VAPOR CLOUD EXPLOSIONS

Table of Contents

Page

List of Figures

1.0 SCOPE

This data sheet provides guidance on evaluating the effects of a vapor cloud explosion (VCE) and basic approaches that can be taken to minimize the chances of such an event.

Flammable vapor releases with accumulation and delayed ignition inside a building will likely have widespread damaging effects within the building and may impact the nearby area. Refer to Data Sheet 1-44, *Damage Limiting Construction*, for information on protection against this exposure, and Data Sheet 7-32, *Ignitable Liquid Operations*, for information on identifying the potential for building explosion hazards.

1.1 Changes

July 2019. This document has been completely revised. The following major changes were made:

A. The title of the data sheet was changed to *Vapor Cloud Explosions* (from *Evaluating Vapor Cloud Explosions Using Flame Acceleration Method)*.

B. Reorganized the document to be consistent with other data sheets.

C. Updated recommendations to help reduce the likelihood and consequences of VCE scenarios.

2.0 LOSS PREVENTION RECOMMENDATIONS

2.1 Introduction

The following recommendations are focused on preventing or reducing the release of flammable vapor that could result in a VCE, and minimizing subsequent damage.

2.2 Process Safety

2.2.1 Develop a process safety program for all processes with inherent VCE potential in accordance with Data Sheet 7-43, *Process Safety*.

2.2.1.1 Identify the potential for a VCE using a process hazard analysis. Implement the appropriate measures to reduce the likelihood and/or consequences of a VCE.

2.2.1.2 Apply inherent safety concepts wherever possible. This could include the elimination of materials that present a VCE potential, such as in refrigeration systems.

2.3 Construction and Location

2.3.1 Conduct a comprehensive facility siting study as described in Data Sheet 7-14, *Fire Protection for Chemical Plants*, including the blast effects resulting from VCE.

2.3.2 Locate control rooms, central process I/O rooms, central utilities, and emergency response facilities outside of areas exposed to blast damage. Where this is impractical, design these facilities with blast-resistant construction sufficient to withstand the expected blast loads.

2.3.3 Minimize the overall level of congestion and confinement within process areas to reduce the potential for flame acceleration.

2.4 Protection

2.4.1 Provide a vapor detection system capable of identifying if there is a release of VCE source materials in process units, tank farms, or other locations in which they may exist. Install LEL detectors compatible with the process environment and types of gas intended to be detected per the OEM guidelines. For additional guidance, refer to Data Sheet 5-49, *Gas and Vapor Detectors and Analysis Systems*.

2.4.1.1 Provide perimeter detection for areas in which a VCE target material is handled and there is a credible release potential. This includes large vessels with holdup of gas or liquefied gas, pressurized liquids above their boiling points, points of connection to feedstock pipelines (metering), and similar.

2.4.2 Arrange the detection system to alarm at a constantly attended control room or equivalent location.

2.4.3 Arrange the detection system to initiate automatic shutdown of the process when the concentration exceeds a predetermined critical threshold.

2.5 Equipment and Processes

The following recommendations apply only to VCE-prone materials.

2.5.1 Arrange equipment and processes to minimize the potential for large releases of VCE source materials.

2.5.2 Minimize hold-up of VCE source materials by limiting vessel sizes within process areas.

2.5.3 Install flow-limiting devices, such as orifice plates, pipe reducers, and excess flow valves (EFVs), to limit the amount of VCE source materials that can be released. EFVs may be internal or external to the vessel. Where external flow-limiting devices are used, locate them as close to the vessel as possible.

2.5.3.1 Provide flow-limiting devices on all connections to the vessel except connections to pressure-relief devices.

2.5.4 Install high-integrity interlocks for high-level conditions in tanks, spheres, vessels, surge drums and systems to prevent overfilling in ISBL and OSBL areas.

2.5.5 Provide a means of isolating process units and VCE source material feeds. Use automatic valves located outside the area being isolated, or provide valves that can be remotely operated from a safe location such as a control room or remote station away from the immediate fire/gas-release impact zone.

2.5.6 Provide a means for de-inventorying/depressurizing process vessels and piping by venting to a flare or equivalent.

2.6 Operation and Maintenance

2.6.1 Implement an asset integrity program in accordance with Data Sheet 9-0, *Asset Integrity*.

2.6.2 Provide written operating procedures and operator training programs in accordance with Data Sheet 10-8, *Operators*. Train operators to handle normal, upset, and startup procedures.

2.7 Human Factor

2.7.1 Develop an emergency response plan for the loss of containment of any VCE source materials. This includes actions to be taken to shut down processes, isolate releases, disperse clouds, etc. See Data Sheet 10-1, *Pre-Incident Planning*, for additional information.

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Vapor Cloud Explosion Principles

In a VCE, the rate of fuel consumption and amount of fuel consumed determines the strength of the blast wave that is produced. The rate of fuel consumption is dependent on the flame speed, which in a vapor cloud explosion is enhanced when propagating through congestion and/or when the expanding burned gas is confined.

In general, the flame must be accelerated to a speed greater than 0.2 times the speed of sound in air (approximately 70 m/sec) before it can generate a damaging blast wave. When a vapor cloud is consumed at flame speeds lower than this, it is usually described as a flash fire. While flash fires can produce direct flame and thermal radiation damage, they usually do not produce damaging pressure effects.

Figure 1 shows the steps leading up to a VCE.

3.1.1. Laminar Burning Velocity (LBV)

The laminar burning velocity (LBV) of flammable gas and vapor is a physical property that describes the speed at which a flame propagates through an unburned fuel-air mixture in a quiescent, non-turbulent state. The maximum LBV occurs at an optimum fuel concentration, which is close to the stoichiometric concentration for most fuels. Although the LBV is a fundamental property of a fuel of specific composition, the actual burning velocity and flame propagation rate in an unintended release is influenced by many factors.

