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PROPANE SAFETY: INVESTIGATION FINDINGS AND LESSONS LEARNED IN THE 2014 PHILIDELPHIA FOOD TRUCK EXPLOSION

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ABSTRACT

On July 1, 2014, a propane cylinder catastrophically failed and exploded on the back of a food truck in Philadelphia, PA. The explosion led to a sudden release of pressurized propane vapor and superheated propane liquid, which rapidly evaporated resulting in a large white cloud that entered and engulfed the rear of the food truck. This cloud ultimately found an ignition source within the food truck and resulted in a significant fireball burning both inside and outside of the food truck. The explosion and ensuing fire fatally injured the food truck owner and her daughter, and also caused injuries to 11 other individuals. This paper will first present the results of our investigation into the cause and origin of the catastrophic failure and explosion event, which included: (1) analyzing video footage of the explosion and ensuing fire; (2) applying propane phase diagrams to determine the expansion and resulting pressures within the cylinder prior to failure; and (3) applying blast techniques to determine the post catastrophic blast and ignition during the event. These techniques included advanced computational fluid dynamic modeling.

The paper will also discuss safety critical design features and processes in the propane industry that must be in place to ensure the safe use and filling of propane cylinders, which include: cylinder requalification; having a fixed maximum liquid level gauge; having a pressure relief valve; and filling cylinders by weight or volume.

BACKGROUND

On July 1, 2014 at approximately 5:30 PM, a propane cylinder exploded on the La Parrillada Chapina food truck and resulted in an ensuing fire while parked near the intersection of Wyoming Avenue and 3rd Street in Philadelphia, PA. The explosion injured 13 people, two of whom passed away roughly 20 days after the incident and two of whom remained hospitalized for over a month.

Food Truck, Propane Cylinders and Gas Appliances

Figure 1 shows photos of the exterior and interior of the food truck involved in the incident. The food truck was designed to carry two 100-lb propane cylinders, one in each storage cabinet on the rear of the truck.



Figure 1: Exterior and interior photos of the food truck and location of propane cylinders.

Both propane cylinders were connected to a single low pressure two-stage automatic changeover regulator via flexible rubber tubing. The regulator was located in the driver side cabinet and the flexible hose from the cylinder in the passenger side cabinet was routed under the rear bumper cover and up into the drive side cabinet (see Figure 2). The outlet side of the regulator split via a tee with one outlet of the tee supplying propane to the driver side appliances and the other outlet supplying propane to the single passenger side appliance. Figure 3 provides an overview of the gas-fired appliances in the food truck. There were five appliances on the driver side (deep fryer, griddle, charbroiler, vertical broiler, and gas range) and a warming table on the passenger side.

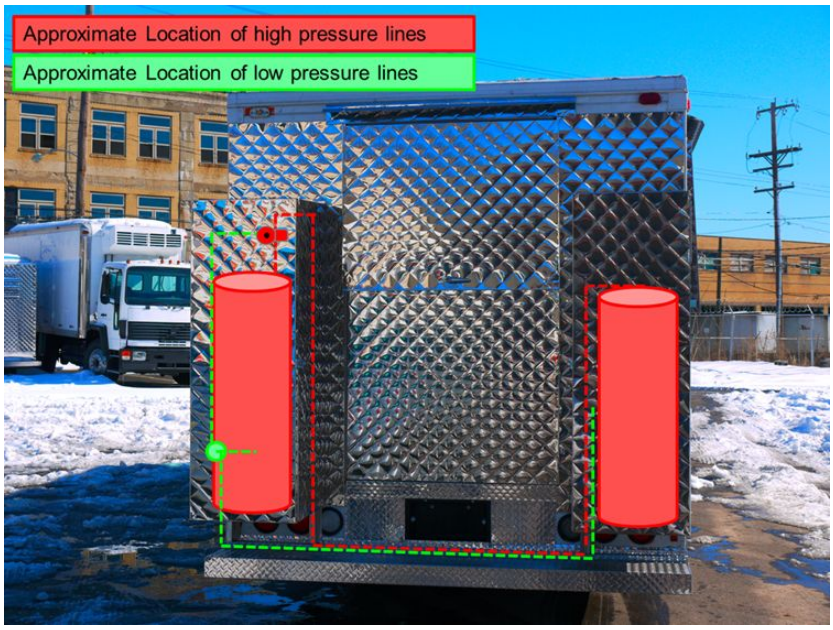

Figure 2: Exterior gas system illustration showing two 100-lb propane cylinders, the high-pressure lines to the regulator (red), and the low-pressure lines (green) into the truck.

