve is closed.
- (6) Steps (2) to (5) are repeated (for different time periods).

X. Results

A. Test #1:

Initial "full" weight = 36.4 lbs.

Outage valve open time = 50 min. = 3,000 s.

Final weight = 27.6 lbs.

Tank temperature immediately before venting = ~70°F

Tank temperature immediately after venting = below 32°F

Tank internal pressure at start of test = ~110 psig¹⁶

B. Test #2:

Initial weight = 27.6 lbs.

Outage valve open time = 20 min. = 1,200 s.

Final weight = 24.4 lbs.

Tank temperature immediately before venting = ~63°F

Tank temperature immediately after venting = below 32°F

Tank pressure at start of test = ~98 psig¹⁷

C. Test #3

This test was conducted with the BBQ bottle upside-down to ensure that (as much as possible) only liquid phase LP Gas is released.

Initial "full" weight = 34.8 lbs.

Outage valve open time = 601 s.

Final weight = 29.2 lbs.

¹⁵ The +/- 0.1 lb accuracy of the scale is a major possible source of error in these empirical experiments. This error source intervenes twice: once at the start of the test, and once at its end. Same applies to the unscientific temperature and pressure gauges used in these tests.

¹⁶ Experimental test pressure in Test #1 (110 psig) is on par with the pressure used in the theoretical emissions calculations (107 psig).

¹⁷ Experimental test pressure in Test #2 (98 psig) is lower than the pressure used in the theoretical emissions calculations (107 psig). Had the experimental test pressure been higher, emissions flow rates would be higher.

Tank temperature immediately before venting = ~60°F

Tank temperature immediately after venting = ~36°F

Tank pressure at start of test = ~93 psig¹⁸

D. *Test Notes:*

Note 1: Liquid LP Gas (i.e. a “white cloud”) was released at the start of Test #1. Gas was emitted once liquid dropped below the outage gauge dip tube.

Note 2: As the tank emptied, the liquid level could be approximated due to the water condensate on the outside of tank.

Note 3: The flow rate exiting the outage gauge slowed as pressure inside tank dropped (due to temperature drop). This flow rate decrease was audibly and physically noticeable.

Note 4: No “liquid” slug was released from outage valve at start of Test #2.

XI. Calculations

A. *Test #1: Liquid and Gas Phase Emissions*

Δ weight = 8.8 lbs. = 4 kg = 4,000 g.

Net Mass flow = 4,000 g / 3,000 s = **1.3 g/s LP Gas**

Note: Duration of liquid and gas phase emissions for Test #1 were measured (liquid LP Gas was released in the first 90 s after opening the outage gauge valve – with the liquid phase portion decreasing over time).

B. *Test #2: Gas Phase Only Emissions*

Δ weight = 3.2 lbs. = 1.45 kg = 1,450 g.

Mass flow rate = 1,450 g / 1,200 s = **1.21 g/s gaseous phase LP Gas**

C. *Estimation of Liquid Phase Emissions Release Rate in Test #1:*

Assumptions:

- Test #2 gas phase emissions rate (1.21 g/s) is used to calculate total gas phase emissions in Test #1.
- Ignored variance due to different starting temperatures.

Gaseous flow = 49 min. = 2,940 s.

Mass released as gas flow = 2,940 s * 1.21 g/s (from Test #2) = 3,557.4 g.

Mass released as liquid flow = 4,000 g – 3,557.4 g = 442.6 g.

“Liquid” flow lasted = 90 s.

“Liquid” flow rate = 442.6 g / 90 s = **4.918 g/s (rounded to 4.92 g/s).**

¹⁸ Experimental test pressure in Test #3 (93 psig) is lower than the pressure used in the theoretical emissions calculations (107 psig). Had the experimental test pressure been higher, emissions flow rates would be higher.

D. *Test #3: Liquid Only Emissions*

Δ weight = 5.6 lbs. = 2.54 kg = 2,540.1 g.

