INTERNATIONAL SYMPOSIUM ON FIRE INVESTIGATION SCIENCE & TECHNOLOGY

PROCEEDINGS



2018 ISFI

First Printing, 2018

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By

National Association of Fire Investigators, International
4900 Manatee Ave W, Suite 104
Bradenton, FL 34209 USA

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ARE LIQUID PROPANE LEAKS REALLY 270 TIMES LARGER THAN GAS? CASE STUDY REGARDING THE PHYSICS OF LIQUID AND GAS PROPANE LEAKS

Scott Davis, PhD., P.E., CFEI
Tom DeBold, P.E., CFEI
and
John Pagliaro, Ph.D.
Gexcon US, USA

ABSTRACT

When investigating a flash fire or explosion, it is common to test and evaluate the integrity of a fuel gas system – such as LPG systems. One common technique is to use a pressurized inert gas, such as nitrogen, to not only identify possible holes for propane to leak through but also quantify the flow rate of the leak. However, if the leak is located under the liquid level of the propane cylinder, there is a common misconception that the mass flow rate for a liquid propane release must be approximately 270 times larger than a vapor release through the same hole size. In a recent case, an investigator concluded that a small hole identified during a leak test using nitrogen gas would be more than sufficient to cause a large flash fire because the hole would have been below the liquid propane level and thus would be 270 times larger than a vapor propane leak through the same hole. This misconception regarding the magnitude of liquid propane leaks stemmed from the fact that liquid propane has a density that is approximately 270 times larger than the density of gaseous propane at atmospheric pressure and temperature.

Under practical conditions, the mass flow rates of liquid propane will actually be much closer to those of vapor releases given identical hole sizes. In fact, the difference will be only approximately 6-8 times larger if both liquid and gaseous propane are stored at ambient temperatures of 20°C. This near 30-fold reduction in liquid flow is due to how propane is stored and the physics governing a compressible vapor release compared to an incompressible liquid release. More specifically, for propane at 20°C the vapor will exit a small hole at the speed of sound and due to the high storage pressure (e.g., approximately 105 psig at 20°C) the density of the vapor leaking will be much higher than atmospheric conditions. Conversely, an incompressible liquid will be limited by the pressure difference upstream and downstream of the hole.

The present study demonstrates the differences in liquid and vapor propane release rates and shows that liquid releases are not 270 larger than vapor releases. This is accomplished by: (1) providing an overview of the theoretical orifice flow equations for pressurized vapor and liquid releases; (2) presenting results from actual releases of liquid and vapor propane from a 120-gallon water capacity tank and a 20 lb cylinder; and (3) presenting CFD results that highlight the importance of accurate estimates of leak rates when it comes to formulating origin and cause hypotheses.

BACKGROUND

On August 9th, 2009 a flash fire occurred in a concession stand at a festival in Clint, Texas. The stand that was selling gorditas, funnel cakes, aqua frescas, snow cones and fried potatoes to benefit a local 4-H club. The booth contained three separate propane-fueled appliances: two fryers, and a steam table to keep prepared food warm. Around 2:00 PM, a large flash fire occurred in the vicinity of the funnel cake

fryer, which was located in the center of the booth, at the same moment a drink cooler filled with residual ice and water was being passed over the heated canola oil in the funnel cake fryer.

During post-incident inspection, investigators found a small leak from a filling valve on a propane tank when pressurizing it nitrogen to around 50 psi. The leak rate measured under these conditions was 4 cubic feet per hour (CFM). Investigators also pressurized the propane tank to higher pressure, and when applying 100 psi, the leak rate through the filling valve dropped to about 1 CFM, and at 150 psi up to 240 psi, there was no measurable leak. Furthermore, there was a protective yellow cap found nearby the filling valve and when it was placed over the valve there was no measurable leak.

Based on the testing results, three investigators opined that a propane leak through the identified leak path caused the flash fire that occurred in the concession. They further opinioned that leaking propane from the valve accumulated in the low-lying areas of the booth.

During the incident investigation, an investigator concluded that the small hole identified during the leak testing with nitrogen would be more than sufficient to cause a large flash fire because the hole would have been below the liquid propane level and thus the mass flow rate would be 270 times larger than the mass flow rate of a gaseous propane leak through the same hole. This claim was apparently based solely on the density difference between the liquid and vapor states of propane at 60°F. In his opinion, this small leak could have produced a large volume of propane that accumulated near the ground of the booth, and when it reached a reliable ignition source, such as one of the open flames under the warming trays, could have ignited causing the flash fire. The following sections discuss where this misconception stems from, what the actual physics are for high-pressure liquid and vapor releases, experimental results that demonstrate the physics, and CFD modeling that highlights the importance of accurate estimates of leak rates when it comes to formulating origin and cause hypotheses.