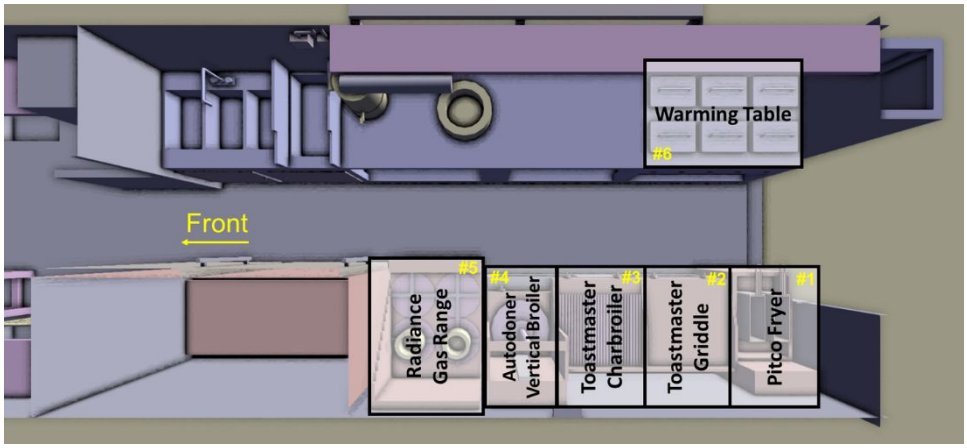

Figure 3: Appliance layout in rear of truck with propane-powered appliances numbered.

Propane Cylinders and Filling Details

Two 100-lb propane cylinders were used on the food truck. The incident 100-lb propane cylinder installed on the driver side was manufactured by Pressed Steel Tank Co. in November of 1948, with a water capacity of 239 pounds and rated for 240 psig service pressure. There was no requalification marking on the cylinder, meaning the cylinder was not requalified for almost 66 years. The POL connection service valve did not have the required pressure relief valve or fixed maximum liquid level gauge, and the end opposite the POL was plugged (see Figure 4).

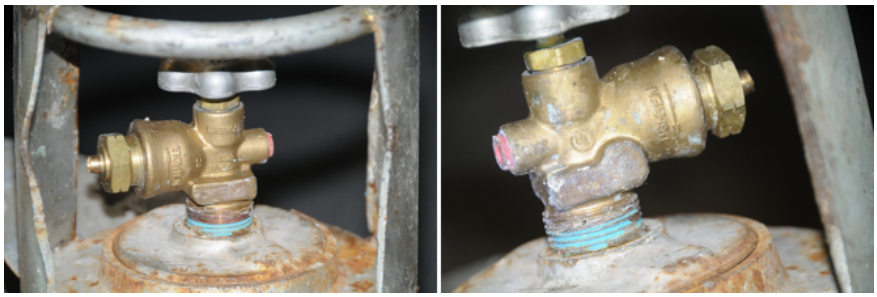

Figure 4: Valve on the incident cylinder installed on the driver's side.

Video footage and sales receipts confirm that propane was purchased from two filling stations in Philadelphia. The records show that a single 100-lb propane cylinder typically lasted 4-5 days before needing to be filled. In addition, the cylinders were not properly filled by weight or by volume using a fixed maximum liquid level gauge, but instead filled with a fixed volume quantity based on the cylinder size (discussed later). Moreover, the incident cylinder was filled despite not being requalified for almost 66 years and without the required pressure relief valve.

Events Leading Up to the Incident

On the morning of June 29, 2014, two days before the incident, the two 100-lb cylinders used on the food truck were filled and installed in the cabinets on the back of the food truck. From the time of fill, the cylinder on the passenger side was the only one put into use, hence the incident cylinder on the driver side had the same quantity of propane as after it was filled on June 29, 2014.

Incident

The incident occurred at approximately 5:30 PM. on July 1, 2014. The owner, her daughter and two other women were working on and around the truck. The incident was captured on surveillance video, and it is clear that the driver side cylinder catastrophically ruptured. The rupturing cylinder discharged compressed vapor and liquid propane that formed a white cloud that entered and engulfed the rear of the food truck which subsequently ignited and created a large fireball, as can be seen in Figure 5. The energy released from the exploding cylinder blew off the driver side propane cabinet and launched the propane cylinder across the street. There was no fire or flames present in any of the video footage prior to the catastrophic failure of the propane cylinder.

Post Incident

Post-incident photographs showed that the cylinder originally mounted on the driver's side of the truck was not in use and the valve was in the off position.

Figure 6 shows the food truck after the incident, where impact marks were observed on the truck panel that was behind the cylinder that catastrophically ruptured. In addition, the bumper cover (under which the propane copper and flexible tubing ran) was found on the ground behind the bumper. The figure also shows the 100-lb cylinder that catastrophically ruptured, became a projectile and landed approximately 94 ft (28.7 m) away from the rear of the food truck.

Post-incident inspection and testing demonstrated that no gas leaks were detected in the propane gas system and confirmed the integrity of the propane system on the food truck. In addition, no flow was detected past any of the appliance manual shutoff valves.



Figure 5: Image sequence from two nearby surveillance cameras showing that the initial cylinder rupture, released liquid propane engulfing the food truck (white cloud) and the subsequent ignition event.



Figure 6: Food truck (left), exploded cylinder cabinet (middle), and ruptured propane cylinder (right).