“Liquid” phase mass flow rate = 2,540.1 g / 601 s = **4.226 g/s liquid LP Gas (rounded to 4.23 g/s)**

XII. Review of Empirical Gaseous and Liquid Emission Rates

Empirical LP Gas Release Rates from a BBQ Tank		
	Liquid Release (g/s)	Gas Release (g/s)
Test #1	4.92 ¹⁹	1.3 corrected to 1.21 ²⁰
Test #2	N.A.	1.21
Test #3	4.23	N/A

Confidence in Test #1 gas flow rate is low due to the prolonged “liquid” slug period. Fortunately, by contrast, the confidence in the Test #2 results is high (for gas phase flow). Confidence in the liquid phase flow in Test #3 is also high. These test results **conservatively** estimate released mass flow rates as the observed pressure drop is significantly more than in real-life filling conditions. Also as the pressure is lower, less of the “ice-like” structures forming in the inside of the gauge will be blown out, so the gas outflow would be higher if these ice-like structures were not impeding the gas flow.

Test #2 and #3 results were slightly affected by different initial tank temperatures (initial pressure would be slightly different: 14 and 9 psi respectively) vs. the theoretical calculations. This further fits with the intent to err on the side of conservative release rates.

XIII. Conclusions

Theoretical vs. Empirical LP Gas Release Rates		
	Theoretical Results	Empirical Results ²¹
Liquid Release (g/s)	25.77	4.23
Gas Release (g/s)	4.25	1.21

It is reasonable to estimate evaporative emission rates from LP Gas outage gauges as: (1) **1.21 g/s** for gas phase, and (2) **4.23 g/s** for liquid phase.

It is important to note that this is an "order-of-magnitude" assessment. Better instruments (e.g. real time temperature and pressure sensors/data loggers) and

¹⁹ The net emissions rate for Test #1 is 1.3 g/s (includes liquid and vapor phase emissions). This emissions rate is broken down into gas and liquid phase flow rates via the time of liquid phase emissions (90 s) and use of the gas phase emissions flow rate obtained in Test #2 (1.21 g/s).

²⁰ See footnote #20.

²¹ In an on-going effort not to overestimate LP Gas releases, whenever two results diverged, the lower number was selected.

testing conditions are required in the event there is a desire to narrow the range of the estimated emissions (e.g. test tanks while being refilled).²²

XIV. Credits:

Special thanks to the following folks for their insightful comments, edits, and suggestions to improve this order-of-magnitude study (in alphabetical order):

- Mr. Joe Adams, Vice-President and General Manager, Slegers Engineering, Inc.;
- Mr. Jeff Borton, Sherwood Gas Products;
- Dr. Vijay Dhir, Dean, UCLA School of Engineering;
- Mr. Robert Falkiner, Quality Assurance Operations and Development, Esso;
- Mr. James Keatley, Consultant;
- Mr. Steve Moore, President, Mutual Liquid Gas & Equipment Co., Inc.;
- Mr. Bob Myers, Consultant;
- Mr. Doug Peck, Vice President of Maintenance, Via Metropolitan Transit;
- Dr. Andy Pickard, Consultant;
- Mr. Bill Platz, President, Delta Liquid Energy;
- Ms. Mary Reynolds, Executive Vice President, Western Propane Gas Association;
- Mr. Arnie Smith, Executive Director, Office of Technology, Fluor Corp; and
- Mr. Jordan Trachsel, BESC. Mech., Project Engineer, Slegers Engineering, Inc.

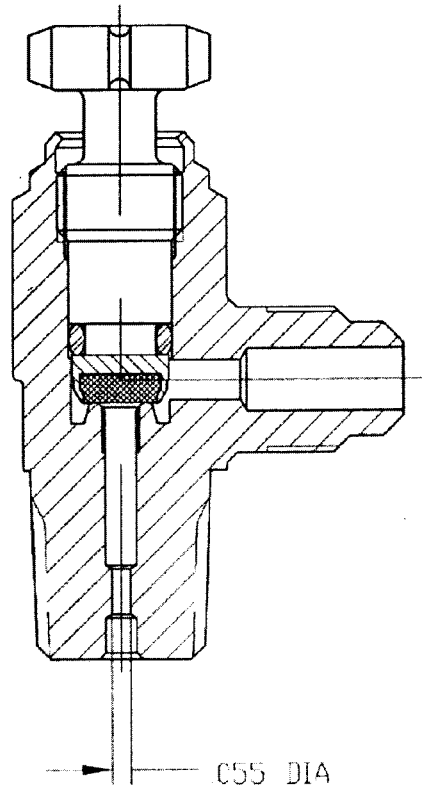
These folks' contributions (a defacto peer review process) validated and enhanced the writers' efforts to seek-out reasonable and credible results.