Propane Properties

The "270" times expansion comes from the density differences in liquid and vapor propane. At 60°F, commercial propane has a liquid density of approximately 503.5 kg/m^3 versus a vapor density of approximately 1.83 kg/m^3.[1]

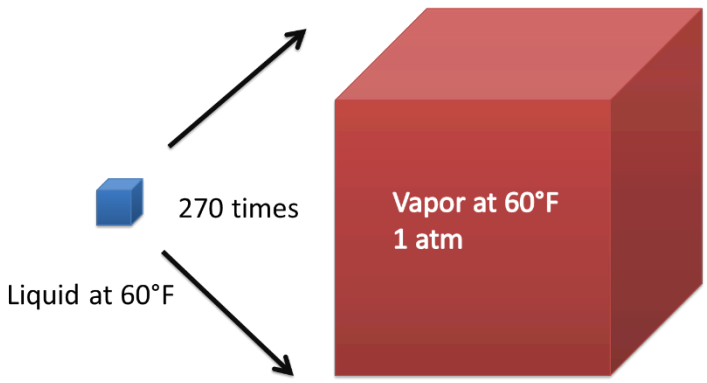

Figure 1: Difference is volume occupied by the same mass of liquid and vapor propane.

[1] NFPA 58-2014 Table B.1.2(b)

At atmospheric temperature and pressure, propane is a vapor. For propane to be a liquid, it either has to be cooled or pressurized. Typical propane tanks, such as the one involved in the incident described above, are filled with liquid propane, and the pressure in the tank corresponds to the vapor pressure of propane, which is a fundamental fluid property.

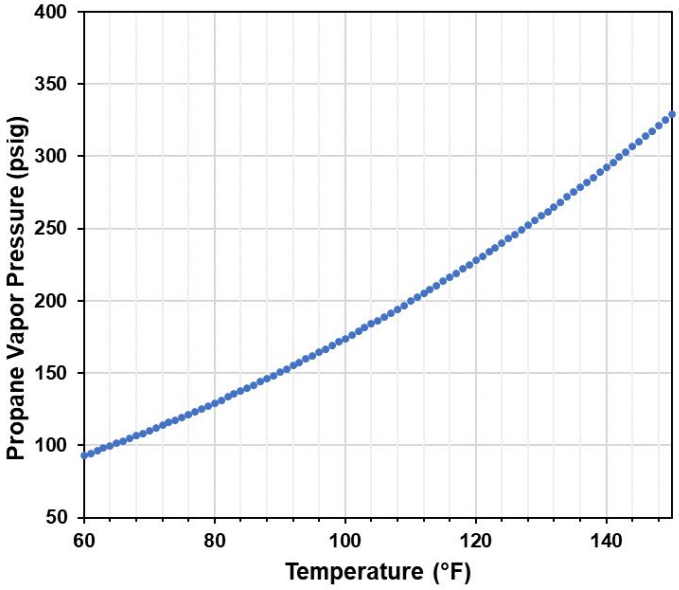

Figure 2: Saturation vapor pressure curve for propane (NIST database).

Figure 2 shows the saturation vapor pressure curve for propane. This shows the resulting pressure at which propane liquid and vapor will remain in equilibrium for a range of temperatures. As shown above, the only factor that determines the vapor pressure present in the tank is the ambient temperature. The pressure is independent of the tank fill (given that it is not overfilled). Therefore, as the liquid level of a tank decreases, the pressure of the tank remains constant, assuming the temperature also remains constant.

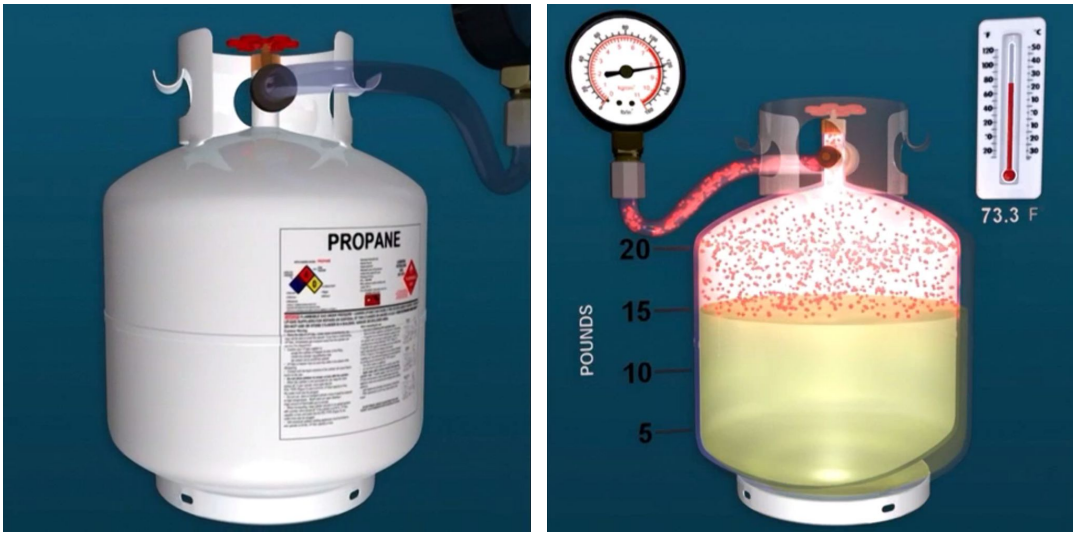

Figure 3: Propane cylinder (left) and cut-away (right) showing propane liquid and vapor in equilibrium.

