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Storage Tank Overfill Vapor Cloud Explosions – Science, Causes, and Prevention

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Abstract

The 2009 Puerto Rico incident reminds us that few events are as devastating as a vapor cloud explosion initiated by a tank overfill. 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 find an ignition sources where either a vapor cloud explosion or a flash fire (deflagration) that may result. In either case, it is important to understand and prevent this type of incident.

Although recent gasoline tank overfill vapor cloud explosions (VCEs) have made the news, much larger crude oil volumes are shipped throughout the world. Therefore, it seems reasonable to investigate how the VCA methodology can be applied to crude oil tank overfills.

In this paper we build on the Vapor Cloud Analysis (VCA) proposed by the UK Health Safety Executive as documented in Research Report 908 and the FABIG Technical Note 12. We summarize the latest results but we extend the method so that it is applicable to crude oil tank overfills. In addition, we show how to positively eliminate the potential for these incidents without large investments or complex systems.

Tracing the History of Tank Overfill VCEs

Serious petroleum tank overfilling incidents occur at a rate of occurrence that seems to be random as seen in Figure 1.

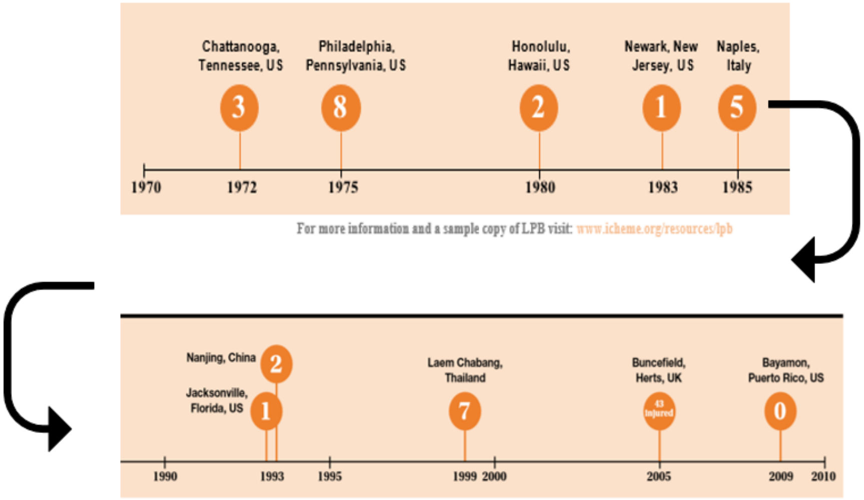


Figure 1 Past Landmark Overfill Cases and Fatalities (Number in circle is fatalities)

We have good data on Buncefield and Capeco which both resulted in a VCE as these were the most recent incidents. Further back in time is the NFPA 30 handbook description of the Texaco 1982 tank overfill VCE.

Several serious gasoline tank overfill VCE events are:

1. Texaco 1982
2. Buncefield 2005
3. Capeco 2009

In each of these events the vapor cloud extended far outside of the property and terminal plot limits.

However, it is the Buncefield incident that produced the most research and knowledge about the mechanism of vapor cloud generation and explosions from fuel tank overfilling.

Overview of Conditions for VCE

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

1. 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 the spilling of fuel from the top of the tank where it can be ejected into a cascade that is a few feet away from the shell. The flow at the Buncefield terminals was 115 kg/s (about 2400 gpm).
2. A substantial time period for the overflow to occur (usually 10 or more minutes)

3. Calm still air or very low wind condition

Flow Rate Proxy

Whether an owner, an operator, or a regulator, wants to assess and control risks over tank overfills the activity must start with an estimate of the potential flow rate into the tank. Getting this information can be surprisingly difficult. If large numbers of tank must be assessed or managed at one time there is a need for a quick way to estimate the tank overfilling flow rates.

Although tank filling flow rates vary considerably a reasonable proxy for flow is the incoming pipeline size. This proxy works because pipe size becomes inefficient if too small or too large. For example, no one would install a 24 inch line to feed 10 gpm into a tank. On the other hand, trying to force too much liquid too fast results in high vibration and pumping power. Most tank filling lines will operating at around 8 to 10 feet per second. We can therefore estimate what a typical flow rate might be simply by using the incoming pipeline size as a proxy for flow. Tables 1 and 2 show the flow rates in bbl/hr and kg/s respectively. Several flow velocities are given that represent the limits of economic line sizes. For general purposes we suggest that estimating flow should be based on the velocity column of 10 feet per second.

Table 1	Flow Rate US BBL per Hour				
	Velocity, feet per second				
Nom Pipe Size	5	8	10	15	20
3	219.4	329.1	438.7	658.1	877.5
4	377.9	566.8	755.8	1133.7	1511.5
6	857.9	1286.8	1715.8	2573.7	3431.5
8	1484.2	2226.3	2968.5	4452.7	5936.9
10	2342.1	3513.2	4684.2	7026.3	9368.5
12	3357.3	5036.0	6714.7	10072.0	13429.3
14	4016.3	6024.5	8032.7	12049.0	16065.3
16	5245.3	7867.9	10490.5	15735.8	20981.1
18	6640.4	9960.7	13280.9	19921.3	26561.8
20	8252.3	12378.5	16504.6	24757.0	33009.3
22	10538.0	15807.1	21076.1	31614.1	42152.1
24	11933.2	17899.8	23866.4	35799.6	47732.8
36	28972.2	43458.3	57944.3	86916.5	115888.7
42	39658.6	59487.9	79317.3	118975.9	158634.5

Table 2	Flow Rate Kg/s				
	Velocity, feet per second				
Nom Pipe Size	5	8	10	15	20
3	11.2	16.8	22.4	33.6	44.8
4	19.3	29.0	38.6	57.9	77.2
6	43.8	65.7	87.7	131.5	175.3
8	75.8	113.8	151.7	227.5	303.3
10	119.7	179.5	239.3	359.0	478.7
12	171.5	257.3	343.1	514.6	686.1
14	205.2	307.8	410.4	615.6	820.8
16	268.0	402.0	536.0	804.0	1072.0
18	339.3	508.9	678.6	1017.8	1357.1
20	421.6	632.5	843.3	1264.9	1686.5
22	538.4	807.6	1076.8	1615.3	2153.7
24	609.7	914.6	1219.4	1829.1	2438.8
36	1480.3	2220.4	2960.5	4440.8	5921.1
42	2026.3	3039.4	4052.5	6078.8	8105.1

As an example, at Buncefield the fuels arrived at the sites in batches through a system of three pipelines, namely: (a) one 10" diameter pipeline from Lindsey Oil Refinery, Humberside, terminating in the HOSL West site, (b) one UKOP 10" diameter pipeline from Stanlow refinery, Merseyside terminating in the BPA North site, and (c) one UKOP 14" diameter pipeline ('Thames-Buncefield') from Shell 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 inch line would be reasonable to flow fuel at 150 to 240 kg/s through an 8 or 10 inch pipeline. In fact, the actual overfill at Buncefield started at 115 kg/hr but ramped upward in the last minutes before the VCE.