While typical laminar burning velocities of most fuels are on the order of 10 to 100 cm/s, the actual flame speed is considerably faster, as illustrated by Figure 2, due to the expansion of burned gas behind the flame. Common fuel-air combustion reactions expand the mixture volume by about a factor of eight and significantly increase the speed of the flame.

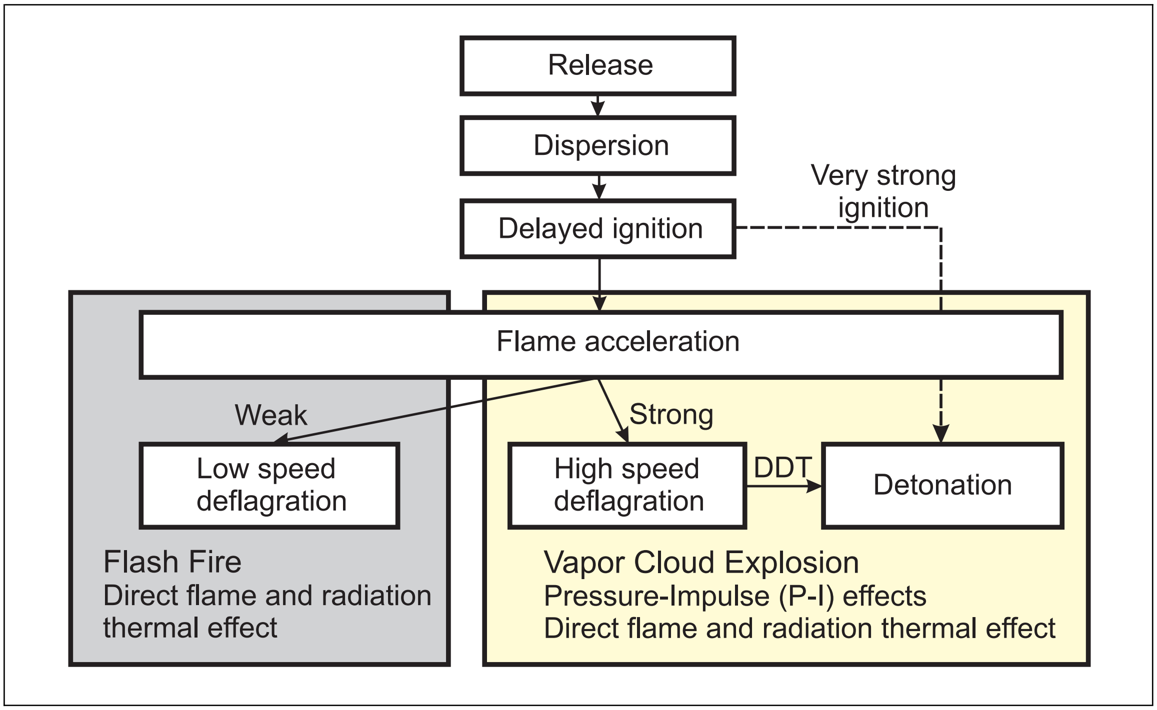

Fig. 1. Simplified VCE mechanism

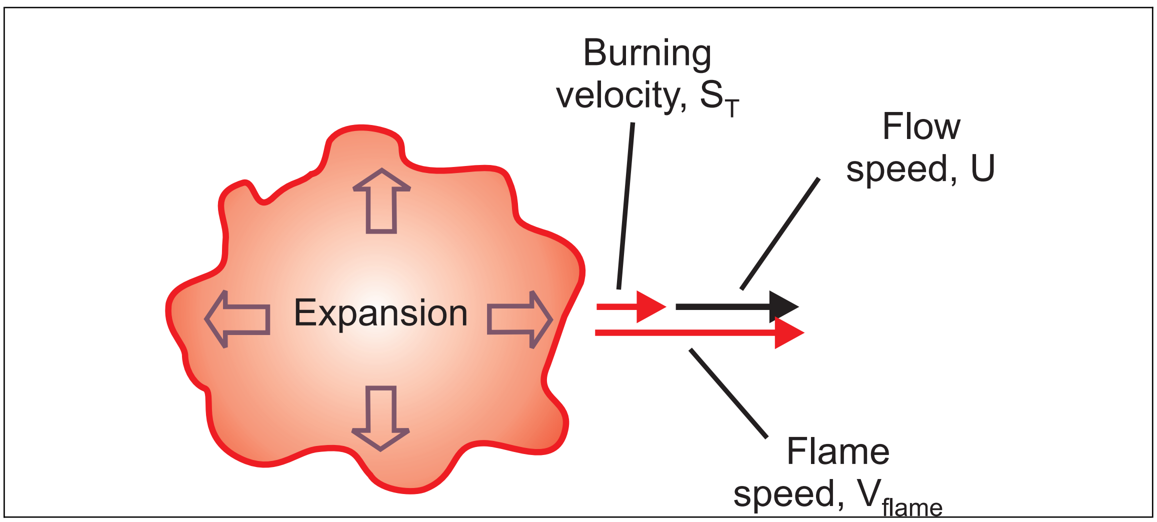

Fig. 2. Sketch of flame propagation causing expansion and flow ahead of the flame

In addition, propagating flames are inherently unstable and accelerate due to expansion of combustion products and flame instabilities. Flame instabilities (e.g., hydrodynamic, thermo-diffusive, acoustic, Richtmyer-Meshkov, and Rayleigh-Taylor) increase the local flame surface area and can significantly increase the rate of fuel consumption and the propagation velocity of the flame.

3.1.2 Flame Acceleration

Confinement and congestion (see Sections 3.2.4.2 and 3.2.4.3) are the most important factors when considering flame acceleration and VCE potential. This is due to the following mechanisms (see Figure 3):

A. Interactions of the flame with obstacles results in a strong increase of the flame area and acceleration of the gas flow ahead of the flame.