Orifice Flow Equations for Liquid and Vapor Releases

Whether liquid of vapor leaks from a hole depends on the location of the hole in relation to the liquid level within the tank. Liquid and vapor releases occur when a hole in the tank occurs below and above the liquid level, respectively (see Figure 4).

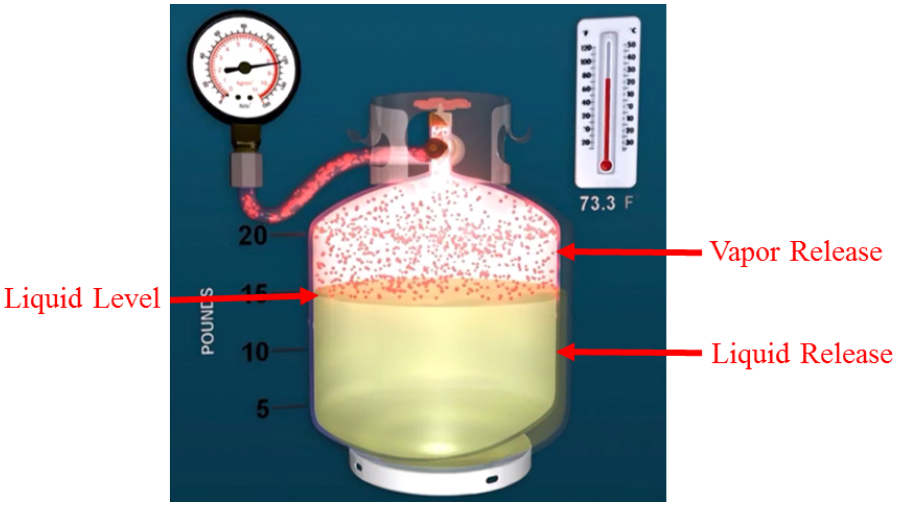

Figure 4: Liquid versus vapor release points.

For standard orifice flow calculations, the mass flow rate is given by the formula below, where ρ is the density of the fluid, u is the velocity of the fluid, and A is the orifice area.

$$\dot{m} = \rho\, u\, A_{orifice} \qquad [1]$$

Liquid propane can be released from pressurized storage vessels (e.g., a propane tank or cylinder) through a liquid withdrawal line or a hole that is located beneath the liquid/vapor interface (see Figure 4). Liquid mass flow rate through an orifice can be calculated based on incompressible fluid flow as described in the following equation,

$$\dot{m} = C_d \times A_o \sqrt{2 * \rho_1 * (P_1 - P_{atm})} \qquad [2]$$

where P_1 is the tank pressure, ρ_1 is the density of the liquid propane in the tank, P_{atm} is the atmospheric pressure, A_o is the orifice area, and C_d is the discharge coefficient to account for the narrowing of the orifice (*vena contracta*) and is typically 0.62 for liquids through sharp-edged orifices.

Propane vapor can also be released from pressurized storage vessels when the withdrawal line or hole is above the liquid/vapor interface (see Figure 4). When the absolute pressure in the propane tank is twice as large as the absolute atmospheric pressure, or if gauge pressure within the tank is approximately 15 psig (1 barg), the velocity at the exit orifice is referred to as "choked" and limited to the speed of sound (Mach =1). As the velocity is limited to sonic conditions, the mass flow rate increases nearly linearly with tank pressure due to the linear increase in vapor density. Vapor mass flow rate through an orifice for pressurized containers can be calculated using the formula below for compressible choked flow:

$$\dot{m} = C_v \times A_o \sqrt{\gamma * \rho_g * P_1 \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \quad [3]$$

where P_1 is the upstream tank pressure, ρ_g is the density of the propane vapor, A_o is the orifice area, and C_v is the flow coefficient typically given as 0.85 for sharp-edged orifices, and γ is the ratio of specific heats of propane vapor.

These equations provide the initial mass flow rate of a liquid and vapor releases as well as the transient mass flow rate as these types of releases progress. A secondary phenomenon that plays an important role when evaluating propane leaks is the evaporative cooling that occurs when propane changes phase from a liquid to a vapor. For example, for vapor releases, the mass flow rate can decrease significantly during a release because the liquid in the tank evaporates to maintain the vapor pressure within the vessel and to continually replenish the vapor that has been expelled. Hence for vapor releases the evaporating cooling occurs inside the vessel and, if the leak is large enough, the mass of liquid and tank is low enough, and the duration of the leak is long enough, the liquid within the tank can cool significantly. As the temperature of the liquid inside the vessel drops, the vapor pressure drops, and this is what causes a significant reduction in leak rate. On the other hand, for liquid releases, the released mass flow rate will remain fairly constant since the temperature of the liquid inside the vessel remains fairly constant during the leak event. This is due to the liquid flashing and evaporating once it has already exited the vessel. Therefore the evaporative cooling occurs external to the tank and cools the surrounding air,