Weather

Provided in Figure 7 are the hourly temperatures recorded by NOAA at the Northeast Philadelphia Airport (Station # 94732) and the Philadelphia International Airport (Station # 13739) between June 29 and July 1, 2014. Also indicated in the figure is the time when the incident cylinders were last filled (black dashed line) and the time when the incident occurred (red dashed line). Note that the temperature around the time of the incident was the highest since the cylinders were filled two days prior.

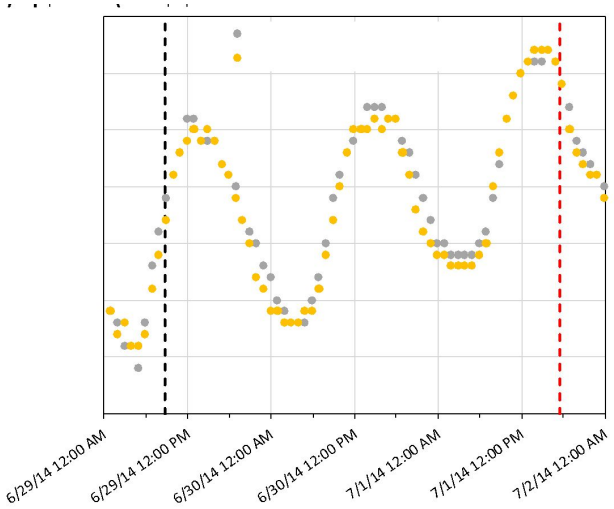

Figure 7: NOAA temperature data from when the cylinders were last filled up until the incident.

ANALYSIS

Propane Basics

Propane is stored in tanks and cylinders as a compressed liquid, and the liquid exists in equilibrium with propane vapor in the container head space. As the temperature of the liquid propane increases, the pressure within the cylinder increases according to the vapor pressure of propane. Similarly, when the temperature of the liquid propane decreases, the pressure within the cylinder decreases. Another important aspect regarding liquefied propane is that as its temperature increases the liquid propane expands and fills up more of the container volume (see Figure 8). In fact, liquid propane expands 17 times more than water during similar temperature increases.

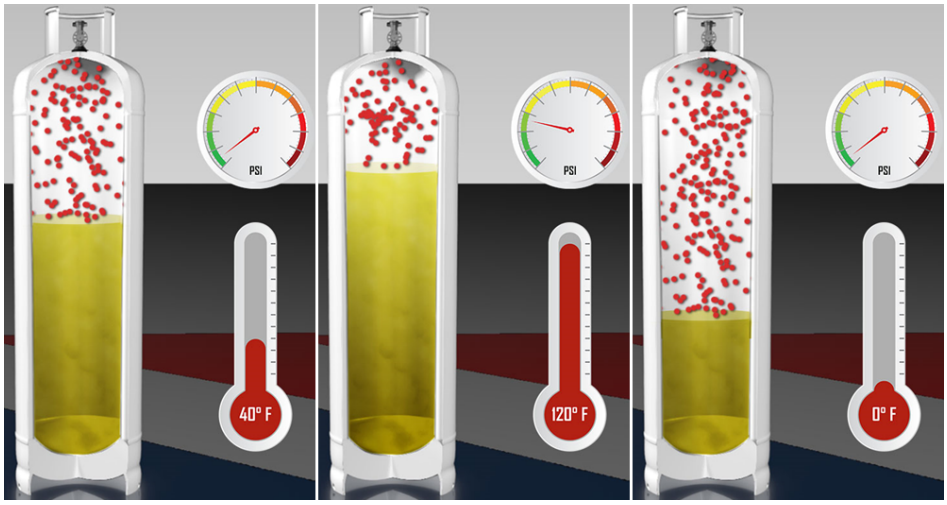

Figure 8: Pressure and propane liquid volume increase as temperature increases and decrease as temperature decreases.

Therefore, when filling a propane cylinder with liquid propane, you must provide adequate vapor space (i.e., ullage or head space) to allow the liquid to freely expand in the cylinder. More specifically, propane cylinders greater than 40-lb through 100-lb propane capacity are required to be filled to only 80% of the volume capacity (or with the weight of propane corresponding to an 80% fill at 40°F, as discussed next) to allow the propane to freely expand into the free space of the cylinder in the event the temperature increases (see Figure 9). In contrast, if not enough vapor space is provided and the expanding propane fills the entire volume of the cylinder, the pressure begins to increase much more drastically as the temperature increases (see Figure 10).

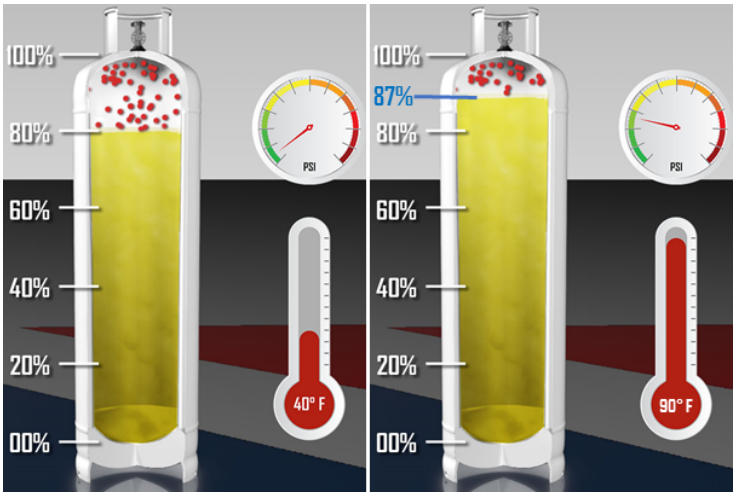

Figure 9: Propane cylinder properly filled to 80% at 40°F and freely expands when heated to 90°F.