Vapor Cloud Analysis Methodology (FABIC TN12)

As background we briefly review the content and material presented in HSE RR908 and FABIG TN12. After the 2005 incident involving the Buncefield incident the HSE funded research to understand how a VCE could initiate as a result of a tank overfill.

The basic mechanism of vapor cloud generation shown in Figure 2.

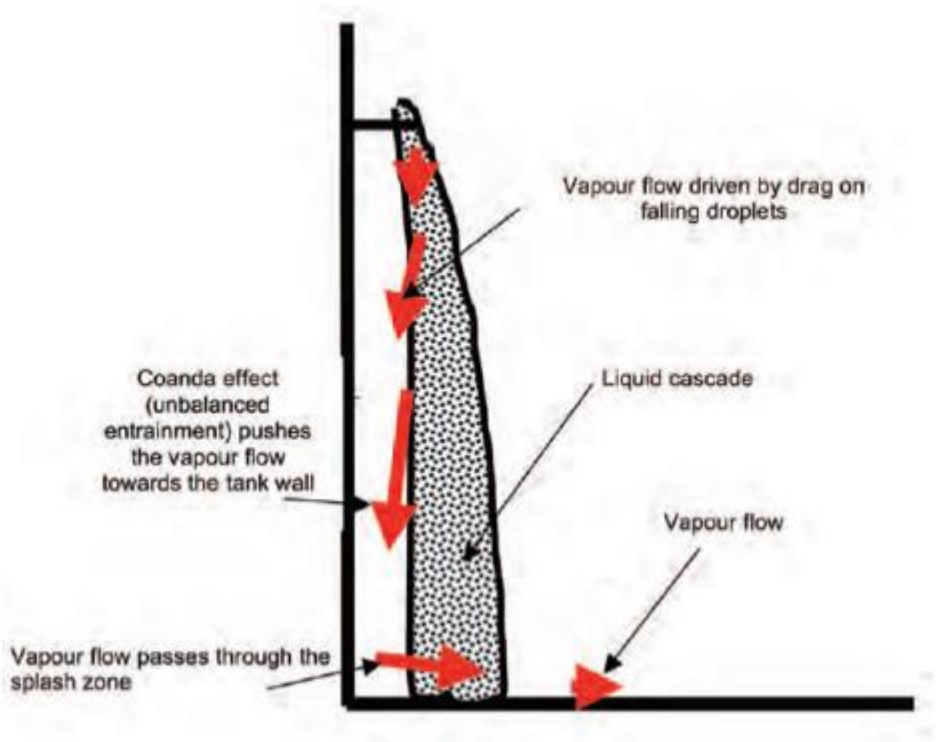


Figure 2 Basic Test Set Up and Results Establishing Vapor Cloud Generation Mechanism

The fuel overfills from an open top tank or another type of tank. When it hits and obstruction such as a wind girder or stiffening ring (see Figure 3) the fuel is thrown outward a few feet where a cascade is formed. The cascade entrains air which becomes almost 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 latest technical work leading to the VCA method is given in the HSE RR908 document where a remarkable and careful measurement and testing of the temperature of the falling fuel, the entrained air, and the vapor streams near and leaving the cascade showed how much fuel could evaporate (see Figure 5).

A typical wind girder is shown in Figure 3. The overflow impinges on the windgirder and is thrown outward as a free fall cascade, the essential requirement to develop the large vapor cloud.

Figure 3 Overflow will impinge on wind girder and form a liquid cascade falling to the ground

A fixed roof tank can generate a vapor cloud as well since there are often stiffening rings as shown in Figure 4.

Figure 4 Fixed Roof Tank Showing Stiffening Rings and Spill Trajectory Into a Spray Cascade

Tests were set up to simulate the cascading fuel as shown in Figure 5.

Figure 5 RR908 Testing and Modeling Development

The details of the experimental set up are given in RR 908. The inference on evaporation was largely supported by systems of thermocouples which measured the temperature changes of the liquid and vapor in and around the cascade. From these measurements reasonably accurate estimates of vaporization were made.

Computation Fluid Dynamics (CFD) analysis methods were used to support this work and aimed to 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 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 minutes) then it serves as a vapor generation source and the heavy vapor cloud in can slump by gravity flowing outward. In the case of a flat terrain as was the case at all 3 overfills mentioned in the introduction the “pancake cloud” flows outward waiting until an ignition source is found.

The Vapor Cloud Analysis (VCA) Method

In both RR908 and FABIG TN12 the basic methodology of computing the size of a vapor cloud that can be generated from a tank overfilling event given the assumptions we provided. The method is outlined next along with problems with its use for general application to crude oil.

Air entrainment into the cascade of falling liquid

The air entrainment is primarily sensitive to the cross section area of the cascade. However, this in turn depend on exactly how the flow of fuel overtops the tank and over what distance. Since tank are never exactly flat at the top this unknown variable is uncertain but its general effect can be examined by simulation. The VCA method assumes that 30 percent of the circumference forms the cascade. This is going to require a fairly high flow rate and is specific to how level the top of the tank is. So this assumption is probably the one that generates the largest uncertainty in the VCA method. Other variables affecting the vaporization are liquid surface tension, liquid mass flow, and height of free fall for the cascade.