PROPANE RELEASE TESTS

Propane releases were performed to demonstrate the differences in mass flow rates for liquid and vapor releases. The test setups are shown in Figure 5. Various size orifices were piped into the release valves of a 120-gallon water capacity tank and a 20-lb cylinder containing propane. The vessels were then placed on a scale and the mass was recorded while propane was released in both the liquid and vapor phase. Tests were performed with a 4.2 mm diameter orifice connected to the vapor and liquid discharge valves on the large tank and with 0.31 mm and 0.74 mm diameter orifices connected to the discharge valve on the 20-lb cylinder. The temperature and pressure at the orifices were measured using a thermocouple and a pressure gauge (Figure 6) and the weight of the vessels was recorded at 1 second intervals.



Figure 5: Test setup - 120-gal tank (left) and 20-lb cylinder (right).



Figure 6; Pressure, temperature, and weight monitoring during a release.

Figure 7 shows the liquid (top image) and vapor (bottom image) releases from the 4.2 mm diameter orifice attached to the 120-gal tank. For the 20 lb cylinder, liquid and vapor releases were performed with the tank upside-down and right-side-up, respectively. Figure 8 shows the mass loss as a function of time for the liquid and vapor releases from the 120-gal tank (note that the slopes provide the mass flow rate).

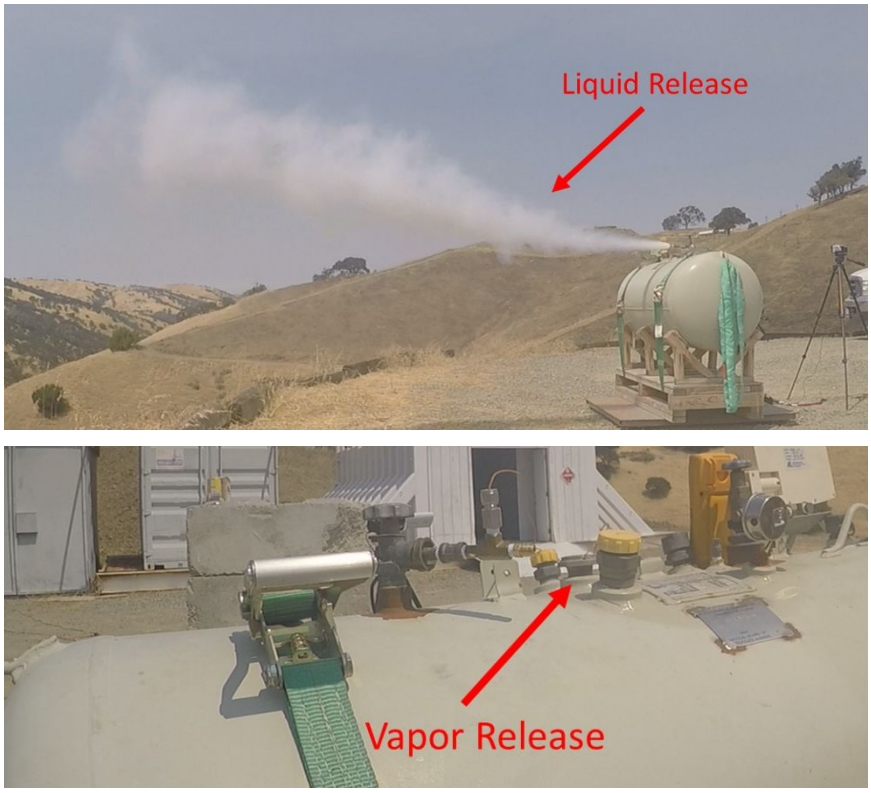

Figure 7: Liquid (upper image) and vapor (lower image) releases from the 120-gal propane tank.

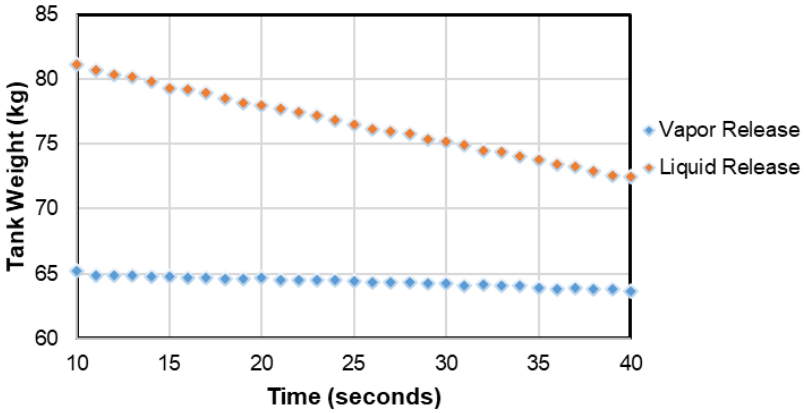

Figure 8: Mass loss rate versus time from a liquid and vapor propane release (4.2 mm orifice on the 120-gal tank).