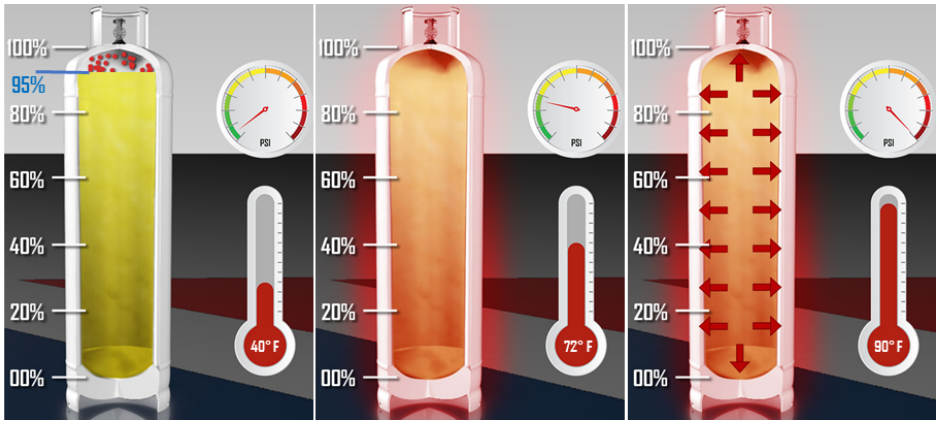

Figure 10: Propane cylinder overfilled at 40°F, expands and fills the entire cylinder at 72°F, at which point the pressure in the cylinder drastically increases as the cylinder is heated to 90°F.

To understand how drastic the pressure can increase, consider two 100-lb propane cylinders filled when the temperature is 40°F. Cylinder A is filled to 80% capacity and cylinder B is *overfilled* to 95% capacity. The solid blue line and dashed red line in Figure 11 show the pressure inside cylinder A and B respectively as the temperature increases (calculated with REFPROP assuming pure propane). At around 72°F, the liquid propane in cylinder A still only occupies a portion of the total cylinder volume whereas the liquid propane in cylinder B now occupies the entire cylinder volume. As the temperature increases further, the pressure in cylinder A remains equal to the propane vapor pressure while in contrast, the pressure in cylinder B increases much more drastically (neglecting any expansion of the cylinder walls). Once propane liquid can no longer expand, any small increase in temperature results in a very large increase in pressure due to its incompressibility, which can ultimately lead to a cylinder failing catastrophically at pressures well in excess of the service pressure. For example, as the temperature increases only 10°F (from 72°F to 82°F), the pressure within a cylinder that still has vapor to allow for expansion only increases 15 psi (from 120 psig to 135 psig), while for the cylinder where the liquid has filled the entire cylinder the pressure rises over 400 psi (from 120 psig to approximately 520 psig). This example demonstrates the significant hazard associated with overfilling a propane cylinder, whereby the pressure can increase more than 20 times higher with temperature.

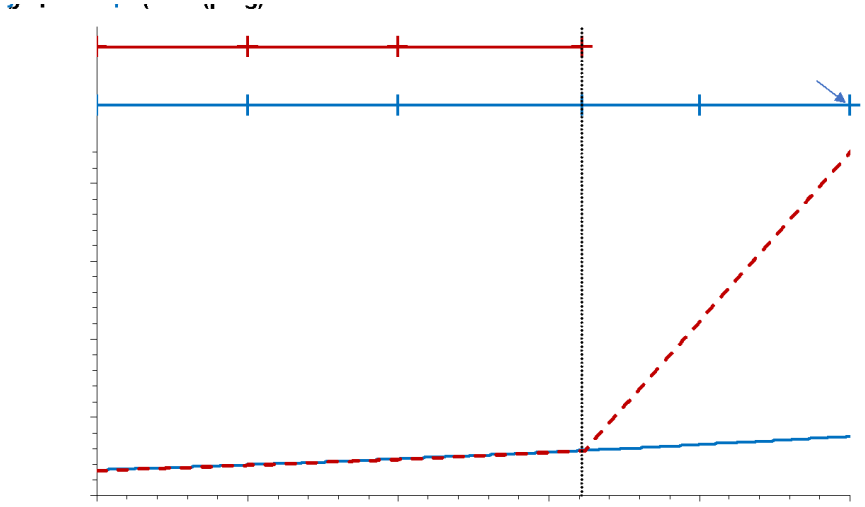

Figure 11: Example showing the pressure inside a properly filled propane cylinder (blue) that is allowed to freely expand in a cylinder as the temperature increases, and an overfilled propane cylinder (red) in which the propane liquid expands to fill the entire cylinder as the temperature reaches approximately 72°F at which point the pressure significantly increases as the temperature increases further.