Fuel-Air Concentration

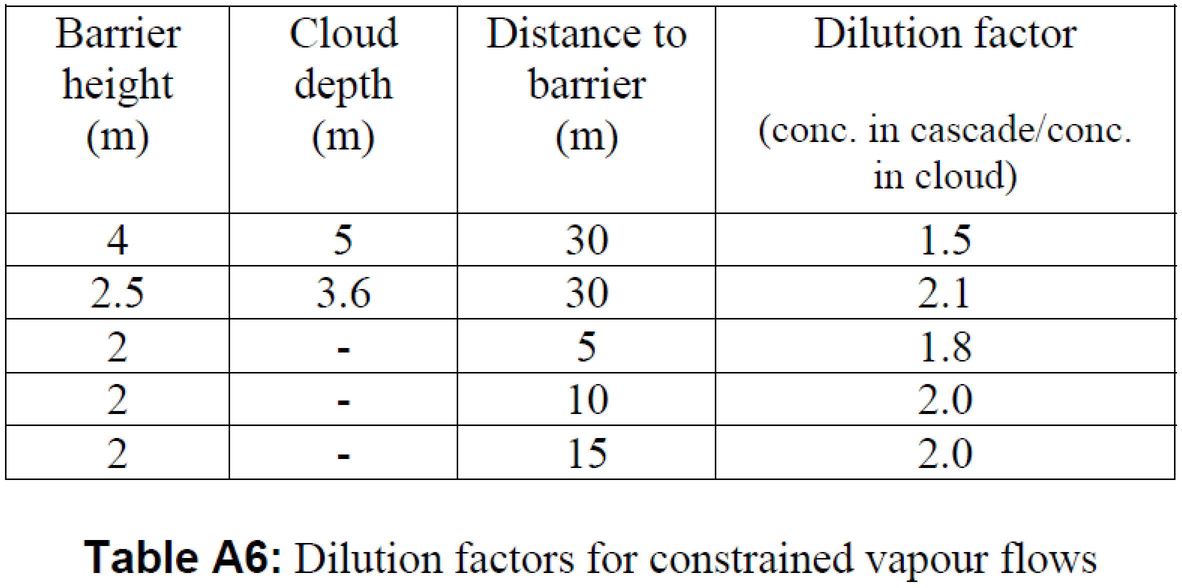
The method assumes that the vaporization is sufficient to bring the air fuel mixture at the foot of the tank to about 70% of thermal equilibrium. This was demonstrated by the testing of hexane.

Saturation Achieved From Splash Zone

Additional vaporization occurs when the cascade hits the ground and splashes creating a further reach toward equilibrium. The air-vapor mixture flows outward away from the tank and is essentially at thermal equilibrium and saturated with fuel. The main variables controlling the equilibrium conditions are fuel-air ratio created by the cascade, the fuel temperature and the ambient air temperature. The VCA method suggests that for hydrocarbon mixtures such as crude oil that the only fraction evaporating in the splash zone are C8 and lighter. The mass evaporated is experimentally determined but the VCA method suggests using 0.02F where F is the mass fuel flow rate.

Near-field (within bund) dilution

The movement of the vapors within and away from the bunded areas as the vapor cloud thickens and flows radially away from the tank causes some dilution. The VCA method chooses a dilution factor of 2 for the ratio of the concentration in the cascade to that in the outflowing vapor cloud. The basis for the dilution factor is given by Figure 6 and since most bunds are 5 or 6 feet in height the dilution factor of 2 seems reasonable.



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	2.0
2	-	15	2.0

Table A6: Dilution factors for constrained vapour flows

Figure 6 RR908 Dilution Factors

Volume flow rate and concentration of the cloud leaving the bund

The mass of the vapor cloud is then simply 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.

Even though many assumptions are made the assumption of a well-mixed cloud at the lower flammable limit (LFL) reasonably fit 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 meters thick. This assumption while not very accurate was in part validated by the video recording 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 unsuitable for any other determination. With the publication of FABIC TN12 the VCA method was extended to those compounds in Table 3.6 (Figure 7).

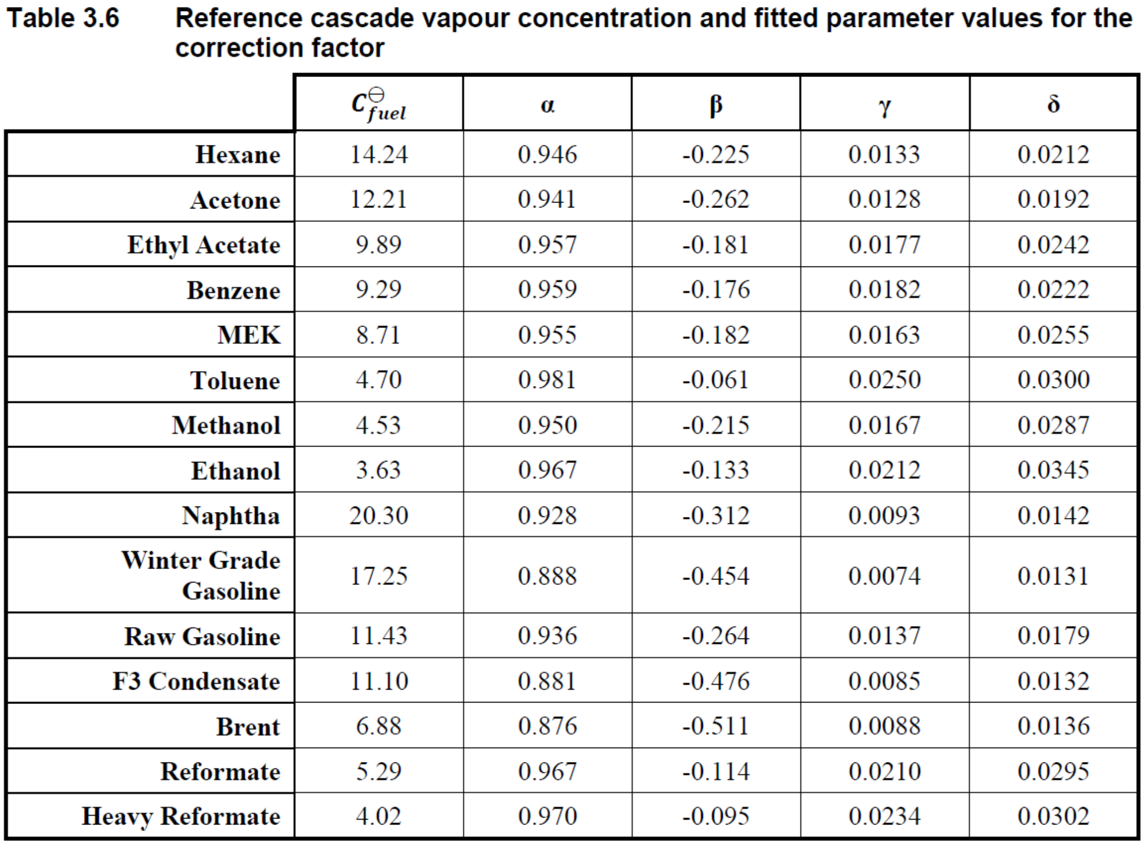


Table 3.6 Reference cascade vapour concentration and fitted parameter values for the correction factor