CALCULATED AND MEASURED MASS FLOW RATES

Table 1 shows the calculated and measured mass flow rates (MFR). As expected, there is excellent agreement between the measured and calculated mass flow rates for both the liquid and vapor releases. Slight differences are associated with the accuracy of the measurements and the choice of discharge coefficient, which is dependent on the specific orifice geometry. Since the orifices used in the present study are slightly beveled, we used discharge coefficients of 0.7 for liquid flow and 0.87 for vapor flow.

For the calculations, notice how the ratio of liquid MFR to vapor MFR is slightly different for the 4.2 mm diameter orifice. This is because the mass flow rates were calculated using the temperature and pressure during the corresponding experiments, and the temperature was higher for this test compared to the other two with smaller orifices. Furthermore, the ratio changes with temperature as the temperature affects the liquid and vapor densities, the tank pressure, and the vapor specific heat ratio. For the present calculations and measurements, the ratio of liquid MFR to vapor MFR is between 6.68 and 7.75.

Table 1: Calculated and measured mass flow rates for the liquid and vapor releases.

Theoretical			
Orifice Dia (mm)	**Liquid MFR (g/s)**	**Vapor MFR (g/s)**	**Ratio**
0.31	1.56	0.20	7.75
0.74	8.81	1.14	7.75
4.2	306	42.6	7.17

Experimental			
Orifice Dia (mm)	**Liquid MFR (g/s)**	**Vapor MFR (g/s)**	**Ratio**
0.31	1.37	0.21	6.68
0.74	8.86	1.12	7.92
4.2	278	41.2	6.74

CFD SIMULATIONS

Results from CFD simulations with FLACS are presented below to highlight the importance of accurate estimates of leak rates as it pertains to formulating origin and cause hypotheses. Figure 9 shows the concession stand replicated in FLACS for the simulations.

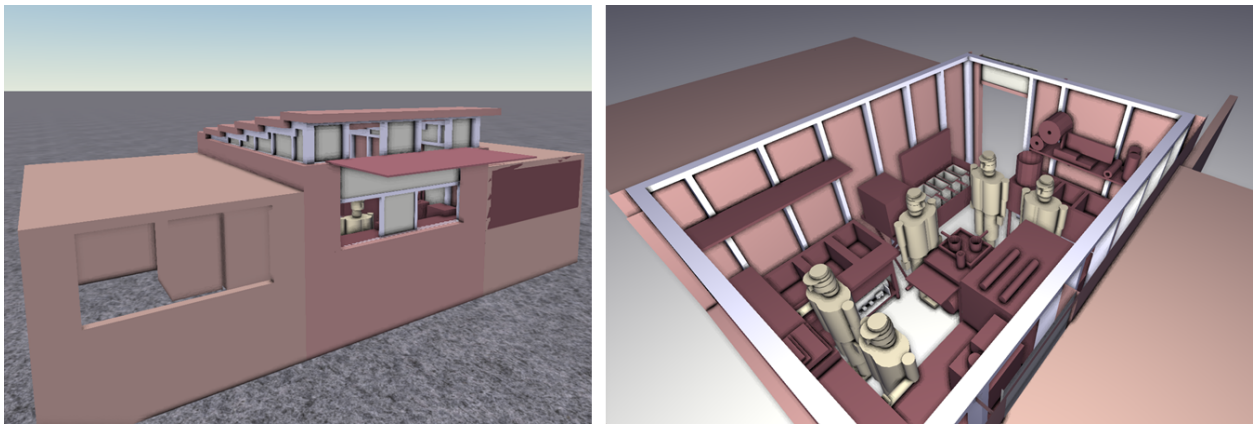

Figure 9: Geometry model in FLACS.

FLACS was developed by Gexcon in the 1980's to simulate gas dispersion and vapor cloud explosions. FLACS can model gas and aerosol releases, dispersion of vapors, ventilation in structures, and the effects of ambient conditions such as wind. It can also model the consequences of ignition of flammable fuel-air clouds.

FLACS has been extensively validated against numerous gas dispersion[2,3,4] and vapor cloud explosion experiments[5], including large-scale realistic release scenarios and explosion tests performed by Gexcon, as well as full-scale experiments performed in a test replica of a semi-confined offshore module. Recent validation studies, including blind validation studies (i.e., simulations were performed prior to, or without knowledge of the experimental results), have demonstrated the ability of FLACS to accurately predict gas dispersion and explosion scenarios. Due to its accuracy and extensive validation, FLACS is oftentimes the required software for consequence modeling studies in complicated oil and gas offshore platforms.

The figures below present the flammable propane vapor clouds (i.e., at concentrations between the LFL and UFL) that form during releases with a range of mass flow rates. More specifically, Figure 10 shows the results for a mass flow rate of 0.055 g/s, which is roughly the mass flow rate that would have occurred if vapor propane was released through the leak discovered in the filling valve (discussed in the

[2] A.G. Venetsanos et al., An inter-comparison exercise on the capabilities of CFD models to predict the short and long-term distribution and mixing of hydrogen in a garage, Intl. J. Hydrogen Energy 34 (2009) 5912–5923.