B. The upstream gas flow interacts with obstacles, generating turbulence due to shear instabilities.

C. Turbulence increases the burning velocity of the flame.

D. Any confinement that prevents the combustion products' expansion in directions other than that of the flame propagation promotes further flame acceleration.

E. The higher rate of fuel consumption increases the gas flow ahead of the flame, strengthening obstacle-induced turbulence as well as increasing the surface area of the flame.

F. This creates a positive feedback loop and results in flame acceleration and pressure rise.

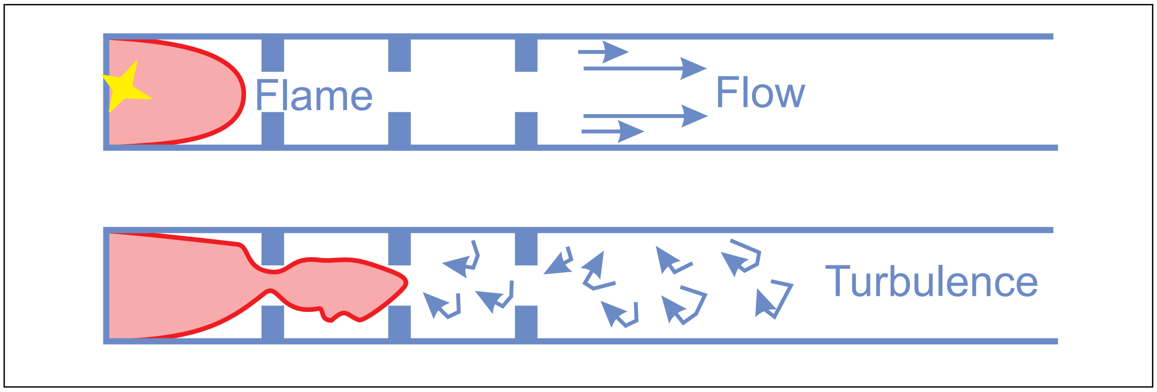

Fig. 3. Flame acceleration in obstructed channel caused by flame area increase and turbulence generation ahead of the flame

In addition to traditional flame acceleration mechanisms, a high-pressure fuel release can also directly generate pre-existing turbulence, increasing the severity of an event. In rare cases, flame acceleration can even occur without obstacles or pre-existing turbulence due to hydrodynamic flame instabilities. This mechanism is relatively weak, requiring long run-up distances for a flame to accelerate to speeds that can produce measurable overpressures. For most source materials, the run-up distances are sufficiently large that this mechanism does not need to be considered.

In most vapor cloud explosion events, the flame propagates through the unburned fuel-air mixture as a deflagration, with a burning velocity (S_T in Figure 2) that is subsonic with respect to the gas just ahead of the flame. Expansion of the combustion products generates a flow ahead of the flame (with a speed U in Figure 2), so that the resulting flame speed relative to the burned gas, or fixed observer (V_{flame} in Figure 2) can approach a value close to the sound speed in the combustion products (≈900 m/s). To sustain high flame speeds, significant congestion and/or confinement is needed, and when a flame exits congestion to propagate in open air, it will decelerate.

In rare cases, the propagating flame in a vapor cloud explosion can transition from deflagration to detonation. In a detonation, a shock wave is coupled with the chemical reaction and the rate the unburned fuel-air mixture is consumed is supersonic relative to the unburned gas ahead of the shock. Unlike high speed deflagrations, a detonation can propagate at high speed through an open vapor cloud without congestion, provided that conditions suitable for continued propagation, such as sufficiently large cloud dimensions and sufficiently uniform concentrations, are present.

3.1.3 Blast Effects

The energy released by a vapor cloud explosion takes the form of thermal energy of the combustion products, mechanical energy of expanding gas movement and thermal radiation. While the high temperature burned gas and thermal radiation may cause significant damage in the near field, the primary source of widespread damage caused by a VCE results from the gas movement, and the generation of a blast wave.

The strength of a blast wave is determined by two components, the velocity of the expanding gas, and the amount of gas that is moving. The maximum peak pressure generated is related to the maximum velocity of the gas, while the duration, and impulse, of the event is determined by the total energy released, or volume of gas moving.

While the shape of the pressure profile experienced at a given location can vary significantly depending on the speed and strength of the VCE, see Figure 4, the damage caused by a blast wave can be generalized in terms of maximum overpressure and impulse. In general, light weight construction can be damaged by relatively low impulse, while heavier construction can require significantly higher impulse, for the same peak overpressure, to produce a given level of damage.

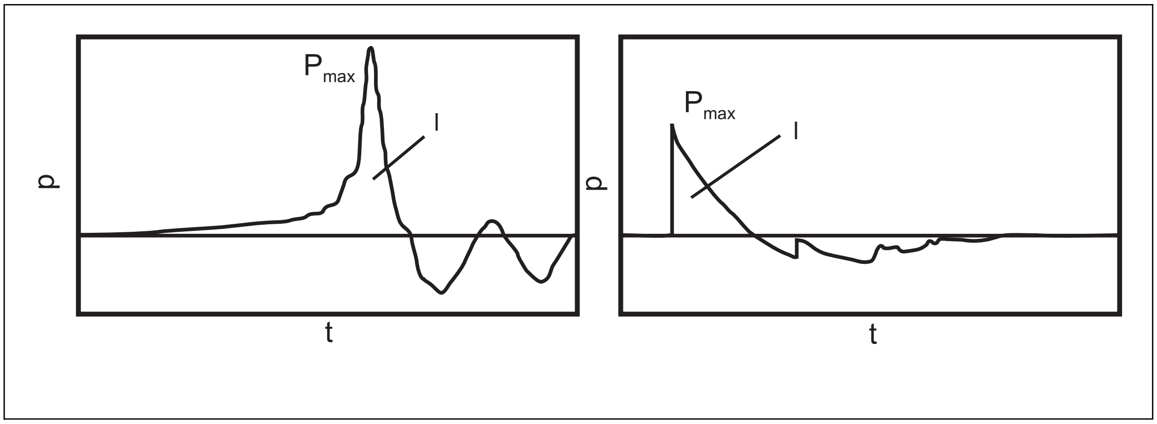

Fig. 4. Examples of experimental pressure and impulse profiles from VCEs

3.2 Estimating the Vapor Cloud Explosion Hazard

For a VCE with damaging overpressures to occur, the following conditions need to be present:

