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Extended vapor cloud analysis methodology—Part 1

The Buncefield explosion was the worst post World War 2 fire/explosion incident. The fire, which shut down Heathrow and Gatwick airports in the UK, resulted in a regulatory tidal wave for aboveground petroleum storage tanks. Due to HSE vapor cloud explosion studies on petroleum storage tanks by the Fire and Blast Information Group (FABIG), new models have been proposed to understand and quantify whether vapor cloud explosions (VCEs) can occur. The following builds on the vapor cloud analysis (VCA) proposed by the UK Health and Safety Executive (UK HSE) as documented in its Research Report 908 (RR908) and FABIG Technical Note 12 (TN12). Any company that transfers a flammable liquid into a storage tank is vulnerable to the vapor cloud that is generated by a tank overfill. Because the liquid typically pours out from the top of the tank and falls into the secondary containment, the liquid may be contained but the vapor can easily traverse the secondary containment wall and reach an ignition source where either a VCE or a flash fire (deflagration) may result. In either case, it is important to understand and prevent this type of incident.

Although recent gasoline tank overfill VCEs have made the news, much larger volumes of crude oil are shipped throughout the world. Therefore, this article investigates a novel approach to adapt and apply the VCA methodology to crude oil tank overfills.

Typical tank and terminal operations resulting in ground spills and leaks do not generate VCEs. Several prerequisites are required to create a VCE:

- A substantial flow of a volatile and flammable organic liquid, such as gasoline in the form of a spray or mist, that can quickly evaporate; in tank overfills, the energy for creating the spray is caused by fuel spilling from the top of the tank where it can be ejected into a cascade that is a few feet away from the shell—e.g., the flow at the Buncefield fuel depot was 115 kg/s (about 2,400 gpm) when a series of explosions occurred on December 11, 2005.
- A substantial time for the overflow to occur (usually more than 10 min).
- Calm, still air or very low wind conditions.

TABLE 1. Flow rate proxy (bbl/hr)

	Velocity, ft/sec				
Incoming pipe size, NPS	5	8	10	15	20
3	219.4	329.1	438.7	658.1	877.5
4	377.9	566.8	755.8	1,133.7	1,511.5
6	857.9	1,286.8	1,715.8	2,573.7	3,431.5
8	1,484.2	2,226.3	2,968.5	4,452.7	5,936.9
10	2,342.1	3,513.2	4,684.2	7,026.3	9,368.5
12	3,357.3	5,036	6,714.7	10,072	13,429.3
14	4,016.3	6,024.5	8,032.7	12,049	16,065.3
16	5,245.3	7,867.9	10,490.5	15,735.8	20,981.1
18	6,640.4	9,960.7	13,280.9	19,921.3	26,561.8
20	8,252.3	12,378.5	16,504.6	24,757	33,009.3
22	10,538	15,807.1	21,076.1	31,614.1	42,152.1
24	11,933.2	17,899.8	23,866.4	35,799.6	47,732.8
36	28,972.2	43,458.3	57,944.3	86,916.5	115,888.7
42	39,658.6	59,487.9	79,317.3	118,975.9	158,634.5

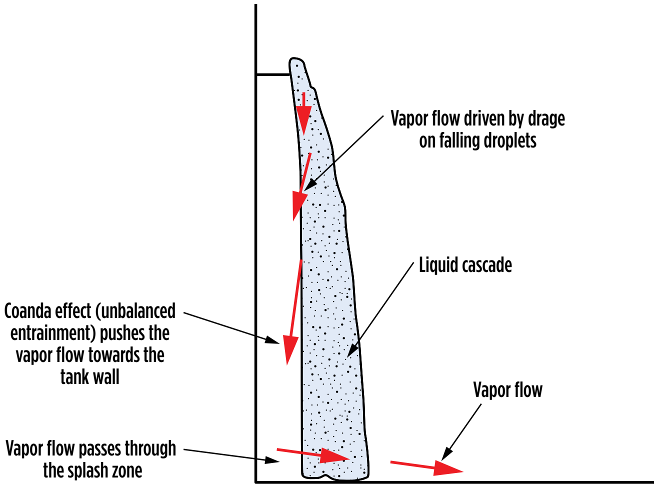

FIG. 1. Basic test setup and results.

