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VCE risks at LNG export facilities

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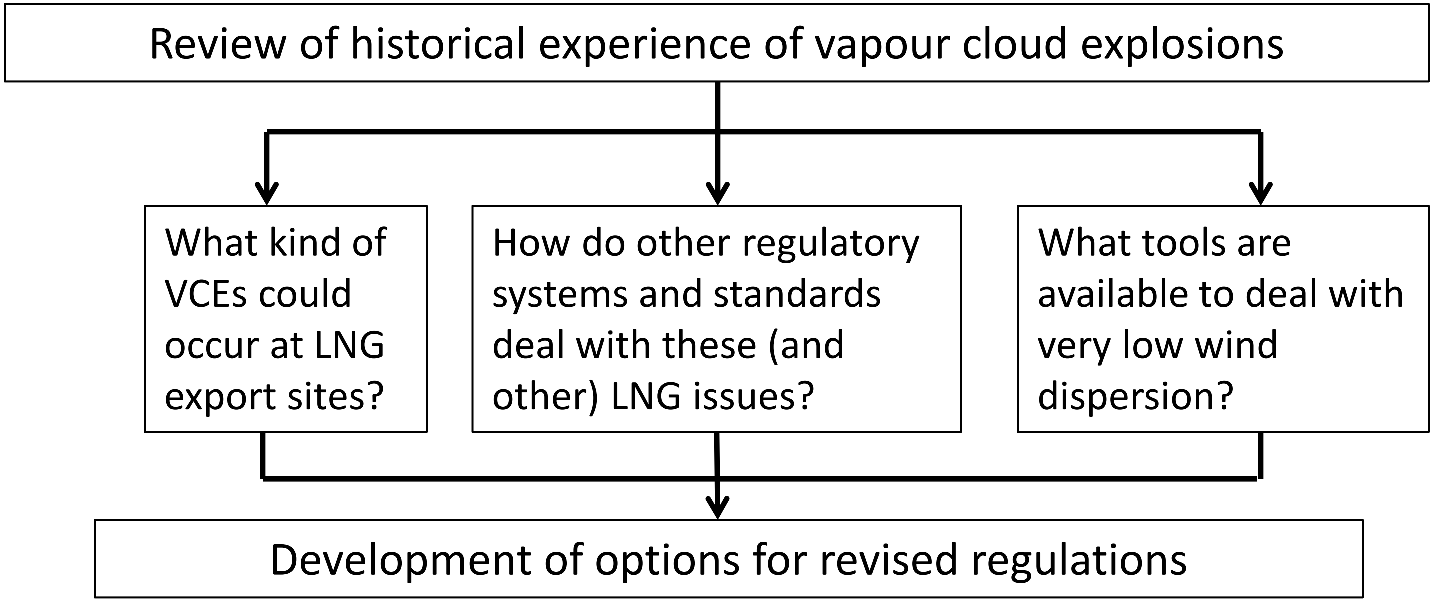
History

Context: Jan 2015: Objection (Jerry Havens et al): DEIS* analyses for Jordan Cove LNG export site: *"ignores international experiences of catastrophic unconfined vapor cloud explosions (UVCE), at least four of which occurred in the last decade, destroying the facilities involved as a result of cascading events"*



PHASE 1
(2015)

Review of historical experience of vapour cloud explosions

PRE-PHASE 2
(Spring 2016)

What kind of VCEs could occur at LNG export sites?

How do other regulatory systems and standards deal with these (and other) LNG issues?

What tools are available to deal with very low wind dispersion?

PHASE 2
(Summer 2016-?)

Development of options for revised regulations

* DEIS - Draft Environmental Impact Statement

Inventories of higher hydrocarbons at LNG sites

Refrigerants: typically of order 50 tonnes

Ethane
Propane
Isobutane
Ethylene
Blends

Condensates: Many hundreds of tonnes

What history should we review?

Gas	Laminar flame speed (cm/s)
Methane	40
Ethane	47
Propane	46
Butane	45
Pentane	46
Hexane	46
Heptane	46

Flame speeds recommended for use in venting assessments NFPA 68 (2013 Ed)

The fundamental combustion properties of all the saturated hydrocarbons in the range C2-C6 are very similar and this is reflected in the explosion damage observed in VCEs. Those operating sites handling LPG should be interested in records of cloud development and VCEs at gasoline sites and vice versa.

Summary of incidents from Phase 1 (excluding pipeline failures)

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Incidents that occurred in nil/low–wind conditions		**Vapour release rate (kg/s)**	**Duration prior to ignition (s)**
Brenham, TX	LPG Storage	100	3600
Newark, NJ	Gasoline storage	35	>900
Big Spring, TX	Refinery	not known	not known
San Juan, Puerto Rico	Gasoline storage	50	1560
Skikda, Algeria	LNG facility	~10	<300s
Buncefield, UK	Gasoline storage	19	1380
Amuay, Venezuela	Refinery LPG storage	13	>5000
Jaipur	Gasoline storage	34	4500
Incidents that probably occurred in nil/low-wind conditions			
St Herblain, France	Gasoline storage	~10	1200
Geismer, LA	Petrochemicals	not known	not known
Naples, Italy	Gasoline storage	20	5400
La Mede, France	Refinery	25	600
Incidents that occurred in light or moderate winds			
Baton Rouge, LA	Refinery	681	150
Norco, LA	Refinery	257	30
Pasadena, CA	HDPE	643	60
Flixborough, UK	Petrochemicals	670	45