	$C^{\ominus}_{fuel}$	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 Acetate	9.89	0.957	-0.181	0.0177	0.0242
Benzene	9.29	0.959	-0.176	0.0182	0.0222
MEK	8.71	0.955	-0.182	0.0163	0.0255
Toluene	4.70	0.981	-0.061	0.0250	0.0300
Methanol	4.53	0.950	-0.215	0.0167	0.0287
Ethanol	3.63	0.967	-0.133	0.0212	0.0345
Naphtha	20.30	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	11.10	0.881	-0.476	0.0085	0.0132
Brent	6.88	0.876	-0.511	0.0088	0.0136
Reformate	5.29	0.967	-0.114	0.0210	0.0295
Heavy Reformate	4.02	0.970	-0.095	0.0234	0.0302

Figure 7 Extended List of Fuels for VCA Method

Note that the only crude oil shown is for Brent. But most of the worlds tank are filled with other types of crude oil with other properties. TN12 is not transparent with respect to the parameters required for the VCA and as given in Table 3.6 stating only "the correction factor contains four fitted parameters (α, β, γ and δ)" which are not simply functions of thermodynamic properties that are readily computed from equilibrium. Therefore, we have developed a simplified approximate method to extend the VCA to any crude oil which is described now.

Estimating VCEs from Tank Crude Oil Overfills

The industry lacks a simple and effective method for calculating the radius of ignition (R_{ign}) and minimum distance to evacuate personnel (R_{esc}) in event of an overfill involving crude oil. Therefore, our goal was to develop a method to calculate the radius of ignition for a wide variety of overfill events and parameters. These parameters include the ambient temperature (T_{amb}), the fuel temperature (T_{fuel}), the height of the tank (H), the diameter of the tank (D), the mass flow rate of overfill event ($\dot{M}$), the time length of the overfill event (t), and, most uniquely, the type of fuel being overfilled. The following calculations make some critical assumptions including: no wind, disk shaped vapor cloud, and the lower explosive limit is based upon hexane.

We examined crude oil data provided by NEB Canadian Statistics. This data source was selected because it supplies the volume fraction of many of the vapor contributing components within crude oil. Further, the information is provided at no cost to the public.

Establish Overflow Event Parameters

A sample of the data is shown next.

General Information					
Crude Name	**Acronym**	**Date**	**Batch #**	**Gravity (deg. API)**	**Location**
Mixed Sweet Blend	MSW	2017-08-06	MSW-814	42.3	Edmonton

Take for example, the following event parameters:

$$D = 75\ m$$

$$H = 25\ m$$

$$\dot{M}_{fuel} = 800\ kg/s$$

$$T_{amb} = 20°C$$

$$T_{fuel} = 14°C$$

$$t = 1400\ s$$

Convert from Volume or Mass Fraction to Molar Fraction

Data from the NEB Canadian Statistics is given in a volume fraction. This is the most common method of displaying crude components fractions.

C3- (vol%)	Butane (vol%)	Pentane (vol%)	Hexane (vol%)	Heptane (vol%)	Octane (vol%)	Nonane (vol%)
0.34	4.37	5.08	7.05	7.3	5.67	4.06

Decane (vol%)	Benzene (vol%)	Toluene (vol%)	Ethylbenzene (vol%)	Xylenes (vol%)	(vol%) unaccounted	Total vol%
2.64	0.26	0.92	0.18	1.24	60.9	100

The lighter components will be the majority of what evaporates into the air when crude is being overfilled. This occurs because the lighter components have a higher vapor pressure than heavier components. We assume idealized equilibrium laws on the vapor phase and liquid phases behavior. We then convert the volume fraction data supplied above into molar fraction.

The following molar densities (mol/L) are provided from *Perry's Chemical Engineering Handbook* and assumes standard temperature and pressure conditions.

C3	Butane	Pentane	Hexane	Heptane	Octane	Nonane
0.04228	0.04294	8.6731	7.6514	6.8244	6.1481	5.5985

Decane	Benzene	Toluene	Ethylbenzene	Xylenes	unaccounted components
5.1336	11.252	9.4086	8.46774	7.620966	5.00000

Notice the “unaccounted components” cell above. For crude oil, the entire molar composition is usually unknown. Therefore, it is necessary to bulk unknown components together into an unaccounted component group. A value is selected with properties like the heavier ends in crdue. The molar density for unaccounted components will vary for every crude oil, but the value of 5.000 optimizes the results for a wide variety of crude oils for the vapor pressure trend, as shown in Figure 8.