[3] P. Middha, O.R. Hansen, J. Grune and Alexei Kotchourko, CFD calculations of gas leak dispersion and subsequent gas explosions: Validation against ignited impinging hydrogen jet experiments, J. Haz. Mat. 179 (2010) 84–94

[4] B.H. Hjertager, M. Bjørkhaug, K. Fuhre, Explosion propagation of nonhomogeneous methane-air clouds inside an obstructed 50m^3 vented vessel, J. Hazard. Mater. 19 (1988) 139–153.

[5] Davis, S.G. Evaluation of the Fire Hazard of ASHRAE Class A3 Refrigerants in Commercial Refrigeration Applications. The Fire Protection Research Foundation, October 2017.

Background section). Figure 11 and Figure 12 show the results for a mass flow rate of 0.385 g/s and 15 g/s, which correspond to the actual mass flow rate of liquid through the identified leak (i.e., about 7 times higher than the vapor flow rate) and the mass flow rate when incorrectly assuming that liquid flow rates are 270 times higher than vapor flow rates.

For the vapor release with a MFR of 0.055 g/s, there is a small flammable pocket in the vicinity of the leak, even after leaking for 500 seconds (see Figure 10), as the flammable pocket has reached steady state and cannot grow larger as the propane is quickly diluted downstream of the valve. Furthermore, the flammable cloud does not come close to any ignition sources and therefore this release would not result in an ignition event. Thus, a vapor release from the identified leak could not have produced the large flash fire observed by the witnesses.