XV. Enclosures:

- (1) Typical outage gauge diagram²³;
- (2) Outage gauge photo in operation on a forklift truck tank at Mutual Propane;
- (3) Matheson Gas Data Book 6th Edition, pages 615 and 620; and
- (4) "Gas/Liquid Discharge from a Pressure Source" article from The Chemical Engineers' Resource Page (www.cheresources.com/discharge.shtml).

²² If and when the LP Gas industry may wish to conduct such efforts, ADEPT is ready to assist.

²³ Courtesy of Mr. Borton (Sherwood Gas Products).



TYPICAL OUTAGE VALVE



DANGER

1. Do Not Overfill. Fill only by approved procedure by using a hand liquid level weight check valve weight and L.P. Gas.

2. Maintain safety relief device in the upper liquid and gas space.

3. This cylinder is designed to contain L.P. Gas.

4. Be sure all fittings are tight and leak proof.

5. Do not drop or abuse the cylinder.

6. Do not expose to fire and heat.

7. Do not attempt repairs or alterations.

8. Do not use for purposes other than intended.

9. Do not use for purposes other than intended.

10. Do not use for purposes other than intended.

11. Do not use for purposes other than intended.

12. Do not use for purposes other than intended.

13. Do not use for purposes other than intended.

14. Do not use for purposes other than intended.

15. Do not use for purposes other than intended.

16. Do not use for purposes other than intended.

17. Do not use for purposes other than intended.

18. Do not use for purposes other than intended.

19. Do not use for purposes other than intended.

20. Do not use for purposes other than intended.

PROPANE

(Synonym: Dimethylmethane)

(Formula: CH₃CH₂CH₃ or C₃H₈)

PHYSICAL PROPERTIES (1)

Molar Mass	
Molecular Weight	0.044 097 kg
One Mole of C ₃ H ₈	0.044 097 kg
Specific Volume @ 21.1 °C, 161.325 kPa	530.6 dm ³ /kg; 8.5 ft ³ /lb
Vapor Pressure @ 21.1 °C	853 kPa; 8.53 bar; 123.7 psia; 8.42 atm
Boiling Point @ 101.325 kPa	231.09 °K; -42.1 °C; -43.7 °F
Triple Point	85.44 °K; -187.7 °C; -305.9 °F
Absolute Density, Gas @ 101.325 kPa @ 20 °C	1.868 kg/m ³
Relative Density, Gas @ 101.325 kPa @ 20 °C (Air = 1)	1.55
Density, Liquid @ Saturation Pressure @ 20 °C	0.500 5 kg/l
Critical Temperature	369.99 °K; 96.8 °C; 206.3 °F
Critical Pressure	4 266 kPa; 42.66 bar; 618.7 psia; 42.10 atm
Critical Volume	4.438 dm ³ /kg
Critical Density	0.225 kg/dm ³
Critical Compressibility Factor	0.271
Latent Heat of Fusion @ 85.50 °K	3.534 kJ/mol; 19.1 kcal/kg
Flammability Limits in Air	2.2-9.5% (by volume)
Dipole Moment, Gas	28 × 10 ⁻³⁰ C.m; 0.084 D
Molar Specific Heat, Gas @ 101.325 kPa @ 26.8 °C	
@ Constant Pressure	74.01 J/(mol·°K)
@ Constant Volume	64.81 J/(mol·°K)
Specific Heat Ratio, Gas @ 101.325 kPa @ 26.8 °C, Cp/Cv	1.142
Molar Specific Heat, Liquid @ 25 °C	111.13 J/(mol·°K); 26.56 cal/(mol·°K)
Viscosity, Gas @ 101.325 kPa @ 20 °C	0.007 90 mPa·s; 0.007 90 cP
Viscosity, Liquid @ -40 °C	0.22 mPa·s; 0.22 cP
Thermal Conductivity, Gas @ 101.325 kPa @ 25 °C	0.016 74 W/(m·°K); 40.0 × 10 ⁻⁶ cal·cm/(s·cm ² ·°C)
Thermal Conductivity, Liquid @ -40 °C	0.148 5 W/(m·°K); 354.9 × 10 ⁻⁶ cal·cm/(s·cm ² ·°C)
Surface Tension @ -40 °C	15.3 mN/m; 15.3 dyn/cm
Solubility In Water @ 101.325 kPa @ 18 °C	6.5 cm ³ /0.1 kg water
Dielectric Constant @ 0 °C	1.61
Autoignition Temperature	741 °K; 468 °C; 874 °F
Flash Point	169.15 °K; -104.0 °C; -155.2 °F
Refractive Index, Liquid @ Saturation Pressure @ 20 °C	1.289 8
Heat of Combustion, Gas @ 25 °C and Constant Pressure	
Gross, to form H ₂ O(liq) + CO ₂ (gas)	2 220.03 kJ/mol; 530.60 kcal/mol
Net, to form H ₂ O(gas) + CO ₂ (gas)	2 044.01 kJ/mol; 488.53 kcal/mol
Heat of Combustion, Liquid @ 25 °C and Constant pressure	
Gross, to form H ₂ O(liq) + CO ₂ (gas)	2 203.42 kJ/mol; 526.63 kcal/mol
Net, to form H ₂ O(gas) + CO ₂ (gas)	2 027.40 kJ/mol; 484.56 kcal/mol