TABLE 2. Dilution factors for constrained vapor flows

Barrier height, m	Cloud depth, m	Distance to barrier, m	Dilution factor (conc. in cascade/conc. in cloud)
4	5	30	1.5
2.5	3.6	30	2.1
2	–	5	1.8
2	–	10	2
2	–	15	2

FIG. 2. Fixed-roof tank showing stiffening rings and spill trajectory into a spray cascade.

Flowrate proxy. Whether it is an owner, an operator, a manager or a regulator, understanding tank overfills begins with an estimate of the potential flowrate. Obtaining this information can be surprisingly difficult. If many tanks must be assessed or managed simultaneously, obtaining potential tank overfill flowrates quickly is a must for personnel.

Although tank filling flowrates vary considerably, a reasonable estimate for flow is the incoming pipeline size (**TABLE 1**). Several flow velocities are given that represent the limits of economic line sizes. For general purposes, the authors suggest that estimating flow should be based on the velocity column of 10 ft/sec.

For example, at the Buncefield fuel depot, the fuels arrived at the site in batches through a system of three pipelines: (1) one 10-in.-diameter pipeline from the Lindsey Oil Refinery in Humberside, terminating in the HOSL West site; (2) one UKOP 10-in.-diameter pipeline from the Stanlow refinery in Merseyside, terminating in the BPA North site; and (3) one UKOP 14-in.-diameter pipeline (Thames-Buncefield) from Shell's Haven and Coryton Refinery, terminating in the BPA main site. Based on the limiting velocities and economic line sizing considerations, the use of a 10-in. line would be reasonable to flow fuel at 150 kg/s–240 kg/s through an 8-in. or 10-in. pipeline. The actual overfill at the Buncefield site started at 115 kg/hr, but ramped upward in the last minutes before the VCE.

VCA methodology (FABIG TN12). As background, the following provides a synopsis on the content and material presented in the RR908 and FABIG TN12 documents. After the 2005 Buncefield explosion and fire, a UK HSE-funded research team was assembled to understand how a VCE could initiate due to tank overfill. The basic mechanism of the vapor cloud generation is shown in **FIG. 1.**

The fuel overfill spills from the open top tank or overflow openings. When it hits an obstruction, such as a wind girder or a stiffening ring, the fuel is thrown outward a few feet where a cascade is formed (**FIG. 2**). The cascade entrains air, which becomes nearly saturated with fuel vapor near the ground. The splashing of liquid on the ground further increases the saturation levels to a final level of at least 90%, given an adiabatic assumption, where the only heat input is from the entrained air. The adiabatic assumption is fair, given no wind conditions.

The latest technical work leading to the VCA method is given in the RR908 document, where a remarkable amount of testing was done. This testing included careful measurement of the temperature of the falling fuel, the entrained air and the vapor streams near and leaving the cascade.

Tests were developed to simulate the cascading fuel. The details of the experimental setup are given in RR908. The inference on evaporation was largely supported by a system of thermocouples that measured the temperature changes of the liquid and vapor in and around the cascade. From these measurements, reasonably accurate estimates of vaporization were constructed.

Computation fluid dynamics (CFD) analysis methods were used to support this work and describe how large vapor clouds can be formed. The bunds, or secondary containment walls, were found to redirect vapor flow back to the cascade and to inhibit large amounts of fresh air from being drawn into the cascade, allowing high-concentration vapors to build within the bunded areas.

If the duration of the overfill cascade is sufficiently long (Buncefield was 23.3 min), then it serves as a vapor generation source, and the heavy vapor cloud can slump by gravity flowing outward. In the case of a flat terrain, as was the case at all three overfills mentioned in the introduction, the "pancake cloud" flows outward, seeking an ignition source.