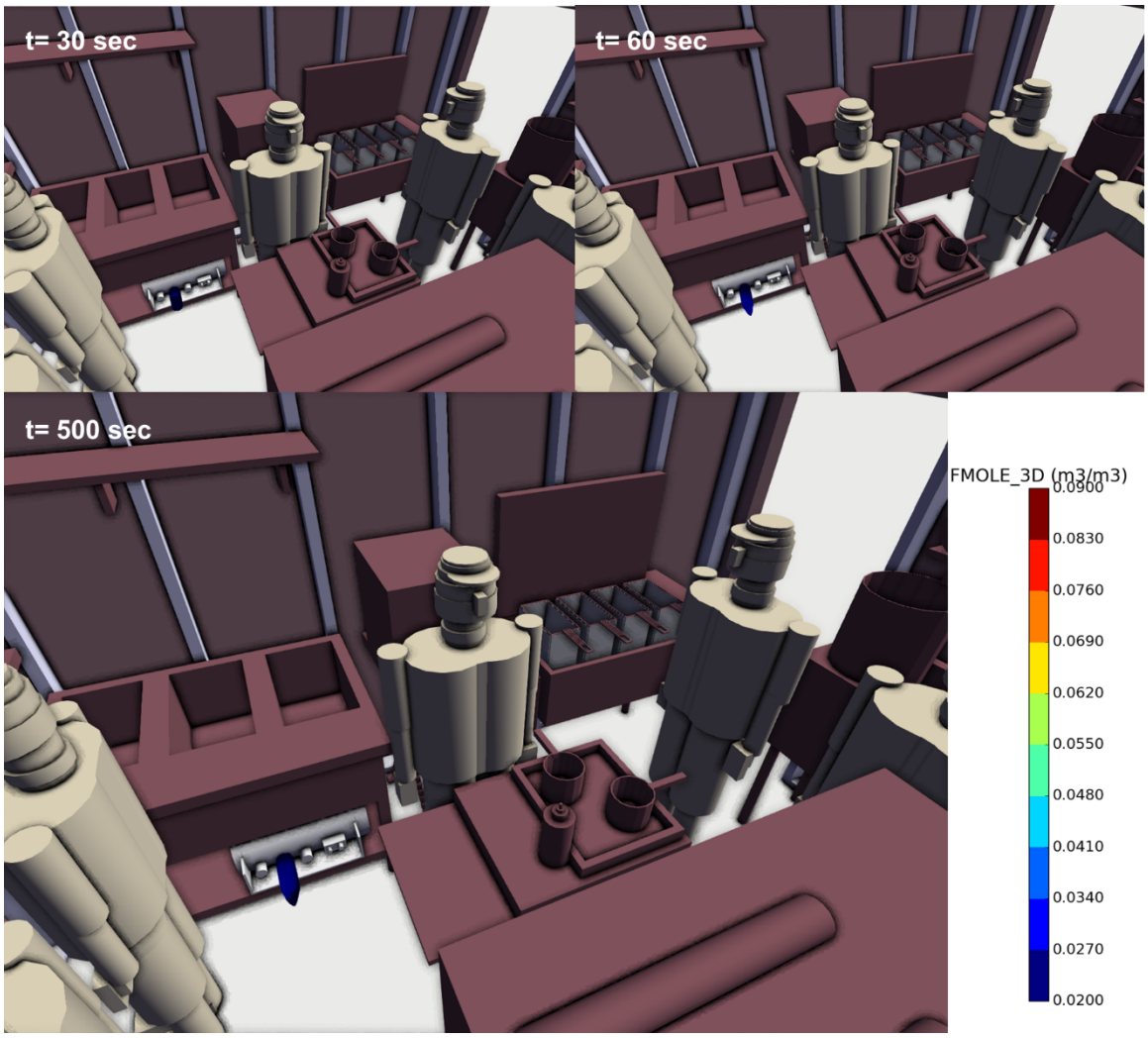

Figure 10: Flammable volume 30 s (upper left), 60 s (upper right) and 500 s (bottom) after the start of the 0.055 g/s leak. The scale is from LFL (blue) to UFL (red).

For the liquid release with a MFR of 0.385 g/s, only a slightly larger flammable pocket forms (see Figure 11), even after leaking for almost 1000 seconds, as again in this scenario the flammable pocket has

reached steady state and cannot grow larger as the propane is quickly diluted downstream of the valve. This scenario also could not have produced the large flash fire observed by the witnesses.

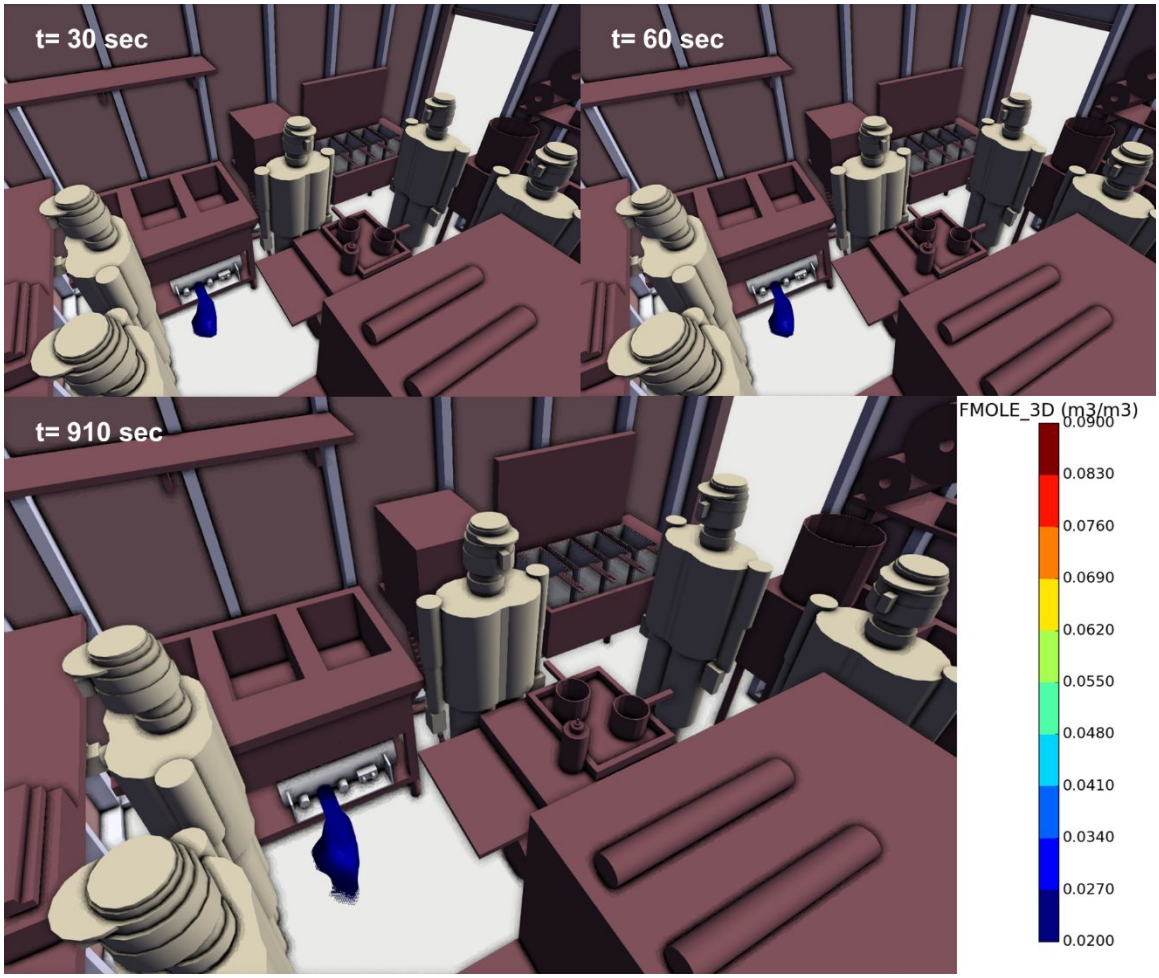

Figure 11: Flammable volume 30 s (upper left), 60 s (upper right) and 910 s (bottom) after the start of the 0.385 g/s leak (MFR 7 times higher than the vapor release). The scale is from LFL (blue) to UFL (red).