Summary of Phase 1

The data showed that incidents studied divided into two types:

1. Sustained releases in nil wind conditions

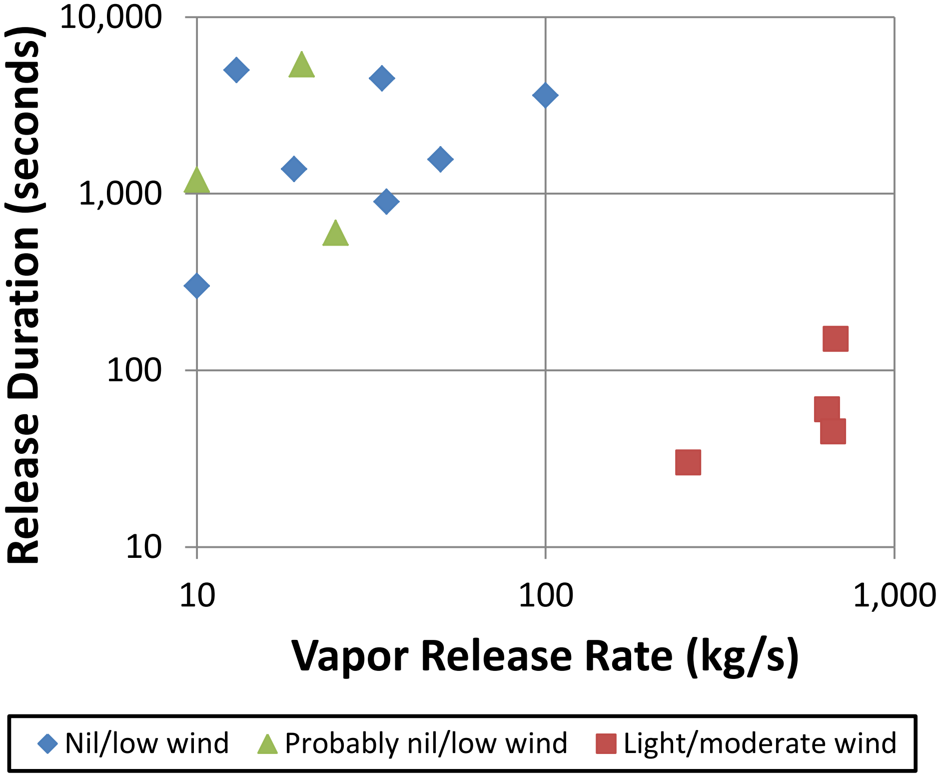
   Rate: <100 kg/s

   Duration: usually >1000 seconds

2. Large releases in windy conditions

   Rate: >200 kg/s

   Duration: usually <100 seconds



Vapour dispersion studies

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Process element	Propane Tank	Propane tanker (via 5m long 2” hose)	Process vessel	Condensate tank	Mixed refrigerant tank
Substances modelled	Propane 100%	Propane 100%	Methane/ propane/ butane mix 33%/33%/33%	Pentane 50% Hexane 50%	Propane 50% Butane 50%
Inventory/release rate(US gal)	25 500		15 000	500 000	100 000
Fluid storage temperature (°F)	ambient	ambient	100	ambient	ambient
Storage pressure (psi)	92	92	600	atmospheric	51
Orifice size (“)	2 and 4	2	2 and 4	4	4
Mass release rate (kg/s)	32 and 128	9	77 and 307	47	99
Release duration (min)	Until vessel empties	10	Until vessel empties	60	Until tank empties
Release direction	Horizontal and Upwards	Horizontal and Upwards	Horizontal and Upwards	Horizontal and Upwards	Horizontal and Upwards
Weather	D5, F2, nil wind	D5, F2, nil wind	D5, F2, nil wind	D5, F2, nil wind	D5, F2, nil wind
Roughness length (m)	0.1	0.1	0.1	0.1	0.1

Windy dispersion (F2 and D5 conditions) modelled with Phast and DRIFT

Nil wind transport modelled in a similar way to FABIG TN 12

Calculation of area affected by LFL contour in nil-wind conditions

In nil-wind conditions vapour air is entrained close to the source. Away from the source, flow speeds fall to the point where turbulence in the heavy vapour current is completely suppressed. The low level flow of vapour is *laminar*.

Calculation of area affected by LFL contour in nil-wind conditions

Residual entrainment of air is by molecular diffusion. A typical molecular diffusion constant for diffusion of air into a fuel rich layer would be around 0.15 cm2/s.

The characteristic timescale for flow of vapour across a large vapour cloud is around 1000 second and the corresponding distance scale for penetration of air into the cloud by diffusion is $\sqrt{Dt}$ = 12 cm. This is a small distance compared with the total depth of the cloud and most of the flow is not affected by air diffusing downwards.

The laminar vapour flow progresses for long distances (driven by buoyancy forces) without significant dilution.

Almost all of the cloud is at the same concentration.

Calculation of area affected by LFL contour in nil-wind conditions

If we assume that the cloud is at the LFL (40 g/m^3) when entrainment ceases then the cloud volume is

$$V(m^3) = \frac{M(kg/s)T(s)}{0.04(kg/m^3)}$$

M the mass release rate
T the release duration

Incident records suggest a typical average height for the cloud is 2m. This analysis is based on the observed extent (area) of the flammable cloud (indicated by the burned area) in comparison with its total fuel content and concentration.