A. A sufficient amount of source material (fuel) in a pipeline, process, storage, or transportation system (see Section 3.2.1)

B. Release of the source material from its containment, vaporization if the source material is liquefied, and mixing of the source material with air forming a vapor cloud with some part of the cloud in the flammable range (see Section 3.2.2)

C. Dispersion of the vapor cloud into a potential explosion site (PES) (see Section 3.2.3)

D. Delayed ignition of the cloud followed by flame acceleration through the PES and the cloud, where spatial confinement and/or congestion is present (see Section 3.2.4)

3.2.1 Source Materials

A source material is an ignitable liquid or flammable gas and could be a chemical process feedstock, intermediate, product or by-product, or used in a support system.

3.2.2 Release

The release phase of the scenario is dependent on the duration of the release, the size of the release opening, the physical properties of the source material, operating pressure and temperature and, to a small degree, the outside environment.

3.2.3 Dispersion of Released Vapor Clouds

Dispersion of the released cloud is highly dependent on the physical properties of the source material, including the force and direction of the release, weather conditions, surrounding terrain, and physical plant layout.

High-momentum releases, such as from an opening in a pressurized pipe or vessel, that do not directly impact the ground or other solid surface, will create an extended cloud in the flammable range. The flammable envelope develops in a matter of seconds after the release starts and then becomes reasonably stable in size for the duration of the release.

Low-momentum clouds, such as those coming from a pool of released liquid or from a pressurized jet release, impacting directly on the ground, may form large clouds over hundreds of feet (meters) from the release. These clouds take longer to develop due to the action of wind and mixing with air.

3.2.4 Potential Explosion Site (PES)

The PES is a defined volume with sufficient confinement and/or congestion to create flame acceleration. A vapor cloud generally needs confinement and/or congestion to transit from a slow flame (flash fire) to a fast deflagration or detonation. Confined, congested, elongated outdoor process structures provide the best conditions to produce these results. A PES could also be an open or partially open process structure, an open equipment pad, or heavily-loaded, multi-level pipe racks where the multiple layers of pipes can create the effect of a solid roof/confinement.

Another way for the vapor cloud to accelerate from a slow flame to a fast deflagration is with long run-up distances that can be achieved in a very large cloud and limited congestion or confinement or a small cloud of highly reactive fuel. With low-reactivity fuels, a very large cloud is needed to achieve the same blast effect as a cloud in a relatively small PES.

3.2.4.1 Selecting a PES

A plant with mostly open space and minimal or small process structures generally does not have the right conditions for effective flame acceleration. Even though suitable amounts of source materials may be present and a vapor cloud release could occur, the layout would likely not support flame acceleration that contributes to overpressure. If the spaces between tanks or roadways were covered with canopies or dense pipe racks, the layout might have the conditions needed for a VCE.

Because confinement and congestion can cause effective flame acceleration, plant layout can directly affect the potential for a VCE.

3.2.4.2 Confinement

Spatial confinement defines how a flame accelerates within the process structure. The greater the restriction on the ability of the combustion products to expand out of the PES during flame acceleration, the greater the potential pressures generated by the PES.

Most outdoor chemical process structures are limited to confining horizontal surfaces such as platforms, solid or grated floors, roofs, and substantial pipe racks. Where there are substantial vertical surfaces, these should also be considered as affecting the degree of confinement.

Confinement can be measured as the percentage of the PES external surface (excluding the ground) that is confined with rigid surfaces that can restrict the ability of combustion products to expand during flame acceleration.

3.2.4.3 Congestion

Congestion is defined by obstacle density through which the flame must move. Repeated and closely spaced obstacles, such as piping, structural columns or beams, vessels, and pumps, in the center of a cloud can provide an efficient geometry for flame acceleration. Generally, a high obstacle density will produce increased flame acceleration. There is some data to indicate that small obstacles such as pipes, columns, beams, and pumps are more effective at accelerating a flame than large process vessels (Cleaver and Shale 1999).

3.2.5 Ignition Sources

The presence or lack of ignition sources should not be considered when calculating material release. For a credible worst-case scenario, the total amount that might be spilled in the specified duration should be used in estimating the cloud size. Loss experience has shown that wind patterns may allow the formation of large clouds without their being ignited by nearby ignition sources.

3.2.6 Energy Release

The chemical energy in the fuel-air mixture is released during combustion as the flame expands through the cloud from an ignition source. The strength of the blast wave generated during combustion depends on the rate of energy release. Flame acceleration models that include the effects of acceleration in the PES and energy release in the unconfined cloud surrounding the PES are known to provide better modeling of both near and far field effects than the TNT methods that have been used in the past. Some practitioners model only the effects produced by the PES or define multiple PES within the cloud and combine the individual components of the event.

3.2.7 Blast Effects and Ensuing Fire Damage

No specific guidance is provided in this document on blast damage effects, but they can be obtained based on generally available data or specific commercial software.