Due to this extremely hazardous condition, there are two means required in the propane industry to protect against catastrophic failure at elevated pressures due to liquid propane expanding in a propane cylinder as the temperature increases: (1) avoid overfilling by ensuring the cylinder is only filled to 80% by volume or its equivalent propane weight; and (2) providing a pressure relief valve, so that in case a certain threshold pressure is exceeded in the cylinder, the valve opens and discharges the contents to reduce the pressure to within tolerable levels. These measures are safety critical means to prevent an overfill and catastrophic cylinder failure. A third and equally critical safety measure is to ensure the physical integrity of the propane cylinder by requalifying the cylinder (discussed below) at required intervals to avoid catastrophic failures even when a cylinder is not overfilled.

Filling 100-lb Portable Propane Cylinders

The problem with filling propane cylinders is that one cannot see inside the cylinder, so the filler does not know how much liquid propane is still remaining in the cylinder at the start of the fill and does not know how much propane to add in order to achieve an equivalent 80% fill by volume at 40°F. Therefore, two fill methods have been established to ensure safe fill levels for 100-lb propane cylinders (similar to the one in the present incident): the fill by weight method and the fill by volume method. The reason you can use one or the other method is that one hundred pounds (100 pounds) of propane fills 80% of the cylinder capacity at approximately 40°F.

In order to fill by weight, the weight of an empty cylinder and associated appurtenances (i.e. valves) is provided on the cylinder as a Tare Weight (TW). For example, if the nominal tare weight for a 100-lb cylinder is 68 pounds, the total weight after the fill should be equal to 68 pounds (TW) + 100 pounds (propane) = 168 pounds (see Figure 12). If the cylinder prior to filling is weighed and the weight is higher than the TW (as shown in the example below), than the extra weight is the remaining propane in the cylinder at the time of the fill. Knowing that 100 pounds of propane is supposed to be in the cylinder

after the fill or that a total weight of the cylinder and the propane is168 pounds, the filler just needs to add the difference between 100 pounds and the amount present in the cylinder prior to filling.

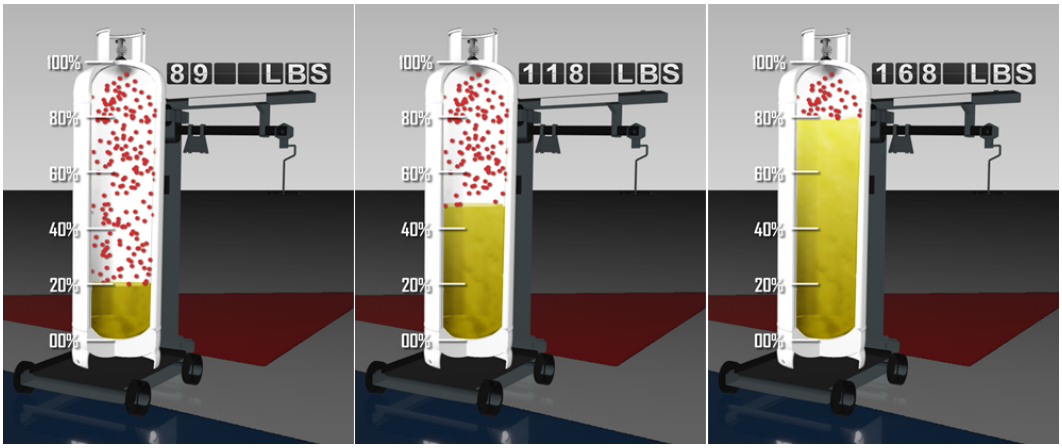

Figure 12: Fill-by-weight illustration with propane remaining in the cylinder prior to filling.

Another method, which is frequently used to fill 100-lb propane cylinders is filling by volume. Similar to the previous example, the filler does not know how much liquid propane is remaining within the cylinder prior to the fill. However, when filling by volume the filler utilizes a fixed maximum liquid level gauge, sometimes known as a spitter valve, to indicate when the liquid level in the cylinder has reached the height corresponding to an 80% fill. All 100-lb DOT cylinders must be fitted with a fixed maximum liquid level gauge (spitter valve), which is a valve that has a dip tube that descends into the cylinder and terminates at the 80% by volume fill level. Prior to filling, the spitter valve is opened and liquid propane is dispensed into the cylinder. When the liquid level is below the end of the dip tube, only pressurized propane vapor will be expelled. However, once the liquid level reaches the open end of the dip tube, liquid propane is forced out the spitter valve resulting is a clearly visible "white" cloud or fog (see Figure 13). This ensures that no matter what the starting amount of liquid is in the cylinder, the final amount will be verified by the fixed maximum liquid level gauge that indicates the propane liquid level has reached the 80% mark.