Two methods are available to estimate the concentration:

1. Detailed calculation based on an understanding of cascade dynamics and near field entrainment (available for gasoline overfills)
2. Approximate arguments based on the observation that the cloud burned and in some cases caused a severe explosion – which points to a concentration in the mid part of the flammable range.

Calculation of area affected by LFL contour in nil-wind conditions

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The plan area is therefore

$$A(m^2) = \frac{V(m^3)}{2(m)}$$

This is the maximum area that could be covered by a 2m deep flammable cloud. If the cloud concentration were stoichiometric (76 g/m^3) the plan area would be proportionally smaller (53%).

Range of LFL contour for scenarios studied

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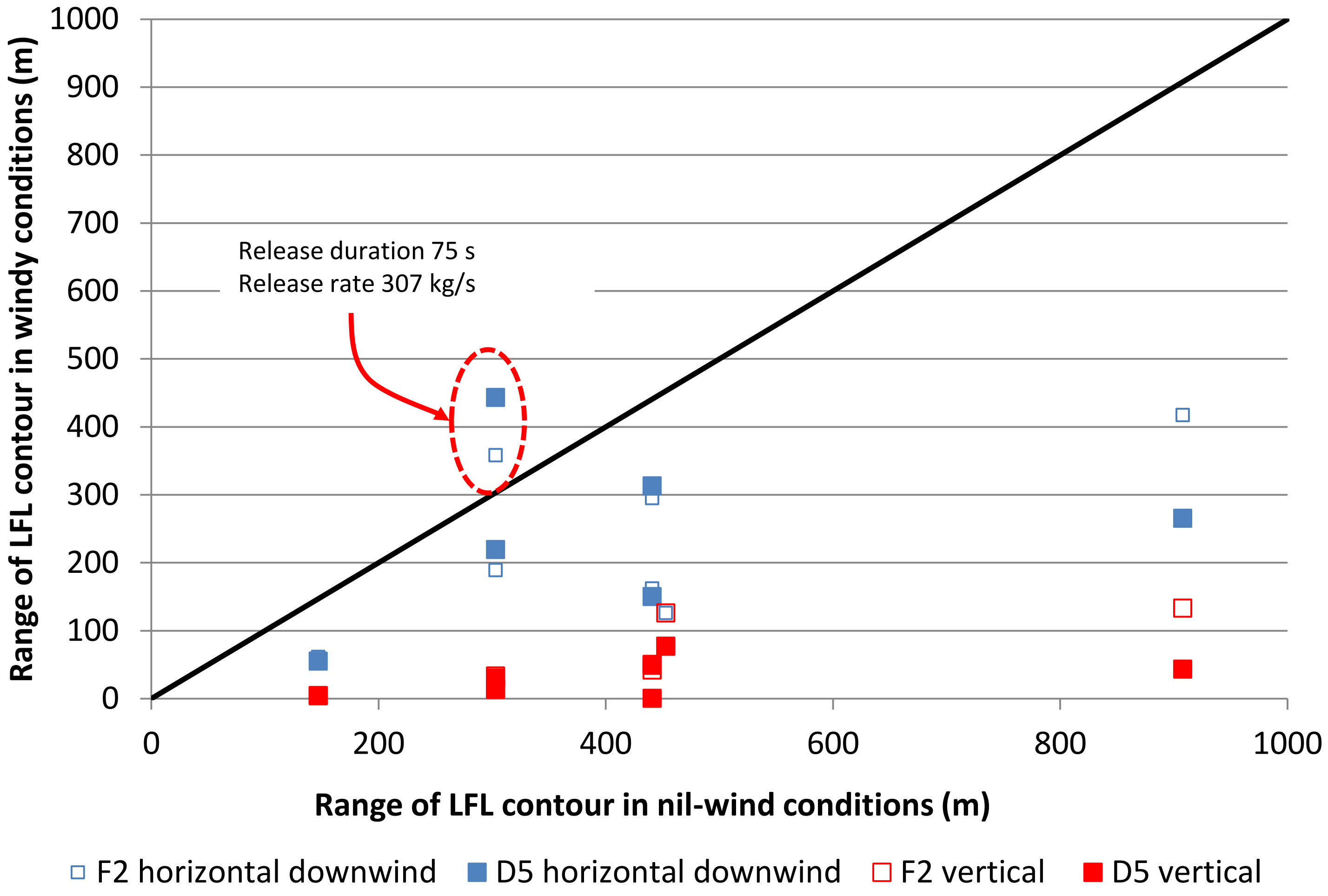
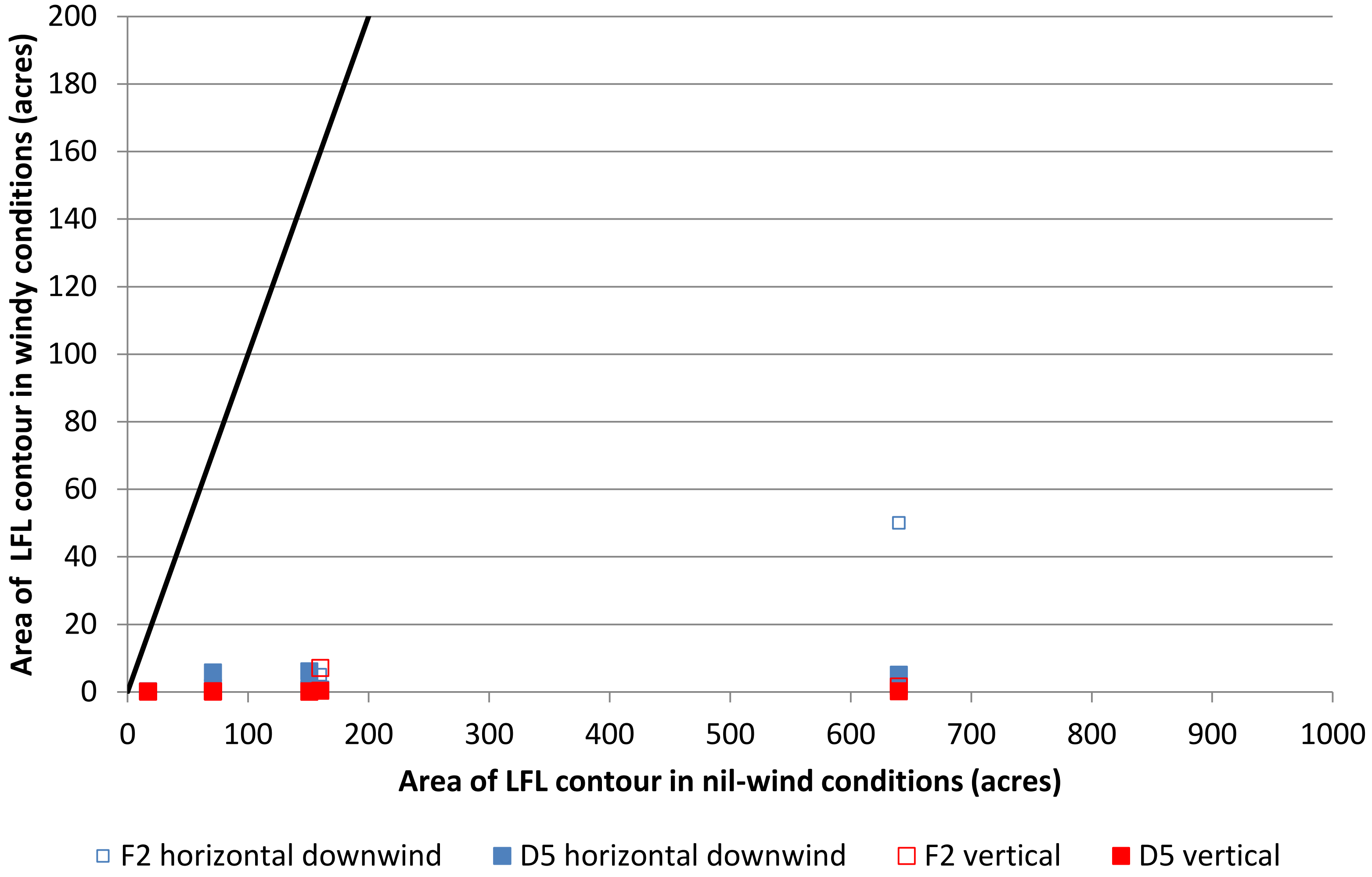