3.3 Loss History

3.3.1 Overview and Statistics

Lenoir and Davenport list 103 suspected VCE incidents that produced observable overpressures during the period 1921 to 1991 (see Section 4.2). Of these events, 96 were well documented; an FM review of them determined VCE incident percentages by release sources (Figure 5) and by material released (Figure 6).

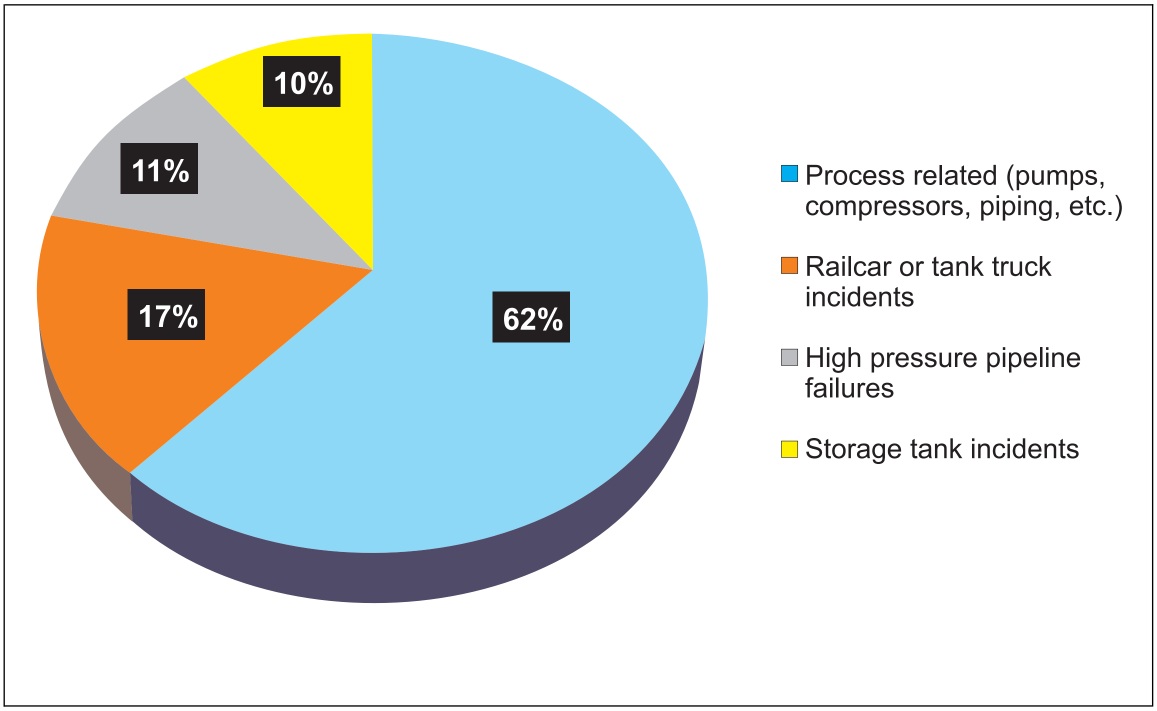

Fig. 5. VCE incident percentages by release source

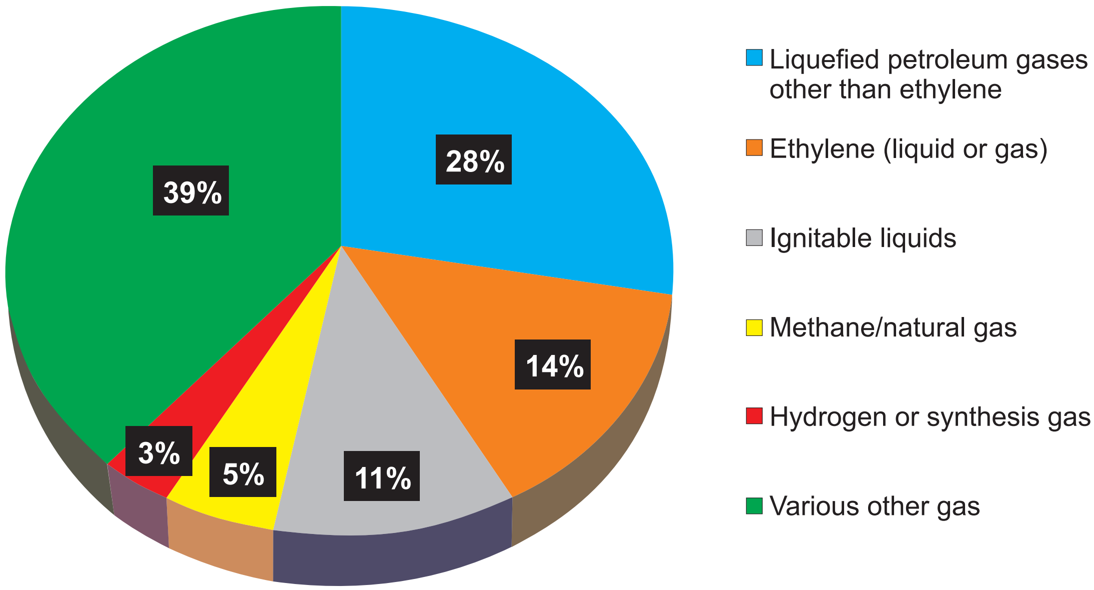

Fig. 6. VCE incident percentages by material released

3.3.2 Process Incidents

3.3.2.1 Bypass Failure at Caprolactam Plant, Nypro UK Ltd, Flixborough, England

This incident was the watershed event that brought the chemical process industries to the realization that flammable gas releases and subsequent explosions were capable of doing catastrophic damage to a large plant, and caused industry to investigate methods to prevent future events (see Figure 7).