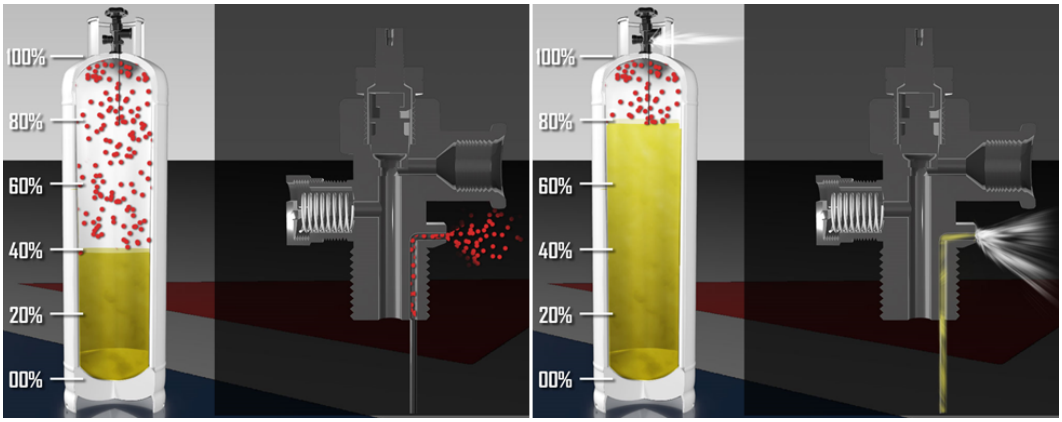

Figure 13: Fill-by-volume illustration with 40% propane remaining in the cylinder prior to filling.

The requirements are very clear for filling 100-lb propane cylinders by volume: (1) the cylinder must have a pressure release valve; and (2) the cylinder must have a fixed maximum liquid level gauge (i.e., a spitter valve). A cylinder shall not be filled by volume if either of these critical safety devices are not present. Furthermore, requirements also mandate that a cylinder shall not be filled either by volume or by weight if it is out of qualification. The next section provides an overview of the design specifications and requalification requirements for DOT and ICC cylinders (i.e., the types of cylinders involved in the incident).

Cylinder Filling Requirements

DOT and ICC Cylinders

All cylinders, including those apparently undamaged, are required to be periodically requalified for continued service. The first requalification for a new cylinder is required within 12 years after the date of manufacture. DOT regulations allow for three alternative methods for cylinder requalification. Two methods use hydrostatic testing (volumetric expansion method – requalifies a cylinder for 12 years; and the proof pressure method – requalifies a cylinder for 7 years), and the third uses a carefully made and duly recorded visual examination by a competent person (external visual inspection method – requalifies a cylinder for 5 years).

NFPA 58 – Liquefied Petroleum Gas Code

NFPA 58 [1] has specific requirements for 100-lb propane cylinders, similar to the incident cylinders on the food truck. One important requirement in Section 5.2.2.2 is that cylinders with an expired requalification date shall not be refilled until they are requalified by the methods prescribed in DOT regulations. Table 5.7.4 requires that cylinders ranging from 2-lb to 420-lb propane capacity shall have pressure relief valves and shall be equipped with such valves as required by DOT regulations. In addition to pressure relief valves, cylinders greater than 40-lb and up to 100-lb propane capacity that are filled by volume shall have a fixed maximum liquid level gauge. When filling a cylinder by volume, Section 5.7.5.1 states that liquid level gauging devices shall be installed on all containers filled by volume. In summary, NFPA 58 requires that 100-lb cylinders must always have a pressure relief valve, must have a fixed maximum liquid valve if filled by volume, and must be within the qualification date to be filled.

NFPA 58 specifically states in Section 7.2.2.8, “Containers shall be filled only after determination that they comply with the design, fabrication, inspection, marking, and requalification provisions of this code.” More specifically, if a cylinder: (1) has an expired requalification date; (2) does not have the proper warning labels affixed to the cylinder; (3) does not have a pressure relief valve; and (4) does not have a fixed maximum level gauge when filling by volume; then it is prohibited to fill a 100-lb cylinder by volume. In addition, when noncompliance is determined in any of the four points above, the container owner and user shall be notified in writing.

PERC “Dispensing Propane Safely” Training Manual

According to the Propane Education Research Council (PERC) Training Manual[2], propane dispenser operators’ responsibilities include: (1) inspecting customer containers to ensure that they are

[1] NFPA 58: Liquid Petroleum Gas Code, 2014 Edition. In *NFPA National Fire Codes* Online. Retrieved from http://codesonline.nfpa.org

[2] PERC: Propane Education and Research Counsel (PERC) Dispensing Propane Safely Manual – 2011.

safe for filling; (2) filling containers to their proper levels and preventing containers from being overfilled; and (3) inspecting valves and accessories prior to filling

After inspection, if any of the following are found, the cylinder must not be refilled and should be marked and set aside in a designated safe area: (1) serious denting; (2) defective valves unless properly repaired or replaced; (3) defective or leaking pressure relief device, unless properly repaired or replaced; (4) out-of-date requalification; and (5) excessive rusting or corrosion**.** Similar to NFPA 58, PERC specifically states that cylinders that are out of qualification must not be refilled. Instead, they are to be marked and set aside in a designated safe outdoor area.