Description

At room temperature and atmospheric pressure, propane is a colorless, flammable, nontoxic gas, with a characteristic

natural gas odor. Propane is one of the group of liquefied petroleum gases. It is normally shipped in low pressure cylinders as a liquefied compressed gas under its own vapor pressure of 752 kPa (109 psig) at 21.1 °C.

PROPANE

phosphorus trichloride and oxygen at 25 °C to yield alkane-phosphonyl chlorides which on hydrolysis give alkylphosphonic acids. (6) In the presence of aluminum chloride, alkanes react with carbon monoxide to give ketones, e.g., isobutane yields methyl isopropyl ketone.

(h) With Organic Reagents

(1) In the presence of actinic light, or in the dark in the presence of organic peroxides, alkanes, e.g., pentane, heptane, and isooctane, react with oxalyl chloride or phosgene to give acid chlorides. (2) Normal alkanes react with acid chlorides in the presence of aluminum chloride to give ketones. (3) Isoalkanes condense with haloalkanes in the presence of Friedel-Crafts catalysts, e.g., isobutane and vinyl chloride in the presence of aluminum chloride yield 1,1-dichloro-3,3-dimethylbutane. (4) Isoalkanes undergo halogen-hydrogen exchange with tertiary or secondary alkyl halides in the presence of aluminum halides. (5) Isoalkanes react with unsaturated aliphatic carboxylic acids in the presence of aluminum chloride to give saturated fatty acids. (6) Tertiary alkanes react with benzoyl peroxide yielding tert-alkyl benzoate, benzene, and carbon dioxide or (if the reaction takes this course) tert-alkylbenzene, benzyl alcohol, and carbon dioxide. (7) Tertiary alkanes and ketones in the presence of sulfuric acid react to give tert-alcohols. (8) Isoalkanes condense with aromatic hydrocarbons in the presence of silica or alumina.

Thermodynamic and Detailed Physical data

Infrared Spectrum

See Figure 2 for the infrared spectrum of gaseous propane.

Vapor Pressure (Below 101.325 kPa) (4)

Temperature, °K	Vapor Pressure		
	kPa	mbar	mmHg
144.25	0.133	1.33	1
157.75	0.667	6.67	5
164.65	1.333	13.3	10
172.25	2.666	26.7	20
180.75	5.333	53.3	40
186.15	7.999	80.0	60
193.55	13.332	133	100
204.75	26.664	267	200
217.55	53.329	533	400
231.05	101.325	1 013.25	760

Vapor pressures above 101.325 kPa (1 atm) are shown below (5).