Fig. 7. Process area damage at Flixborough

On June 1, 1974, cyclohexane vapor was released after the rupture of a 20 in. (500 mm) process pipe bypassing a reactor. One of the six reactors in series began to leak and the decision was made to bypass that reactor (see Figure 8). Bellows were installed in the piping between the reactors to address alignment issues and operated for several months. The plant was shut down to repair a leaking sight glass. The bellows in the bypass failed on startup. The VCE and subsequent fire destroyed the entire facility. Property damage was estimated at US$220 million (indexed to 2017 values). The plant was not rebuilt (Parker 1975).

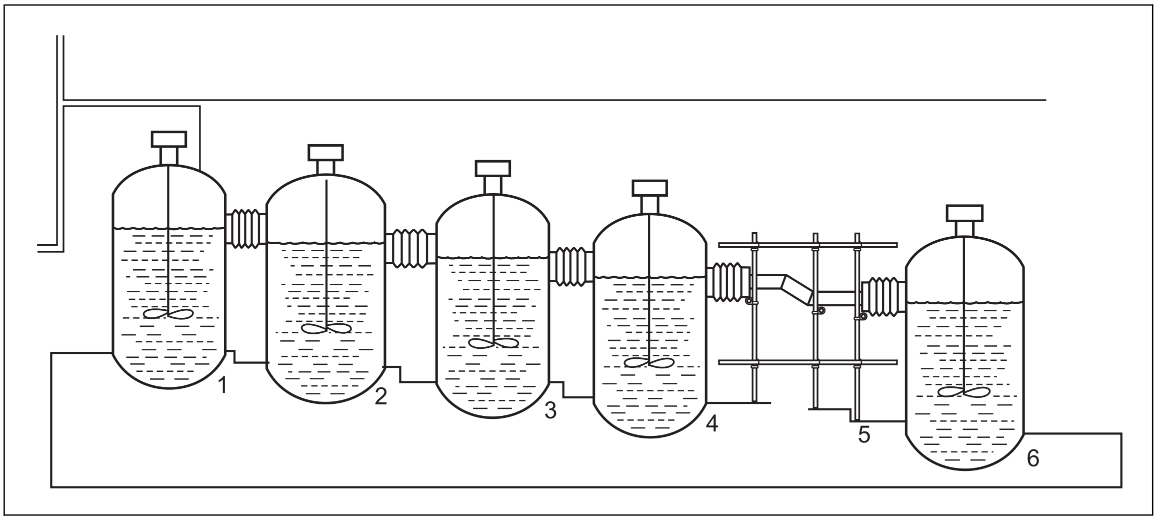

Fig. 8. Arrangement of reactors at Flixborough before the incident

3.3.2.2 Release from Polyethylene Unit, M Phillips Petroleum, Pasadena, TX, USA

This event in the United States was the equivalent of the Flixborough event in the UK, in that it brought renewed effort to preventing releases that could result in a large VCE. It also instigated OSHA PSM regulation.

On October 23, 1989, ethylene and isobutane were released from a ball valve on the settling leg of a vertical loop reactor. The vapor cloud drifted toward the center of the high-density polyethylene unit (HDPE) before ignition, which is believed to have occurred 1 to 2 minutes after the release. Pressure effects were evident at 6 miles (9.6 km) from the epicenter. Two HDPE units were destroyed (see Figure 9). Investigations revealed that a maintenance lock-out device had been removed, the ball valve was open, and the settling leg was open to atmosphere where a spool leading to the product take-off valve should have been connected. Property damage was approximately US$1.5 billion (indexed to 2017 values) (Marsh 2018). It took almost two years to restore full HDPE production capacity (U.S. OSHA 1990).

3.3.2.3 Discharge from Atmosphere Vent, MBP, Texas City, TX, USA

This incident was a leading factor in the revision of API 521 (ISO 23251) in 2007 (see Section 4.2.), which put new restrictions and limits on the use of blow-down drums and added guidance on recognizing the way systems can present a vapor cloud hazard.

On the morning of March 23, 2005, the raffinate splitter tower (mix of C5-C8 hydrocarbons) in the refinery's isomerization unit was restarted after a maintenance outage. During the startup, operations personnel pumped liquid hydrocarbon into the tower for over three hours without any liquid being removed, which was contrary to startup procedure instructions. Critical alarms and control instrumentation provided false indications that failed to alert operators of the high level in the tower. The 170 ft (52 m) tall tower was overfilled and liquid overflowed into the overhead pipe at the top of the tower. The overhead pipe ran down the side of the tower to pressure-relief valves located 148 ft (45 m) below. As the pipe filled with liquid, the pressure at the bottom rose rapidly from about 21 psi to 64 psi. The three pressure-relief valves opened for six minutes, discharging a large quantity of hydrocarbon liquid to a blow-down drum (Figure 10) with a vent stack open to the atmosphere. The blow-down drum and stack overfilled, which led to a geyser-like release out of the 113 ft (34 m) tall stack. According to the CSB investigation, this blow-down system was an antiquated and unsafe design originally installed in the 1950s that had never been connected to a flare system to safely contain liquid and burn flammable vapor released from the process.

Fig. 9. Damage to Phillips plant following the VCE

Severe damage occurred to the isomerization unit, resulting in more than US$1.5 billion in gross loss costs at the time of loss. The property damage was US$280 million (indexed to 2017 values) (Marsh 2018).

3.3.3 High-Pressure Transmission Pipeline Incidents

Rupture of high-pressure transmission pipelines for petroleum gases and liquids is a potential VCE exposure that should be considered in chemical plants (11% of the incidents reported by Lenoir & Davenport; see Section 3.3.1). They happen on a regular basis; there have been 10 major incidents with detailed investigation reports posted on the US National Transportation Safety Board website since 2004. Three prominent events that caused widespread damage were a natural gas liquids release in Brenham, Texas, USA (1992); a propane pipeline in Port Hudson, Missouri, USA (1970); and a propane and mixed gas liquids pipeline in Siberia, Russia (1989). One event involving a refinery is summarized below.