Before filling cylinders by volume, the dispenser operator must first confirm that the cylinder is appropriate for filling by volume and not attempt to fill a cylinder by volume if the fixed maximum liquid level gauge is damaged or inoperable.

CAUSE AND ORIGIN OF THE EXPLOSION

Catastrophic cylinder rupture on the driver side

The origin of the explosion was the area within the rear cylinder cabinet that housed the driver side 100-lb propane cylinder. Examination of the evidence and video confirmed that the explosion was caused by a catastrophic rupture of the driver side 100-lb propane cylinder filled two days prior. The video footage shows the rupture and explosion event, where the catastrophically failing cylinder discharges compressed propane vapor and liquid propane, that formed a white cloud or fog that entered and engulfed the rear of the food truck which subsequently ignited resulting in a large fireball, as can be seen in Figure 5 above. CFD modeling with FLACS[3] also supports a catastrophic cylinder rupture as the cause of the incident. The flashing liquid propane expansion resulting occurring after a cylinder rupture was modeled and the resulting transient propane cloud, which is shown in Figure 14, is consistent with the expanding cloud seen in the surveillance footage. Furthermore, the ignition event was also modeled and the size of the ensuing fireball, which is shown in Figure 15, was also consistent with the video footage and witness testimony.

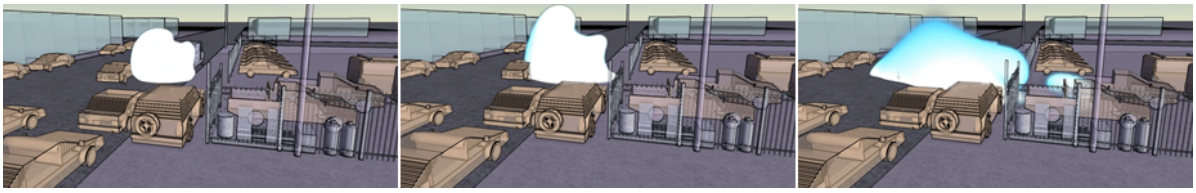

Figure 14: Propane cloud resulting from a catastrophic cylinder rupture.

[3] FLACS is a computational fluid dynamic (CFD) model for simulating 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 be used to model the consequences of ignition of flammable fuel-air clouds determined from dispersion modeling. More information is available at gexcon.com.

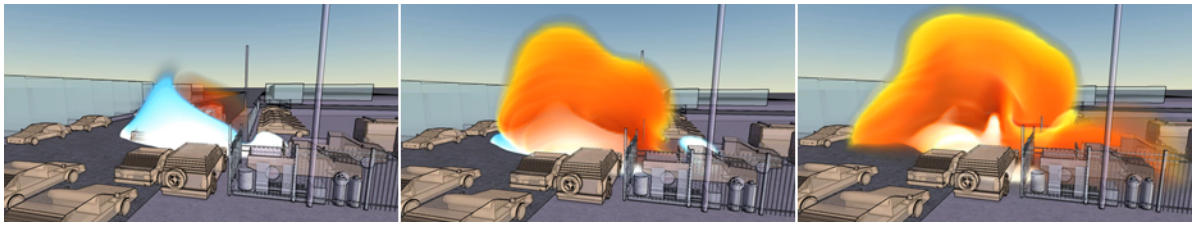

Figure 15: Ensuing fireball when the released propane is ignited.

As discussed earlier, propane is stored as a compressed liquid. When a catastrophic failure such as this occurs, the liquefied gas which the vessel had contained is suddenly released to the atmosphere, where it rapidly boils and flashes back to its gaseous state as a result of the sudden reduction in pressure. When the liquid flashes or boils, the vapor expands to occupy a much greater volume than the original liquid, and as a result, a blast wave is generated and projectiles/missiles are expelled from the initiating site. The cloud that formed was likely two-phase, meaning it contained both vapors and liquid.

In the food truck incident, the energy released from the exploding cylinder deformed and blew off the driver side propane cabinet and launched the propane cylinder across the street. The event created projectiles and missiles, where large fragments of the cylinder, its appurtenances, and the cylinder cabinet were thrown over approximately 100 feet. All evidence evaluated was consistent with a BLEVE or near BLEVE event due to a catastrophic rupture of the cylinder. Such an event can be caused by simple overpressurization of the cylinder due to an overfill, damage compromising the strength of the cylinder, or external flame impingement weakening a section of the vessel wall. In the present incident, there was no evidence of damage compromising the strength of the cylinder or external flames impinging on the cylinder and thus these was ruled out as factors in this explosion.

Cause of the Catastrophic Cylinder Failure

The incident cylinder that catastrophically failed should have never been filled by volume as: (1) it did not have the safety critical pressure release valve; (2) it did not have a fixed maximum level gauge; and (3) it had not been requalified for almost 66 years. This means that the integrity of the cylinder had not be examined or hydrostatically tested for over 66 years. The OSHA investigation report indicated that according to unofficial information from DOT, it appears that one of the cylinders may have been overfilled or that gas from the cylinder in use may have flowed into the cylinder which exploded. Since the incident cylinder service valve was closed after the incident and it was also protected by check valve, gas flowing from the other cylinder was ruled out.