Area covered by LFL contour for scenarios studied

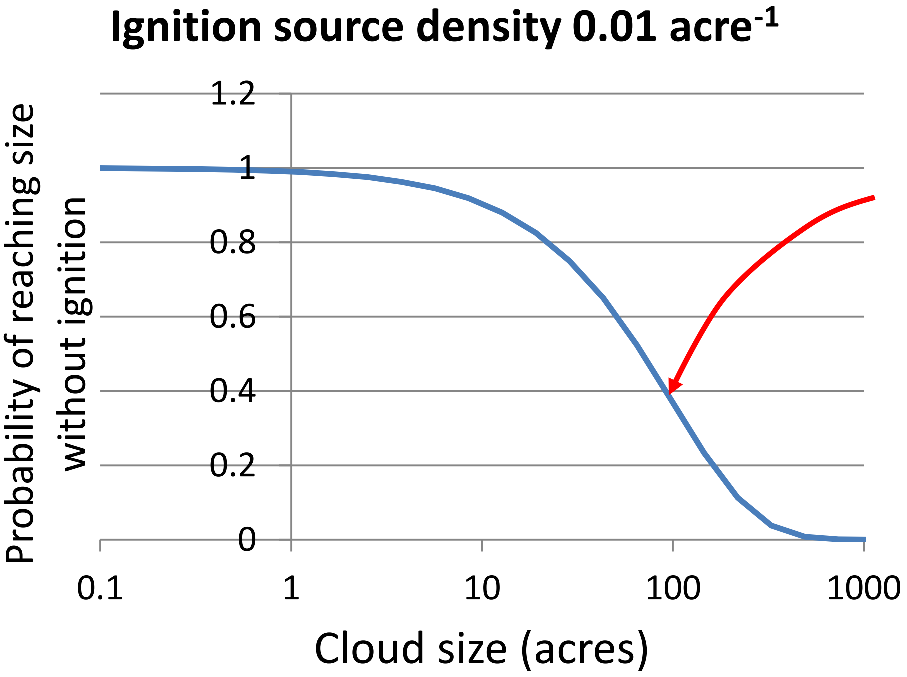


For most of the sources studied the area of the flammable cloud is hundreds of times greater in nil-wind conditions than in F2 conditions.