VCA method's key input parameters. The key input parameters for the VCA method include the following:

- **Air entrainment into the cascade of falling liquid.** The air entrainment is primarily sensitive to the cross-sectional area of the cascade. However, this depends on how the flow of fuel overtops the tank and over what distance. Since tanks are never exactly flat at the top, the cross-sectional area of the overfill cascade is uncertain, but its general effect can be examined by simulation. The VCA method assumes that 30% of the circumference forms the cascade. Other variables affecting the vaporization are liquid surface tension, liquid mass flow and height of free fall for the cascade.
- **Fuel vapor concentration at the foot of the cascade.** The VCA method assumes that the vaporization is enough to bring the air fuel mixture at the foot of the tank to about 70% of thermal equilibrium. This was demonstrated by measuring the concentration of hexane vapor in a replicated cascade.
- **Additional vaporization from fine splash products.** Additional vaporization occurs when the cascade hits the ground and splashes, creating a further push toward vapor equilibrium. The air-vapor mixture is essentially at thermal equilibrium and is saturated with fuel. The main variables controlling the equilibrium conditions are the fuel-air ratio created by the cascade, the fuel temperature and the ambient air temperature. The VCA method suggests that hydrocarbon mixtures, such as crude oil, the only fraction evaporating in the splash zone, are C_8 (octane) and lighter. The mass evaporated is experimentally determined, but the VCA method suggests using 0.02 × F × (fraction less than or equal to C_8), where F is the mass fuel flowrate.
- **Near-field (within bund) dilution.** The movement of the vapors within the bunded areas causes dilution. The VCA method chooses a value of 2 for the ratio of the concentration in the cascade to that in the outflowing vapor cloud. This is reasonable, since most bunds are 5 ft or 6 ft in height. The report results are listed in **TABLE 2.**
- **Volume flowrate and concentration of the cloud leaving the bund.** The mass of the vapor cloud is calculated as: Mcloud = 2 (Mair + Mvaporized + Msplash). The volume of the cloud is assumed to be that of ambient air, even though warming from the ground and heat transfer from the vapor cloud will change the volume slightly.
- **Idealized hazard ranges for clouds spreading in "zero" wind speed conditions.** Despite the many assumptions made for a well-mixed cloud at the lower flammable limit (LFL), the model still fits the data. The method assumes that the terrain is flat and that the vapor flows out over the secondary containment as a disk that is 2-m (6.5-ft) thick. This assumption, while not very accurate, was, in part, validated by the video recordings made at Buncefield and elsewhere.
- **Extended VCA methodology for crude oil tank overfilling.** The VCA method was originally published in RR908. However, in the RR908 document, the method was only applicable to a specific grade of gasoline and was unsuitable for any other determination. With the publication of FABIG TN12, the VCA method was extended to those compounds shown in **TABLE 3. Note:** The only crude oil shown is for Brent. However, most of the world's tanks are filled with other types of crude oil containing other properties. FABIG TN12 is not transparent with respect to the parameters required for the VCA. As shown in **TABLE 3,** the correction factor contains four fitted parameters (α, β, γ and δ) that are not functions of thermodynamic properties that are readily computed. Therefore, the authors have developed a simplified approximate method to extend the VCA to any crude oil, which will be the focus of Part 2.

TABLE 3. Concentration at the foot of the tank and Greek constants for various FABIG TN12 fuels

	C^{θ}_{fuel}	α	β	γ	δ
Hexane	14.24	0.946	−0.225	0.0133	0.0212
Acetone	12.21	0.941	−0.262	0.0128	0.0192
Ethyl acetone	9.89	0.957	−0.181	0.0177	0.0242
Benzene	9.29	0.959	−0.176	0.0182	0.0222
Methyl ethyl ketone	8.71	0.955	−0.182	0.0163	0.0255
Toluene	4.7	0.981	−0.061	0.025	0.03
Methanol	4.53	0.95	−0.215	0.0167	0.0287
Ethanol	3.63	0.967	−0.133	0.0212	0.0345
Naphtha	20.3	0.928	−0.312	0.0093	0.0142
Winter-grade gasoline	17.25	0.888	−0.454	0.0074	0.0131
Raw gasoline	11.43	0.936	−0.264	0.0137	0.0179
F3 condensate	11.43	0.936	−0.264	0.0137	0.0179
Brent	6.88	0.876	−0.511	0.0088	0.0136
Reformate	5.29	0.967	−0.114	0.021	0.0295
Heavy reformate	5.29	0.967	−0.114	0.021	0.0295

Part 2 of this article will be featured in the January 2019 issue. HP

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BROCK TROTTER has coauthored publications for Endress+Hauser and Emerson regarding tank level equipment and overfill prevention. He has also performed engineering analysis for an expert witness regarding petroleum overfills and has authored a paper regarding API 2350, "Overfill Protection for Storage Tanks in Petroleum Facilities."