For the incorrect liquid release rate of 15 g/s (270 times higher than the vapor release rate), flammable concentrations of propane dominate the ventilation and quickly accumulate along floor, filling the lower portion of the concession stand within 60 seconds of the start of the release (see Figure 12). While this release rate could have resulted in a large flash fire (depending on the ignition timing), theory and measurements tell us that this flow rate is unrealistic and impossible given the size of the identified leak. While this incident could not have been caused by the identified leak at the filling valve, opposing investigators defied the laws of physics by improperly concluding liquid leaks are 270 times those of vapor and neglected to find the actual cause of the incident. The cause of the incident was the unfortunate accident that resulted when the ice chest filled with water was dropped into the hot fryer oil, causing the water to near instantaneously expand and expel a mist of hot oil that ignited and resulted in a large fire ball .

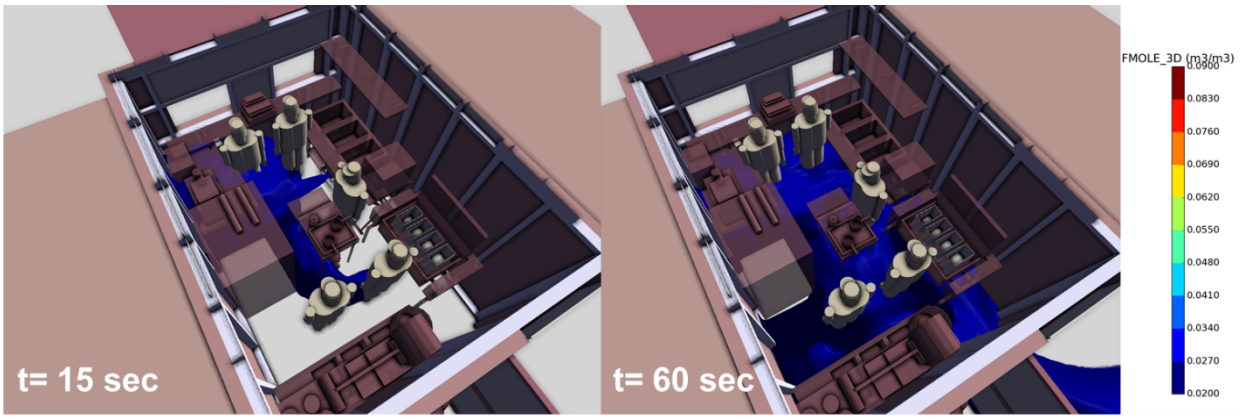

Figure 12: Flammable volume 15 s (left) and 60 s (right) after the start of the 15 g/s leak (mass flow rate 270 times higher than the measured vapor release). The scale is from LFL (blue) to UFL (red).

CONCLUSIONS

It is important to understand that propane flow through an orifice not simply, $\rho u A_{orifice}$. High-pressure flow through an orifice is more complex and therefore the ratio of mass flow rates is not equal to the ratio of liquid density to vapor density at atmospheric conditions. Theory and measures show that given the same hole size, liquid propane releases are 6-8 times greater than vapor propane. An accurate estimate of release rate is essential to understanding the consequences of an identified leak, especially when evaluating propane leaks or other gas leaks as the cause of an incident.

ABOUT THE AUTHORS

Dr. Scott Davis is the president of Gexcon US and specializes in mechanical and aerospace engineering, and the engineering analysis and testing of combustion, thermal, and fluid processes. Dr. Davis applies his expertise to the investigation, prevention, and risk assessment of fires, explosions, and dispersion hazards such as flammable vapors and carbon monoxide exposures. He is responsible for fire and explosion related consulting activities, which include post-incident investigative work as well as performing risk assessments and safety studies for offshore Oil & Gas installations, petrochemical facilities, and various other industries. Dr. Davis develops and delivers worldwide industrial seminars to owners, operators, safety engineers, and regulatory agencies, on the hazards associated with gas explosions, dust explosions and LNG.

Tom DeBold is an engineer within the Explosion and Fire Safety group at Gexcon US Inc. He specializes in fire protection, mechanical, thermal and fluid engineering. Mr. DeBold performs post-incident investigative work related to fires and explosions. Mr. DeBold has experience in evaluating cause and origin in residential and commercial fires and explosions. He performs incident reconstruction, on/off-site testing, and computational fluid dynamics (CFD) to establish credible accident scenarios. His fire protection engineering expertise includes post-incident fire suppression/extinguishment system failure analyses and review of compliance with applicable codes.

Dr. John Pagliaro is a senior engineer at Gexcon US who specializes in the areas of combustion, fire dynamics, heat transfer, thermodynamics, fluid mechanics, and experimental design. He investigates and analyzes fires, explosions, carbon monoxide exposures, chemical releases, and failures involving gas delivery systems, industrial and residential gas-fired appliances, dust handling facilities, heavy machinery, self-reactive materials, and electronic components. Dr. Pagliaro uses numerical and experimental methods to formulate and test cause and origin hypotheses.

REFERENCES