This would be especially true if the jet were not horizontal or hit something close to source.

What are the implication for ignition probability?

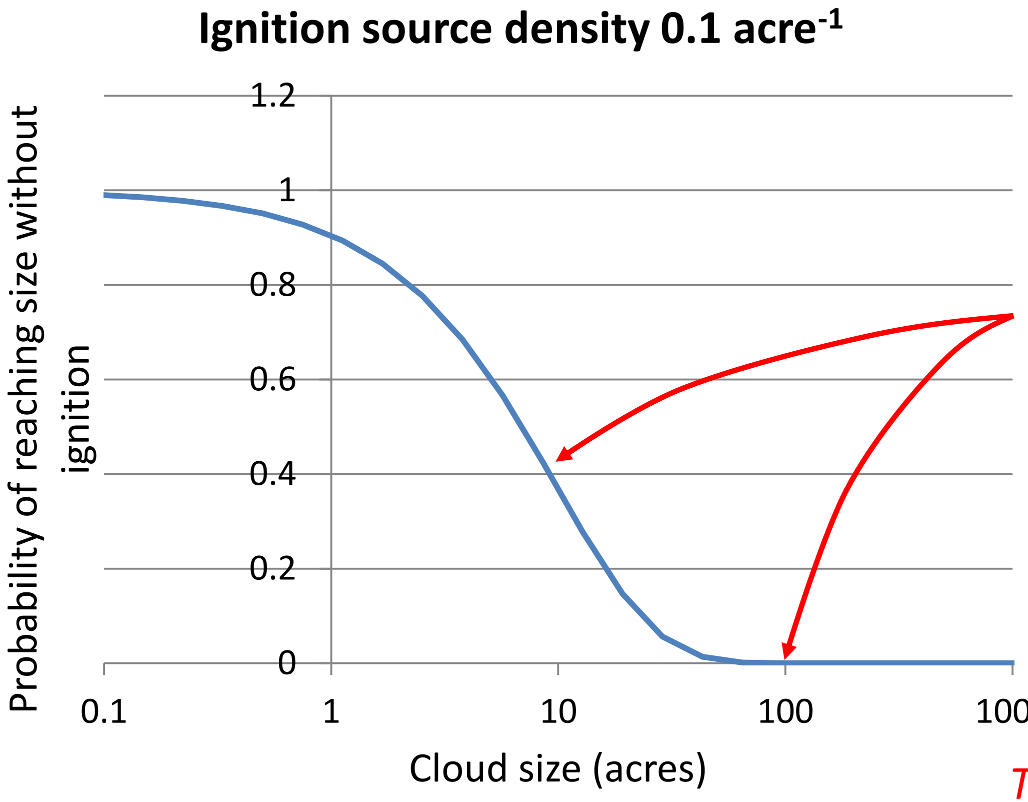
The four most recent large vapour cloud incidents (Buncefield, Jaipur, San Juan Amuay) reached an average size of around 100 acres. The density of effective ignition sources must have been around 0.01 acre^{-1}



A significant proportion of incidents should reach 100 acres

This corresponds to incident data

An ignition source density of 0.1 acre^{-1} gives a 6 x 10^{-5} chance that a cloud will reach 100 acres without ignition.



Incidents with a burn area of 10 acres should outnumber those with of 100 acres by 10,000 : 1

This does not match incident data

Typical results for a 2" propane release (50 tonnes)

Release rate 32 kg/s
Ignition source density 0.01 acre^{-1}

Weather	Area of flammable cloud (acres)	Ignition probability
Windy (F2 or D5)	0.1 to 1	0.1% to 1%
Nil wind	150	~70%

F2 conditions are roughly twice as likely as nil-wind but the chances of ignition are about 100 times less.

D5 conditions are roughly ten times more likely than nil-wind but the chances of ignition are 200 - 500 times less

This illustrates why nil-wind incidents dominate VCE records for small vapour sources.

Findings on dominant elements in flammable risk assessment .

The project findings suggest that nil-wind and windy dispersion cases should be considered in risk assessments according to the following scheme.

Hole size (for LPG)	**Mass release (vapour)**	**Scenarios controlling risk**
1”	<10 kg/s	Nil-wind
2”	10 – 50 kg/s	Nil wind
4”	50 – 250 g/s	Nil-wind and windy
6” or more	>250 kg/s	Windy

In the context of higher hydrocarbon releases at LNG export terminals (2” and 4” releases) analysis of both windy and nil-wind scenarios is probably required to give a reliable picture of risk.

Comparison with a toxic risk assessment

Chlorine IDLH = 10 ppm (Immediate Danger to Life and Health)

2 inch release from a 100 tonne tank at saturation pressure (47 kg/s)

Weather	**IDLH Extent down wind (m)**	**IDLH Extent cross wind (m)**	**IDLH Area PHAST (acres)**
Horizontal Releases			
Windy F2	37,000	3,000	27,500
Windy D5	6,800	850	1,430
Nil wind*	Radius 450m	Radius ~ 450m	157

* Cloud concentration after establishment of stable gravity current assumed 20,000ppm

Assessment based on F2 and D5 conditions makes sense for a chlorine release.

Part 2: Findings on explosion severity

Very large gasoline clouds that burned with a severe explosion (vehicles and drums crushed)	Very large gasoline clouds that burned as a flash fire
Buncefield Jaipur Newark , NJ San Juan Naples Saint Herblain	None found

Gasoline clouds are useful because overfills and sprays tend to produce large clouds with concentrations towards the middle of the flammable range - concentrations over the UFL are not likely.