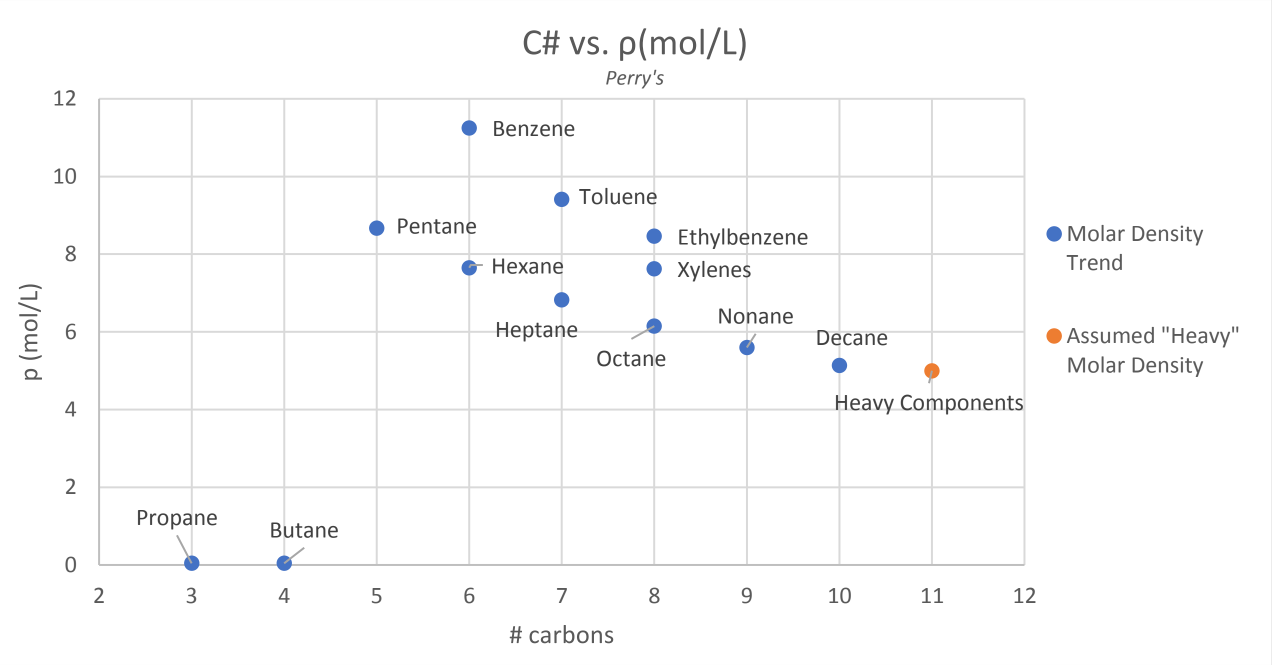


Figure 8 Carbon Number vs. Molar Density of Hydrocarbons

Hexane example for 1 L of sample:

$$mol_{hexane} = (100\,L)(7.05\,vol\,\%)\left(7.7514\frac{mol}{L}\right) = 53.942\,mol$$

$$mol_{total} = \Sigma mol_i$$

$$mol_{total} = 546.17\,mol$$

$$mol_i\,\% = \frac{mol_i}{mol_{total}} = \frac{53.942}{546.17} = 9.9\,mol_{hexane}\,\%$$

In application, we must apply the method above to each component. This process yields the following values for molar composition of the crude sample.

	Parafins							
Crude Sample	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
MSW-814	0.002632	0.034357	8.066969	9.876483	9.121361	6.38258	4.161693	2.481408

Aromatics				**Other**
C6	**C7**	**C8**	**Xylenes**	**Heavy Components**
0.535643	1.584839	0.279069	1.730231	55.74273533

Pure Component Vapor Pressure Calculation

To find the total vapor pressure of the crude oil, we must calculate the pure vapor pressure at our ambient temperature ($T_{amb} = 20°C$). The P(Vap) of pure substances is achieved by the following equation and information from Perry's Chemical Engineering Handbook, 8th ed..

$$\ln\left(P_{vap\,pure}\right) = C1 + \frac{C2}{T} + C3 \cdot \ln(T) + C4 \cdot T^{C5}, \qquad P_{vap\,pure} = [Pa]$$

Results at $T_{amb} = 20°C$:

T(K)	*293*	C1	C2	C3	C4	C5	**Pvap (Pa)**
Parafins	C3	59.078	-3,492.60	-6.0669	1.09E-05	2	834184.2
	C4	66.343	-4,363.20	-7.046	9.45E-06	2	206981.9
	C5	78.741	-5,420.30	-8.8253	9.62E-06	2	56278.83
	C6	104.65	-6,995.50	-12.702	1.24E-05	2	16121.63
	C7	87.829	-6,996.40	-9.8802	7.21E-06	2	4666.773
	C8	96.084	-7,900.20	-11.003	7.18E-06	2	1391.773
	C9	109.35	-9,030.40	-12.882	7.85E-06	2	416.4769
	C10	112.73	-9,749.60	-13.245	7.13E-06	2	125.5671
Aromatics	C6	83.107	-6,486.20	-9.2194	6.98E-06	2	9913.166
	C7	76.945	-6,729.80	-8.179	5.3E-06	2	2902.748
	C8	89.063	-7,733.70	-9.917	5.99E-06	2	945.5245
	C9	91.379	-8,276.80	-10.176	5.62E-06	2	334.2583
Naphthenes	C5	66.341	-5,198.50	-6.8103	6.19E-06	2	34429.28
	C6	51.087	-5,226.40	-4.2278	9.76E-18	6	10311.3

We can ignore the vapor pressure contributions of components with more carbons than C8 (octane). These heavier components can be ignored because their vapor pressures are very low relative to the light components of crude oil such as propane and butane. Unknown heavy components contribute negligible vapor pressure, therefore simplifying the model without losing much accuracy.

With pure vapor pressure data and molar composition of a crude oil, we can calculate an idealized total vapor pressure using Raoult's Law.