Temperature, °K	Vapor Pressure		
	kPa	bar	atm
231.05	101.325	1 013.25	1
247.55	202.650	2.03	2
274.55	506.625	5.07	5
300.05	1 013.250	10.1	10
331.25	2 026.500	20.3	20
351.85	3 039.750	30.4	30
367.95	4 053.000	40.5	40
369.95	4 255.650	42.6	42.0

For additional vapor pressure data, see Table 1 and Figure 3.

Table 1. THERMODYNAMIC PROPERTIES OF SATURATED PROPANE LIQUID AND VAPOR (8)

Temperature		Pressure		Entropy J/(mol·°K)		Enthalpy kJ/mol		Latent Heat of Vaporization kJ/mol	Specific Volume dm ³ /kg		Density kg/dm ³	
°K	°F	kPa	atm	Liquid	Vapor	Liquid	Vapor		Liquid	Vapor	Liquid	Vapor
189.50	-118.57	10.132	0.1	150.147	258.273	14.291	34.788	20.497	1.587 4	37 735	0.630 0	0.000 03
216.54	-69.90	50.662	0.5	164.321	254.008	17.147	36.560	19.413	1.669 0	786.7	0.599 2	0.001 27
231.10	-43.69	101.325	1	170.635	251.834	18.556	37.317	18.761	1.716 7	412.7	0.582 5	0.002 42
248.06	+6.91	202.650	2	177.617	249.910	20.237	38.170	17.933	1.777 9	216.1	0.562 5	0.004 63
259.33	18.18	303.975	3	182.049	248.949	21.370	38.718	17.348	1.821 0	147.7	0.549 1	0.006 77
268.05	26.90	405.300	4	185.436	248.322	22.269	39.128	16.859	1.859 5	112.4	0.537 8	0.008 90
275.24	35.76	506.625	5	188.196	247.862	23.018	39.445	16.427	1.893 6	90.71	0.528 1	0.001 02
281.44	40.29	607.950	6	190.579	247.527	23.682	39.713	16.031	1.925 3	75.92	0.519 4	0.013 17
286.90	56.75	709.275	7	192.670	247.234	24.272	39.930	15.658	1.954 8	65.20	0.511 6	0.015 34
291.83	65.62	810.600	8	194.468	246.942	24.807	40.119	15.312	1.984 3	57.06	0.504 0	0.017 52
296.30	73.67	911.925	9	196.182	246.733	25.313	40.286	14.973	2.011 5	50.59	0.497 1	0.019 77
300.44	81.12	1 013.250	10	197.813	246.524	25.794	40.428	14.634	2.038 7	45.42	0.490 5	0.022 02
317.42	111.69	1 519.815	15	204.377	245.687	27.826	40.934	13.108	2.172 5	29.50	0.460 3	0.033 90
330.70	135.59	2 026.500	20	209.645	244.893	29.628	41.281	11.653	2.304 0	21.23	0.434 0	0.047 10
341.71	155.41	2 533.25	25	214.287	244.182	31.263	41.478	10.215	2.444 6	16.07	0.409 1	0.062 23
351.23	172.54	3 039.750	30	218.635	243.262	32.848	41.498	8.650	2.621 5	12.44	0.381 5	0.080 39
359.61	187.63	3 546.375	35	223.109	241.882	34.428	41.181	6.753	2.877 7	9.565	0.347 5	0.104 55
367.18	201.25	4 053.000	40	228.754	239.123	36.510	40.324	3.814	3.329 0	6.683	0.300 4	0.149 63
370.0	206.33	4 265.782	42.10	234.733	234.733	38.580	38.580	0.000	4.437 9	4.437 9	0.225 3	0.225 33

<<< For Best Viewing, Use Your Maximum Window Size at a Resolution of 800 by 600 >>>

[Home](#)[About Purchasing](#)[Book Reviews](#)[Contents](#)[Site Map](#)

Source Terms For Accidental Discharge Flow Rates

Click in table below on desired source term (metric version):

Gas Discharge From Pressure Source	Liquid Discharge From Pressurized Vessel	Liquid Discharge From Non-Pressurized Vessel
Evaporation From Non-Boiling Liquid Pool	Evaporation From a Pool of Cold Boiling Liquid	Discharge Of A Flashing Saturated Liquid
Discharge of a Flashing Sub-Cooled Liquid	Adiabatic Flash of a Liquefied Gas Release	References