Explosion severity

Very large LPG clouds that burned with a severe explosion (vehicles and drums crushed)	Very large LPG clouds that burned as a flash fire
Amuay Brenham Port Hudson (pipeline) La Mede Skikda	Donnellson, Iowa (pipeline)

What is the significance of the flash fire at Donnellson?

Is this an example of a very large, pre-mixed LPG cloud that burned as a flash fire – without transition to a severe explosion?

Explosion severity

It is possible that the cloud at Donnellson was over the UFL (see below).

Flame would have spread over the top surface of the cloud before burning slowly down through the rich layer below.

	Mass release (tonnes)	**Area of cloud (m^2)**	**Mass/unit area (g/m^2)**	**Equivalence ratio** (assuming average height 2m)
Buncefield	26	150,000	173	1.1
San Juan	78	450,000	170	1.1
Donnellson	~150	300,000	500	3.3 (>UFL)

Conclusion

If a very large cloud forms (at a concentration well within the flammable range) it is likely that there will be a severe explosion.

Currently this would be an appropriate basis on which to base risk assessment.

What kind of severe explosions occurred and what caused transition from a flash fire?

Detonations

Overpressure: 15-20 bar

Examples: Flixborough, La Mede (?)

Transition caused by flame propagation in highly confined and congested plant areas.

Severe explosion extends across the whole cloud - from the point of transition.

Signature of a detonation

Detonations produce continuously curved steel posts and tubes

Flixborough

Experimental detonation

Severe (episodic) deflagrations

Overpressure 2-5 bar

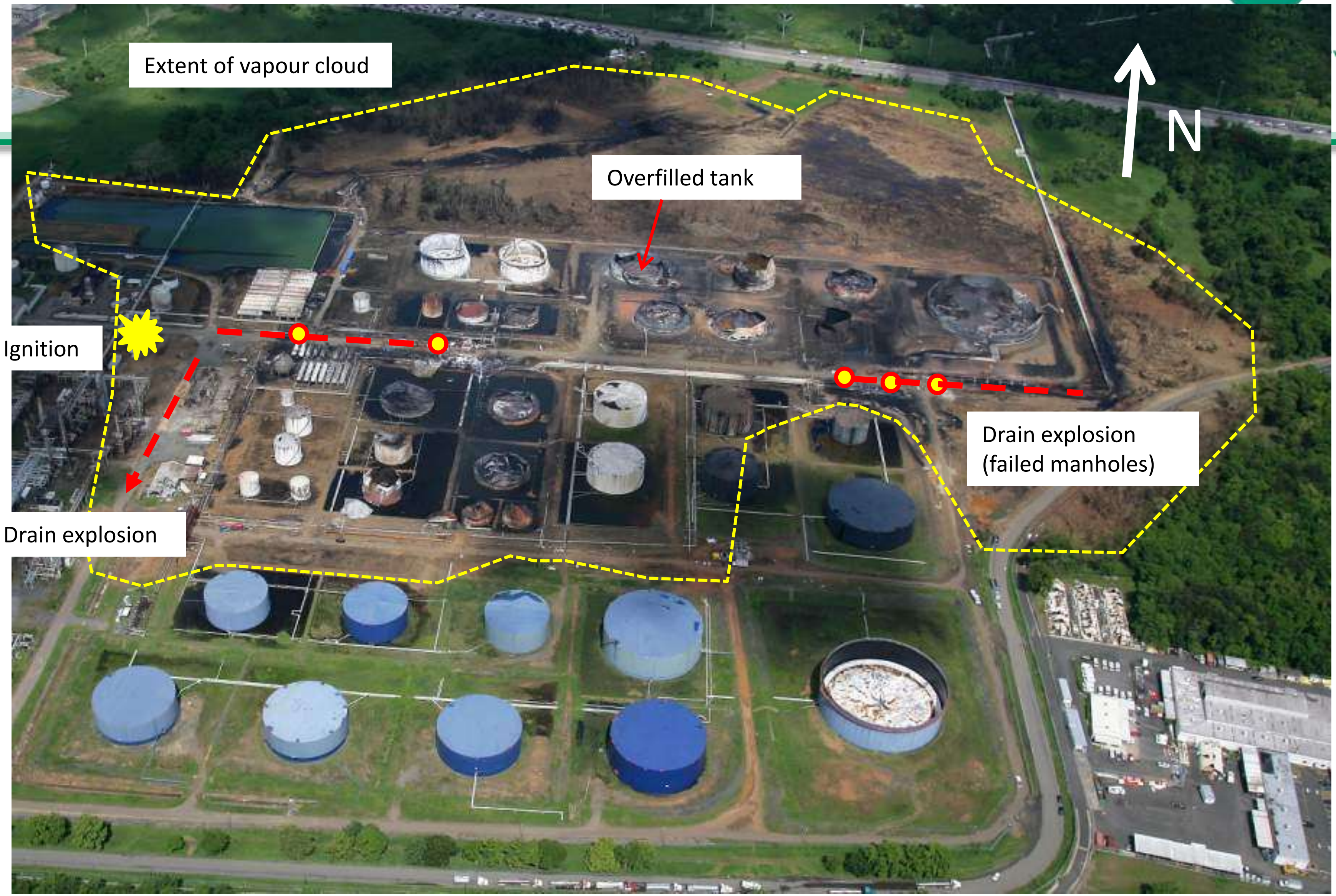
Examples: San Juan, Buncefield, Jaipur etc.