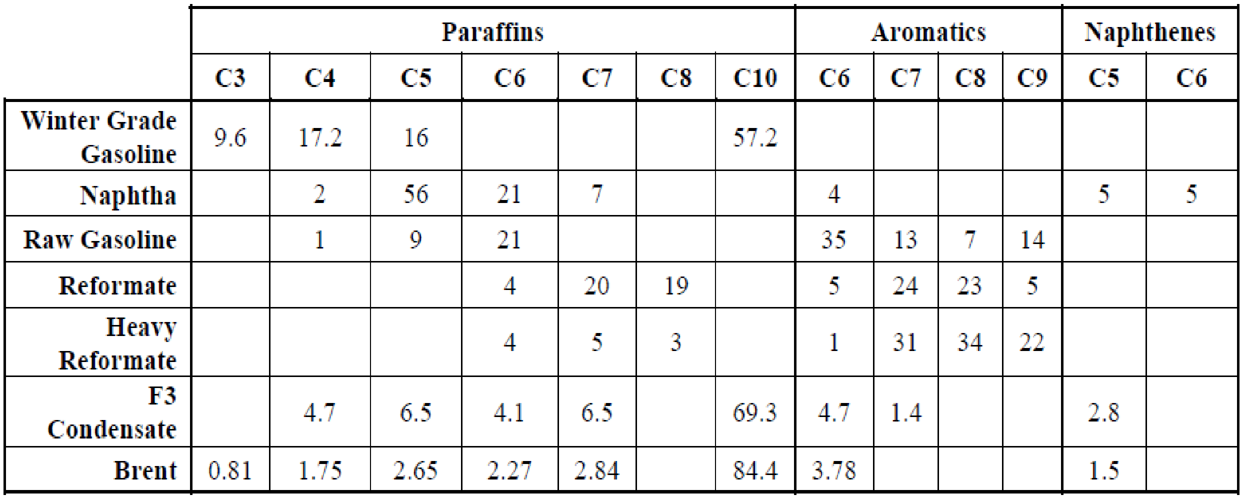
$$P_{vap\ total} = \Sigma P_{i\ vap}$$

$$P_{i\ vap} = P_i^* \cdot x_i.$$

The MSW-814 crude oil sample yields a $P_{vap\ total} = 6816\ Pa$. The total vapor pressure of the components is crucial to calculating the R_{ign} and R_{esc}.

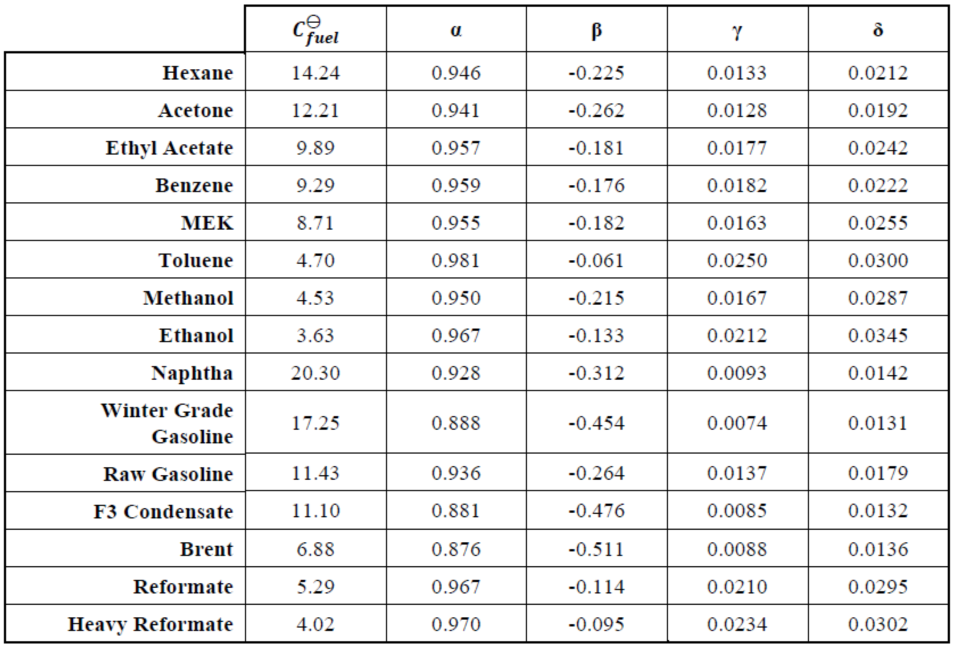
Vapor Pressure and Cθ Correlation

To calculate the R_{ign} and R_{esc}., we need a concentration of vapor at the base of the storage tank. The concentration at the foot of the tank can be determined using a linear regression for of the $\ln(P_{vap\ total})$ vs. Cθ from the FABIG TN12 documents.



	Paraffins							Aromatics				Naphthenes	
	C3	**C4**	**C5**	**C6**	**C7**	**C8**	**C10**	**C6**	**C7**	**C8**	**C9**	**C5**	**C6**
Winter Grade Gasoline	9.6	17.2	16				57.2						
Naphtha		2	56	21	7			4				5	5
Raw Gasoline		1	9	21				35	13	7	14		
Reformate				4	20	19		5	24	23	5		
Heavy Reformate				4	5	3		1	31	34	22		
F3 Condensate		4.7	6.5	4.1	6.5		69.3	4.7	1.4			2.8	
Brent	0.81	1.75	2.65	2.27	2.84		84.4	3.78				1.5	

Figure 9 Molar Compositions from FABIG TN12 Samples



	$C^{\ominus}_{fuel}$	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 Acetate	9.89	0.957	-0.181	0.0177	0.0242
Benzene	9.29	0.959	-0.176	0.0182	0.0222
MEK	8.71	0.955	-0.182	0.0163	0.0255
Toluene	4.70	0.981	-0.061	0.0250	0.0300
Methanol	4.53	0.950	-0.215	0.0167	0.0287
Ethanol	3.63	0.967	-0.133	0.0212	0.0345
Naphtha	20.30	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	11.10	0.881	-0.476	0.0085	0.0132
Brent	6.88	0.876	-0.511	0.0088	0.0136
Reformate	5.29	0.967	-0.114	0.0210	0.0295
Heavy Reformate	4.02	0.970	-0.095	0.0234	0.0302

Figure 10 C(Theta) and Correction Factors for FABIG TN12 Samples

The trend relates the natural logarithm of the total vapor pressure to the concentration at the foot of the tank as follows:

$$C\Theta = 3.3073 \cdot \ln\left(P_{vap\ total}\right) - 21.696$$

This trend is determined by a least squares regression fit of the data supplied by the FABIG TN12 document, as shown by the blue data and trendline in Figure 11. The trend yields a strong fit with an $R^2 = 0.9097$.