Hence, there were two possible causes of the catastrophic cylinder failure: (1) there was liquid and vapor propane present in the cylinder, and as it was heated on the hottest day after the fill, the cylinder failed at pressures associated with the vapor pressure of propane; or (2) the cylinder was significantly overfilled with liquid propane, and as it was heated on the hottest day after the fill, the liquid expanded and filled the entire volume, thus resulting in a considerable pressure increase within the cylinder as the temperature continued to rise.

<u>History of Overfill</u>

Propane sales receipts show that the 100-lb cylinders used on the food truck were consistently overfilled. In fact, the overfills ranged from filling the cylinder to 86% up to almost completely full at 97%. Note

however that the receipt from the fill on June 29, 2014, two days prior to the incident, was unavailable and therefore the exact fill level at the time of the incident was unknown.

Catastrophic Failure

At the time of the incident, the incident cylinder was exposed to approximately the hottest temperature that it had been exposed to since it was filled two days prior on June 29, 2014. Hence, it is necessary to understand the possible pressures that could have been present within the cylinder in order to understand under what conditions it failed.

Recall that as long as the liquid has not expanded to fill the entire volume of the cylinder, the pressure within the cylinder will rise according to the vapor pressure of propane, where the pressure rises on the order of 10 psi as the temperature rises 10°F. However, if the liquid expanded to fill the entire volume of the cylinder as the temperature increases (i.e., the cylinder was initially overfilled), the pressure at this point will increase dramatically as the temperature continues to rise, rising approximately 400 psi as the temperature rises just 10°F. On June 29, 2014, the temperature was approximately 77°F (25°C) at the time the incident cylinder was filled.

The advanced phase diagram analysis shows three very important facts: (1) if the cylinder was properly filled to 80% on the day of the incident, the liquid propane would not have expanded to fill the cylinder until unrealistically high temperatures that were not observed on the day of the incident, and the pressures would be below those necessary to open a pressure relief valve and to exceed the strength of the cylinder; (2) overfilling the cylinder increases the likelihood of having the liquid expand and fill the entire cylinder, where the pressure can rise hundreds of psi if there is a small rise in temperature; and (3) pressures capable of reaching design stresses for catastrophic failure of the cylinder would have been achievable at temperatures on the day of the incident if the incident cylinder was significantly overfilled.

For example, even if we conservatively assume the failed propane cylinder reached 105°F (i.e., 15 °F above ambient due other unknown heating sources) at the time of the incident and the incident cylinder was filled to 97% or greater (similar to a previous fill), the pressure in the cylinder would have been approximately 700 psig or greater. In contrast, if the cylinder was properly filled to 80% on the day of the incident, the pressure would have been less than 200 psig or below the service pressure. Given there was no evidence of external trauma to the cylinder or thinning of the cylinder walls due to corrosion, the analysis shows that the cylinder was significantly overfilled two days prior to the incident.

ROOT CAUSE – LESSONS LEARNED

Regardless of the cylinder failure pressure, two facts hold true: (1) if the failure pressure was above 375 psig, a properly installed pressure relief valve would have prevented the failure; and (2) if the failure pressure was below 375 psig, or even below the rated service pressure of 240 psig, required and systematic requalification tests per DOT standards would have detected the compromised cylinder integrity and the cylinder would have been taken out of service. Hence it was the filling station's combined conduct of overfilling a cylinder by volume that caused this incident, namely the cylinder: (1) did not have a fixed maximum liquid level gauge, hence no means of knowing how much liquid propane remained in the cylinder prior to filling and the total amount after filling; (2) did not have a pressure relief valve, a critical safety device designed to prevent catastrophic failure in the event of a pressure build up in

the cylinder; and (3) had not been requalified in almost 66 years, a necessary means to find defects or compromised mechanical integrity of the cylinder.

Overfilling a propane cylinder is an extremely hazardous condition, as it can result in very high pressures within the cylinder. Even if a cylinder is properly fitted with a pressure relief valve, an overfill can lead to an unnecessarily hazardous discharge of liquid propane via the relief valve in the vicinity of the cylinder. If, however a pressure relief valve is not provided (as was the case with the incident cylinder), an overfill can result in significant pressure build up in the cylinder and can lead to catastrophic rupture as observed in the present incident.

Due to this extremely hazardous condition, there are two means required in the propane industry to protect against catastrophic failure due to liquid propane expanding in a propane cylinder as the temperature increases: (1) avoid overfilling by ensuring the cylinder is only filled to 80% by volume or its equivalent propane weight; and (2) providing a pressure relief valve, so that in case a certain threshold pressure is exceeded in the cylinder, the valve opens and discharges the contents to reduce the pressure to within tolerable levels. These measures are safety critical means to prevent an overfill and catastrophic cylinder failure.

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.

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REFERENCES