Transition triggered by buildings, pipe racks, vegetation, drains…

Severe explosion extends across the whole cloud - from the point of transition.

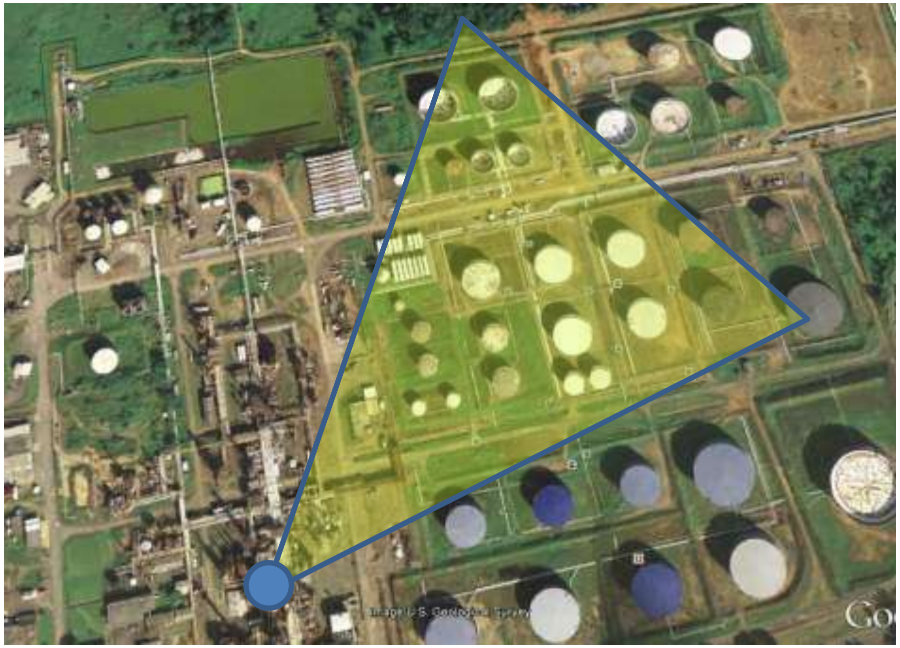
Severe deflagrations do not leave continuously curved posts