3.3.3.1 Ethane Propane Mix, Baton Rouge, Louisiana, USA

On December 24, 1989, an 8 in. (200 mm) above-ground pipeline at approximately 700 psig (48 bar) carrying a mix of ethane and propane from a refinery to nearby off-site storage facilities catastrophically failed during record low temperatures. The resulting vapor cloud that was released in a remote tank farm travelled an estimated 1500 ft (460 m) across open land into the refinery, where it was ignited at a fired heater. The resulting burning cloud flashed back to the tank farm where obstacles and confinement in the form of pipe racks and a rail underpass were sufficient to cause significant flame acceleration. The explosion produced blast pressures felt 15 miles (24 km) away, ruptured 17 of 70 pipelines in the pipe rack, ignited two large storage tanks containing 3.6 million gal (14,000 m^3) of diesel fuel, and 12 smaller tanks with approximately 900,000 gal (3,400 m^3) of lube oil. The loss was estimated at US$155 million property damage (indexed to 2017 values) (Marsh 2018).

3.3.4 Fixed Storage Tank Incidents

VCE events initiated as a result of release from a storage tank have been relatively rare compared to other sources (10% of the incidents reported by Lenoir & Davenport; see Section 3.3.1), but several have occurred in the recent past that have cause widespread damage.

Fig. 10. Blow-down drum at BP, Texas City (photo from the U.S. CSB final report)

3.3.4.1 Light Hydrocarbon Liquids, Pernis, Netherlands

From 60 to 120 tons (55 to 109 tons) of light hydrocarbon liquids were released January 20, 1968 when a slop oil tank frothed over due to the breaking of an oil water emulsion in the tank. The low-pressure tank (a few inches [cm] above atmosphere) failed at the seam due to the frothing action. The resulting cloud diameter was 450 ft (140 m). The explosive yield was estimated to be 22 tons (20 tons) TNT equivalent. The loss exceeded US$100 million in property damage.

3.3.4.2 Winter Grade Gasoline, Buncefield, Hertfordshire, UK

The Hertfordshire Oil Storage Terminal supplied 8% of the oil and fuel supplies of the UK, including about 40% of the aviation fuel to London's Heathrow and Gatwick airports. It covered 50 acres (20 hectares) and was supplied by three pipelines from a number of refineries in the UK.

Starting at approximately 7 p.m. on December 10, 2005, Tank 912 began receiving gasoline by pipeline at a rate of about 2400 gpm (550 m^3/hr). From approximately 3 a.m. on December 11, the tank level gauge was unchanged, but fuel continued to be received. Calculations indicate the tank began to overflow at about 5:20 a.m., and CCTV showed a vapor cloud that had spread to an adjoining commercial property and reached almost 6.6 ft (2 m) deep shortly before the 6:01 a.m. explosion.

The release was estimated to be approximately 300 tons (272 tonnes) of gasoline. Official accident reports estimate that approximately 10% of this fuel vaporized. The explosion caused widespread damage in the surrounding office and residential areas (windows broken as much as 1 mile [1.6 km] away), and the subsequent fires destroyed much of the tank farm (see Figure 11).

3.3.5 Mobile Transportation Incidents

VCE incidents causing damage to industrial facilities that have involved transportation vehicles such as railcars, tank trucks, or waterway vessels are not unusual (17% of the incidents reported by Lenoir & Davenport; see Section 3.3.1).

Fig. 11. Buncefield terminal; fire following VCE

3.3.5.1 Railcar, Liquefied Petroleum Gas, East St. Louis, Illinois, USA

On January 22, 1972, a railcar full of liquefied petroleum gas (LPG) (primarily propylene) rolled into another railcar during rail yard switching operations. The collision occurred at approximately 15 mph (24 kph), roughly 10 mph (16 kph) faster than normal practice. The coupling on a stationary car punctured the moving LPG car and released 24,300 lb (53,500 kg) of vapor at 220 psig (15 barg) into the rail yard. The vapor cloud covered an area of more than 215,000 ft^2 (20,000 m^2) and reportedly ignited in two different locations. The explosion was enhanced by the tightly congested arrangement of railcars throughout the large rail yard. An estimated 1,000 buildings were damaged to various degrees. The property damage was estimated at US$45 million (U.S. NTSB 1973).

4.0 REFERENCES

4.1 FM

Data Sheet 5-49, *Gas and Vapor Detectors and Analysis Systems*
Data Sheet 7-14, *Fire Protection for Chemical Plants*
Data Sheet 7-43, *Process Safety*
Data Sheet 9-0, *Asset Integrity*
Data Sheet 10-1, *Pre-Incident Planning*
Data Sheet 10-8, *Operators*

4.2 Other

American Petroleum Institute (API). *Guide for Pressure-Relieving and Depressuring Systems*. API 521. Fifth Edition, 2007. (Identical to ISO 23251, *Petroleum Petrochemical and Natural Gas Industries Pressure Relieving and Depressuring Systems*. First Edition, 2006.)

American Society of Mechanical Engineers (ASME). *Scheme for Identification of Piping Systems*. ANSI/ASME A13.1.

Buncefield Major Incident Investigation Board. *The Buncefield Incident, 11 December 2005: The Final Report of the Major Incident Investigation Board.* Volume 1. December 2008.

Center for Chemical Process Safety (CCPS). *Guidelines for Evaluating Process Plant Buildings for External Explosions and Fires*. 2010.

Center for Chemical Process Safety (CCPS). *Guidelines for Facility Siting and Layout*. 2003.

Center for Chemical Process Safety (CCPS). *Guidelines for Pressure Relief and Effluent Handling Systems*. 1998.

Center for Chemical Process Safety (CCPS). *Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards*. Second Edition, 2010.