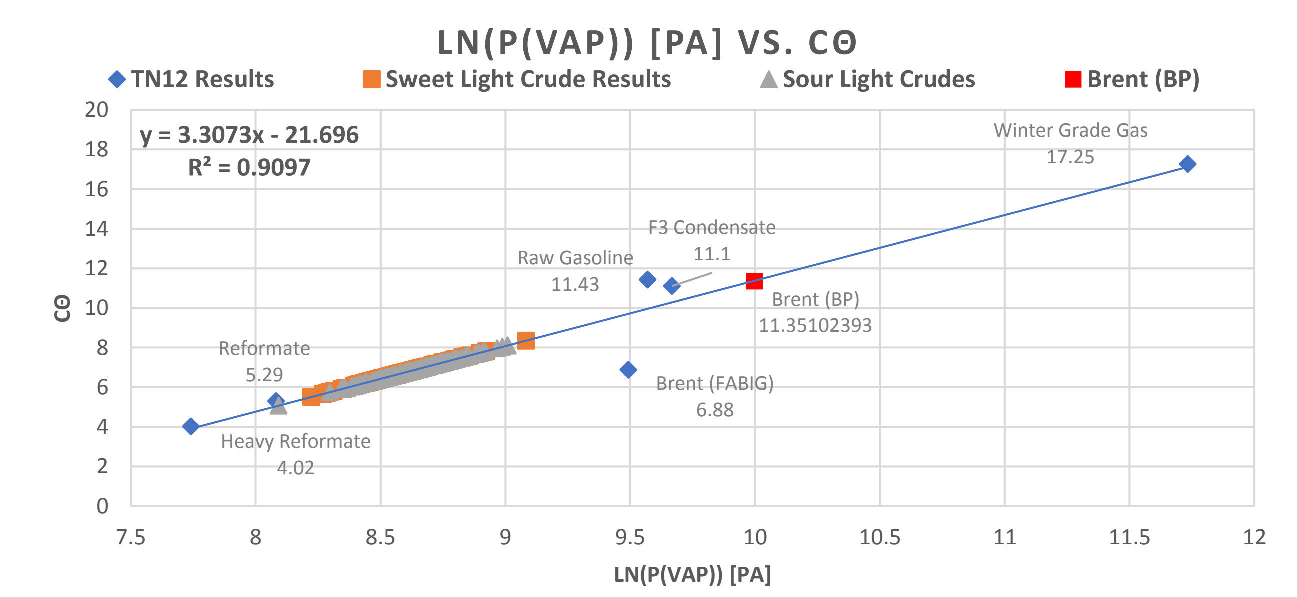


Figure 11 FABIG TN 12 Linear Regression and Crude Results

The difference in the two values for Brent crude is explained by the different molar fractions of each sample.

	Parafins							
**composition chart FABIG TN12 & BP*	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
Brent (FABIG TN12)	0.81	1.75	2.65	2.27	2.84	0	0	84.4
Brent (BP)	1.433409	3.41828	3.692294	3.26147027	0	0	0	0

Using the total vapor pressure from components

$$C\theta = 3.3073 \cdot \ln(6816\,Pa) - 21.696 = 7.4976\,kg/m^3$$

Correction Factor

The value of Cθ must then be multiplied by a correction factor (F). The value of this correction factor has an average of 0.07834679 ($\bar{x} = 0.07834679$) and standard deviation of 0.336811 ($\sigma_{\bar{x}} = 0.336811$). These values are only appropriate under the following conditions: T_{amb} : -20°C to 30°C, T_{fuel} : -20°C to 30°C, $\frac{M_{air}}{M_{fuel}}$: 0.3 to 3. The FABIG TN states, “over these ranges the corrections factor (F) has an average accuracy of $\pm 2\%$ with large deviations of up to 15%.”

	α	**β**	**γ**	**δ**
x	0.91967	-0.319	0.0138	0.01958
σ	0.04346	0.18706	0.0069	0.00815

$$F = \alpha\left(\frac{M_{air}}{M_{fuel}}\right)^{\beta} \exp\left(\gamma(T_{air} - 10)\right) \exp\left(\delta\left(T_{fuel} - 10\right)\right)$$

$$C_{foot} = C\theta \cdot F$$

For the example scenario: $T_{amb} = 20°C, T_{fuel} = 14°C, Greek\ variables = \bar{x}$

$$F = 1.3237$$

Remaining Steps in Calculating the Radius of Ignition and Escape

$$\therefore C_{foot} = C\theta \cdot F = 7.4976 \cdot 1.323759 = 9.9251\,kg/m^3$$

This is the concentration value needed to continue the process of calculating the R_{ign} and R_{esc}.

$$M_{air} = 90\left(\frac{D}{25m}\right)^{0.75}\left(\frac{H}{10m}\right)^{0.45}\left(\frac{M_{fuel}}{\frac{115kg}{s}}\right)^{0.25}$$

$$\therefore M_{air} = 503.2\,kg/s$$

It is now necessary to consider the mass of fuel vaporized and splashed. Vaporized fuel is based on the concentration on the foot of the tank and M_{air} as so:

$$M_{vap} = M_{air} \cdot (\frac{C_{foot}}{100 - C_{foot}})$$

$$\therefore M_{vap} = 55.45\ kg/s$$

Only components that are C8 and below will contribute to M_{splash}. To calculate this component fraction, just add the component fractions that are C8 and below.

$$M_{splash} = 0.02 \cdot M_{fuel} \cdot x_{\leq C8}$$

$$\therefore M_{splash} = 574.14\ kg/s$$

Now that we have calculated the mass contributions by air, vaporized fuel, and fine droplet splash we may calculate the total mass of the vapor cloud.

$$M_{cloud} = 2(M_{splash} + M_{vap} + M_{air})$$

$$M_{cloud} = 2265.6\ kg/s$$

The density of air at the ambient conditions, $\rho_{air} = 1.3015\ kg/m^3$, is then used to determine the volume of the vapor cloud.

$$V_{cloud} = \frac{M_{cloud}}{\rho_{air}} = 1740.8\ m^3$$

Using the mass of explosive components and volume of the cloud, we may calculate the concentration of explosive vapor in the cloud.

$$C_{cloud} = \frac{M_{splash} + M_{vap}}{V_{cloud}} = 0.3617\ kg/m^3$$

All values used to calculate R_{ign} and R_{esc} are now calculated.

$$R_{ign} = (\frac{1}{\pi} \cdot V_{cloud} \cdot t)^{1/2}$$

$$R_{esc} = (\frac{1}{2\pi} \cdot V_{cloud} \cdot t)^{1/2}$$

$$R_{ign} = 880.8\ m$$

$$R_{esc} = 622.8\ m$$

The overall process requires first defining the components within the fuel system and the other parameters. Then determine the vapor pressure due to the contributing components. This vapor pressure is used with the linear regression from the FABIG TN12 data to obtain the Cθ value. Cθ is then corrected by the correction factor (F) to obtain C_{foot}. Calculate the M_{air}, M_{splash}, and M_{vap} to get M_{cloud}. Use the M_{cloud} to obtain the V_{cloud}. Then determine the $C_{cloud}, R_{ign}, and\ R_{esc}$ from V_{cloud}.