To return to opening page and select United States version, click [here](#)

[Gas Discharge To The Atmosphere From A Pressure Source:](#) ^{1, 2}

When gas stored under pressure in a closed vessel is discharged to the atmosphere through a hole or other opening, the gas velocity through that opening may be choked (i.e., has attained a maximum) or non-choked. Choked velocity, which is also referred to as sonic velocity, occurs when the ratio of the absolute source pressure to the absolute downstream ambient pressure is equal to or greater than $[(k + 1) / 2]^{k / (k - 1)}$, where k is the specific heat ratio of the discharged gas. For many gases, k ranges from about 1.09 to about 1.41, and thus $[(k + 1) / 2]^{k / (k - 1)}$ ranges from 1.7 to about 1.9 ... which means that choked velocity usually occurs when the absolute source vessel pressure is at least 1.7 to 1.9 times as high as the absolute ambient atmospheric pressure.

When the gas velocity is choked, the equation for the mass flow rate is:

$$(1) \quad Q = C A [k d P]^{1/2} [2 / (k + 1)]^{(k + 1) / (2k - 2)}$$

or this equivalent form:

$$(1) \quad Q = C A P [k M / (R T)]^{1/2} [2 / (k + 1)]^{(k + 1) / (2k - 2)}$$

[It is important to note that although the gas velocity reaches a maximum and becomes choked, the mass flow rate is not choked. The mass flow rate can still be increased if the source pressure is increased.]

Whenever the ratio of the absolute source pressure to the absolute downstream ambient pressure is less than $[(k + 1) / 2]^{k / (k - 1)}$, then the gas velocity is non-choked (i.e., sub-sonic) and the equation for mass flow rate is:

$$(2) \quad Q = C A [2 d P]^{1/2} [k / (k - 1)]^{1/2} [(P_A / P)^{2/k} - (P_A / P)^{(k + 1) / k}]^{1/2}$$

or this equivalent form:

$$(2) \quad Q = C A P [2 M / (R T)]^{1/2} [k / (k - 1)]^{1/2} [(P_A / P)^{2/k} - (P_A / P)^{(k + 1) / k}]^{1/2}$$

where:

- Q = mass flow rate, kg / s
- C = discharge coefficient (dimensionless, usually about 0.72)
- A = discharge hole area, m²
- k = c_p / c_v of the gas
= (specific heat at constant pressure) / (specific heat at constant volume)
- d = gas density, kg / m³, at source pressure and temperature
- P = absolute source or upstream pressure, Pa
- P_A = absolute ambient or downstream pressure, Pa
- M = gas molecular weight
- R = the Universal Gas Law Constant = 8314.5 (Pa) (m³) / (kgmol) (°K)
- T = gas temperature, °K

The above equations calculate the initial instantaneous mass flow rate for the pressure and temperature existing in the source vessel when a release first occurs. The initial instantaneous flow rate from a leak in a pressurized gas system or vessel is much higher than the average flow rate during the overall release period because the pressure and flow rate decrease with time as the system or vessel empties. Calculating the flow rate versus time since the initiation of the leak

is much more complicated, but more accurate. Click [here](#) to learn how such calculations are performed.

Note: kgmol = kilogram mole

 [Return to Top](#)

E-mail milt@air-dispersion.com for a Microsoft Word copy of these Source Terms for \$5.

Liquid Discharge From A Pressurized Source Vessel: ^{1, 2}

Initial instantaneous flow through the discharge opening:

$$(1) \quad Q_i = C A [(2 g d^2 H) + (2 d) (P - P_A)]^{1/2}$$

Final flow when the liquid level reaches the bottom of the discharge opening:

$$(2) \quad Q_f = C A [(2 d) (P - P_A)]^{1/2}$$

Average flow:

$$(3) \quad Q_{avg} = (Q_i + Q_f) \div 2$$

where:

- Q = mass flow rate, kg / s
- C = discharge coefficient (dimensionless, usually about 0.62)
- A = discharge hole area, m²
- g = gravitational acceleration of 9.807 m / s²
- d = source liquid density, kg / m³
- P = absolute source pressure, Pa
- P_A = absolute ambient pressure, Pa
- H = height of liquid above bottom of discharge opening, m