Center for Chemical Process Safety (CCPS). *Safe Design and Operation of Process Vents and Emission Control Systems*. 2006.

Cleaver, R. P., and G. A. Shale. "Mathematical Models for Gas Explosions on Industrial Sites." *Proceedings of the International Conference and Workshop on Modeling the Consequences of Accidental Releases of Hazardous Materials*. American Institute of Chemical Engineers (AIChE). 1999.

Daycock, J.H., and P.J Rew. *Development of a Method for the Determination of On-Site Ignition Probabilities. Health and Safety Executive*. RR226. 2004.

Dorofeev, S. B. "A Flame Speed Correlation for Unconfined Gaseous Explosions." *Process Safety Progress*. 26:2 (June 2007): p. 140-149.

Lenoir, E. M., and John A. Davenport. "A Survey of Vapor Cloud Explosions: Second Update." *Process Safety Progress*. 12:1 (January 1993): p. 12-33.

Marsh & McLennan. *100 Largest Losses, 1972-2011 (in the Hydrocarbon Industry)*. 22nd Edition. 2012.

Parker, R. J. *The Flixborough Disaster: Report of the Court of Inquiry.* H.M. Stationary Office,1975.

U.S. Chemical Safety and Hazard Investigation Board. "Statements of CSB Chairman John Bresland and CSB Investigations Supervisor Don Holmstrom Updating the Public on the Investigation of the Nov. 4 Explosion at the Silver Eagle Refinery in Woods Cross, Utah, November 17, 2009."www.csb.gov (accessed August 13, 2012).

U.S. Chemical Safety and Hazard Investigation Board. *Refinery Explosion and Fire*, BP, Texas City, Texas, March 23, 2005. Report No. 2005-04-I-TX. March 2007.

U.S. National Transportation Safety Board (NTSB). *Highly Volatile Release from Underground Storage Cavern and Explosion*, Mapco Natural Gas Liquids, Inc., Nov. 4, 1993. PAR-93-01.

U.S. National Transportation Safety Board (NTSB). *Railroad Accident Report: Hazardous Materials Railroad Accident in the Alton and Southern Gateway Yard in East St. Louis, Ill.*, January 22, 1972. NTSB-RAR-1. 1973.

U.S. Occupational Safety and Health Administration (OSHA). *The Phillips 66 Company Houston Chemical Complex Explosion and Fire: A Report to the President.* April 1990.

APPENDIX A GLOSSARY OF TERMS

Blast: A transient change in the gas density, pressure and velocity of the air surrounding an explosion. A discontinuous change is known as a shock wave. A gradual change is known as a pressure wave.

Deflagration: A propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance rapidly, but at less than sonic velocity in the unreacted material.

Detonation: A propagating chemical reaction of a substance in which the reaction front advances into the unreacted substance at or greater than sonic velocity in the unreacted material.

Explosion: A release of energy that causes a blast.

Flash Fire: The combustion of a flammable gas or vapor and air mixture in which the flame propagates through that mixture in a manner such that negligible or no damaging overpressure is generated.

Ignitable Liquid: Any liquid or liquid mixture that is capable of fueling a fire, including flammable liquids, combustible liquids, inflammable liquids, or any other reference to a liquid that will burn. An ignitable liquid must have a fire point.

Impulse: A measure that can be used to define the ability of a blast wave to do damage. It is calculated by the integration of the pressure-time curve.

Overpressure: Any pressure above atmospheric caused by a blast.

Potential Explosion Site (PES): An open process structure with congestion and confinement that is the location of a vapor cloud release and the epicenter of the blast effects once the cloud is ignited

Turbulence: A random-flow motion of a fluid superimposed on its mean flow.

Vapor cloud explosion: The explosion resulting from the ignition of a cloud of flammable vapor, gas or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressures.

APPENDIX B DOCUMENT REVISION HISTORY

The purpose of this appendix is to capture the changes that were made to this document each time it was published. Please note that section numbers refer specifically to those in the version published on the date shown (i.e., the section numbers are not always the same from version to version).

July 2019. This document has been completely revised. The following major changes were made:

A. The title of the data sheet was changed from *Evaluating Vapor Cloud Explosions Using Flame Acceleration Method* to *Vapor Cloud Explosions*.

B. Reorganized the document to be consistent with other data sheets.

C. Updated recommendations to help reduce the likelihood and consequences of VCE scenarios.

April 2014. Minor editorial changes were done for this revision.

October 2013. A number of items were clarified to reflect field experience using the data sheet.

Natural gas and propane when used as a fuel have been excluded as a VCE material, but still need to be considered when used a chemical process raw material. Pyrophoric fuels (except silane) have been added to the list of excluded materials.

The thresholds for PES size and mass needed to conduct a detailed VCE study have been revised.

October 2012. This document has been completely rewritten to reflect the use of a flame acceleration method (FAM) rather than a TNT equivalency method to predict a VCE. FAM analysis uses the flammable cloud outside the release structure and pressure-impulse analysis, rather than overpressure only, to determine damage.

The only major change in excluded materials is natural gas, which is now recognized as a possible VCE source; however, large amounts are needed and this is reflected in the release amount thresholds given in Section 3.2.6.

Threshold quantities for completing a study have been revised.

January 2012. Terminology related to ignitable liquids has been revised to provide increased clarity and consistency with regard to FM Global's loss prevention recommendations for ignitable liquid hazards.

May 2008. Minor editorial changes were made.

May 2005. Editorial corrections to Table 7B were made.

January 2001. Editorial corrections to Figure 2, Table 1 added to compounds.

September 1998. Minor reformatting and re-issue as Data Sheet 7-42.

January 1998. Editorial corrections were made.

September 1997. Editorial corrections to Table 1 were made.

April 1994. Initial issue as Data Sheet 7-0S and 7-0SC.