We provide spreadsheets and detailed calculations[1] on our website that allows the user to determine the size of a crude oil VCE generated.

Eliminating the Potential for a VCE

It is surprising that we found no references as to how to positively eliminate the large vapor cloud from forming. In the past many tanks were constructed with an "overflow pipe" which directed an overflow to the ground. While this has typically been done for reasons unrelated to vapor cloud formation it was applied to smaller tanks only. This idea has not been used on large tanks above 50 meters that we are aware of. The problem with applying this idea to tanks constructed to a standard is that the standards do not anticipate a design aimed at mitigation of potential overfill vapor cloud events.

There are several ways to completely eliminate the potential for any fuel tank overfilling process. They are all based on the idea of not dropping the liquid from height and forming the fuel cascade. L

Method 1

In method 1 a safety instrumented system would open a valve on the side of the tank and trigger to dump the overflow to a contained area either inside the bund area, to another tank, or to a sump area. In spite of the fact that this would be totally unacceptable practice, the formation of a ground pool would pose much less risk that a falling fuel cascade should there be an overfill. It can be validated using the risk management principles of IEC 61511 that this option will be appropriate in some circumstances.

Method 2

In Figure 12 a overflow gutter is used. Because the typical sizes for large crude oil filling rates requires pipes that are 24 to 42 inches, a pipe located near the top of the tank with an elbow pointing down and flowing to grade is simply not practical due to the size. In addition, there would be problems meeting the design specifications required of API 650. The gutter design shown provides a way of meeting API 650 in intent, but also one that is practical. It should be noted, however, that the need for these overflow should be brought to the attention of the API if this methodology is to be considered a viable way of eliminating tank overfilling vapor cloud risks.

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[1] Link to PEMY Consulting LLC dropbox folder is https://www.dropbox.com/sh/dztqjc2oxyvgjdq/AABuPI8aVt0l3CnwAEYdZXfla?dl=0

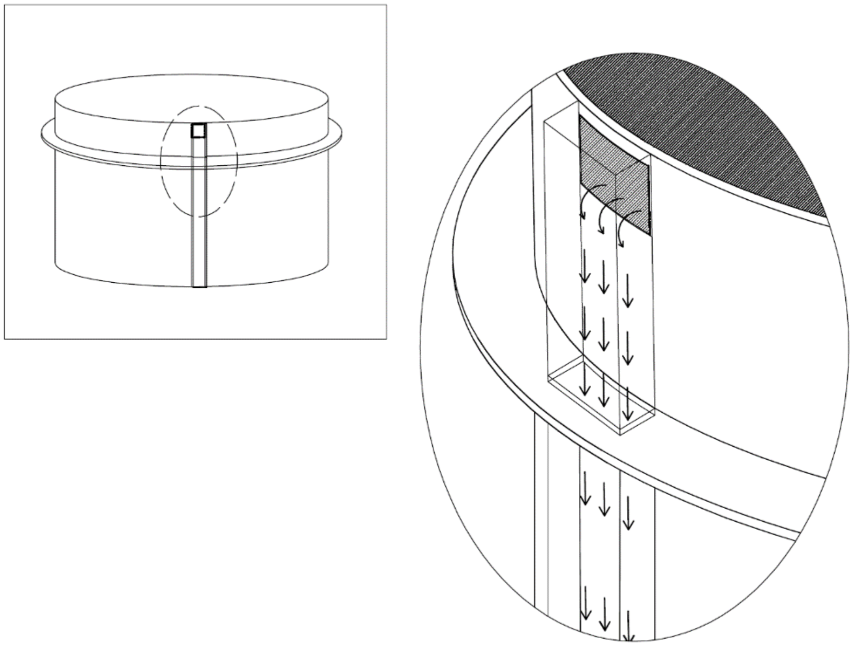

Figure 12 Overfill Gutter

We point out that the concept of redirecting a overflow to a ground spill by either method discussed above is a major change to current practice. It is one, like most major changes, requires consideration for new tank versus existing tanks and the concepts of “grandfathering”. However, after incidents such as Buncefield, societal tolerance is reducing for events such as these. In the UK, facilities have already been required to apply IEC 61511 to tank overfill controls (i.e. safety instrumented systems). The methods offered in this paper provide more choice about how to mitigate the VCE potential. It cannot be emphasized enough that careful risk assessment and management is required so that undue efforts and costs are applied to risks which may not warrant these types of controls. There are many examples of resource squandering that have resulted from over prescribing regulatory measures where the benefits have not been warranted by the costs.

Summary and Conclusions

The research provided by the UK HSE resulted in 2 documents that provide a method for determining the size of a potential vapor cloud that might develop from a petroleum tank overfill. Research Report 908 was the first document to be published and later the Fabig Technical Note 12 was published. In research report RR908 the VCA method was applied through examples of overfills involving gasoline and to ethanol. TN12 extended the method to a list of 15 fluids. But only one of the fluids was crude oil. That fluid was Brent Crude oil and in an example given in the document a vapor cloud with an ignition radius of 612 meters was computed.

Because crude oil comprises the largest fraction of tank filling with flammable hydrocarbon a practical method is needed to determine VCE risks from crude oil overfills. We have provided a simple method that can be used for crude oil data that is readily available.

References

United Kingdom Health Safety Executive Publication, RR113, “Review of Vapour Cloud Explosion Incidents”

United Kingdom Health Safety Executive Publication, RR908, “Vapor Cloud Formation Experiments and Modelling” Graham Atkinson and Simon Coldrick

Fire and Blast Information Group (FABIC) Technical Note 12

IEC 61511 "Functional safety - Safety instrumented systems for the process industry sector"

API 650 “Welded Tanks for Oil Storage”