Case History – San Juan 23rd October 2009

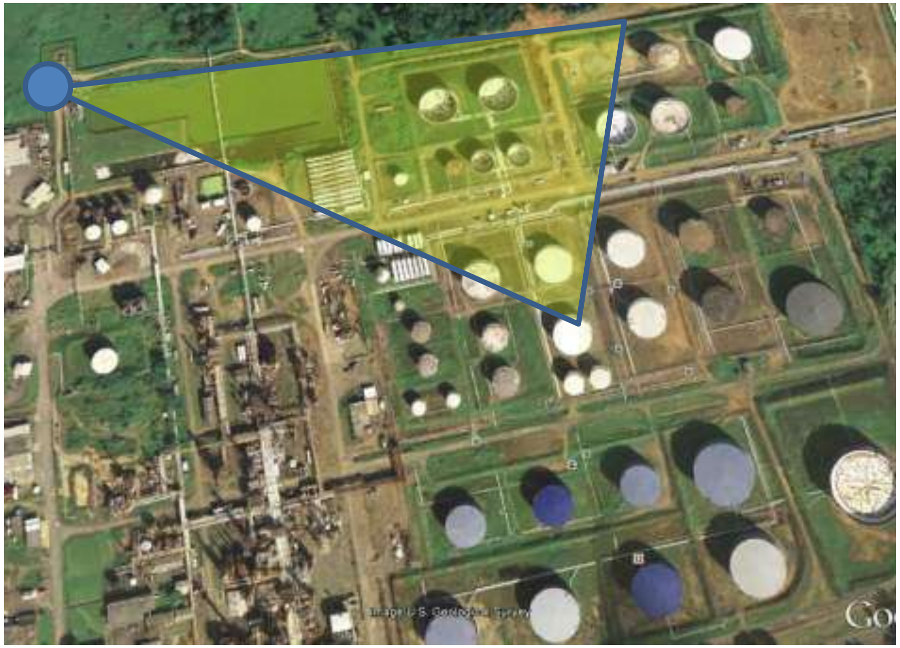


Key features

CCTV views allowed progress of the flame to be monitored

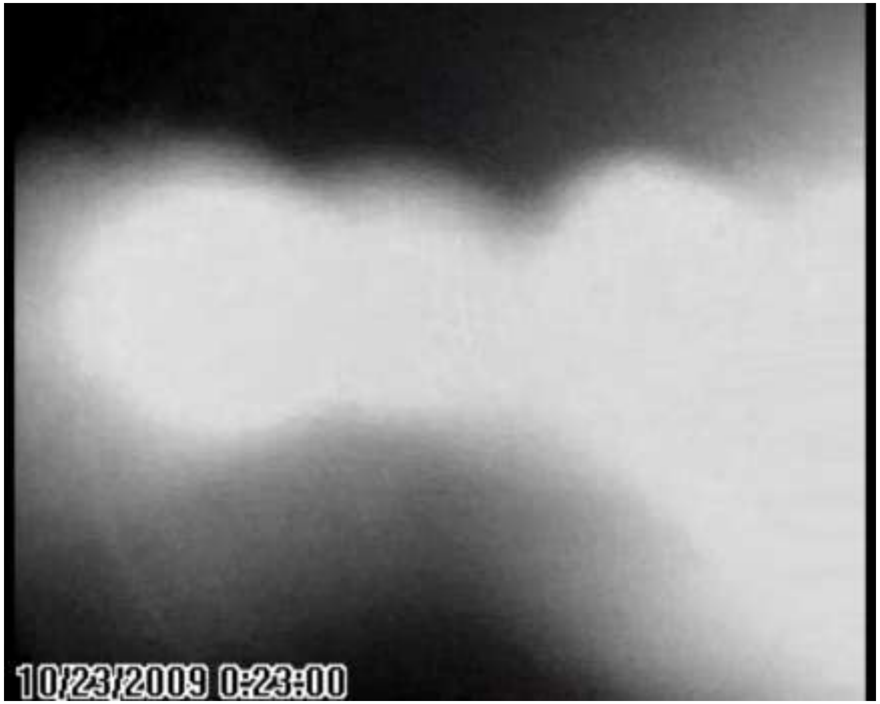


Camera 1



Camera 2

For the first 3 - 4 seconds the images are blurred and overexposed



After around 3 seconds flame propagated violently down a drain (near the edge of the cloud) but did not trigger transition to a fast flame.

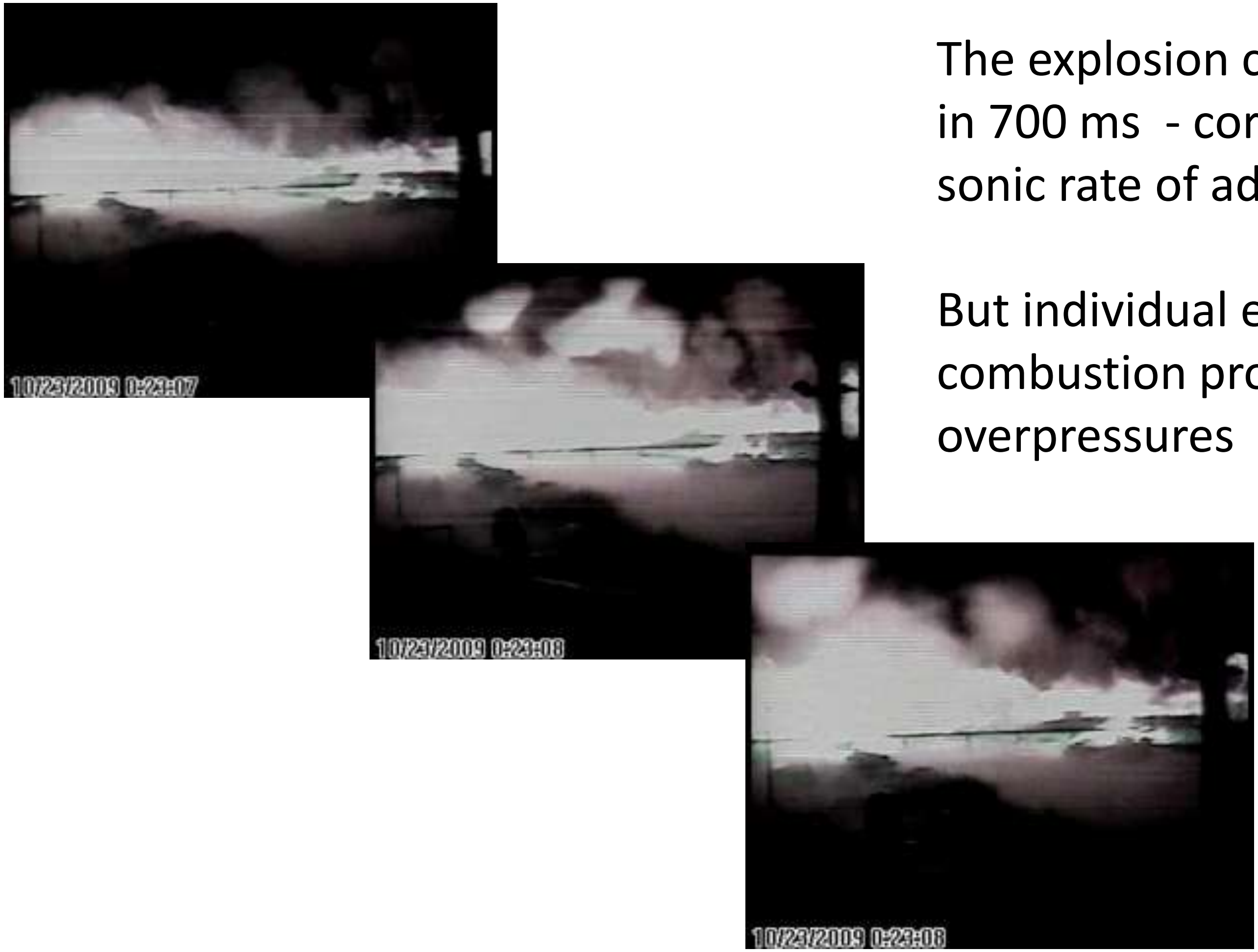
Drain explosion in progress

For around 8 seconds the flame spread steadily across the site covering about 250 m (~30 m/s).

Then there was transition to a violent explosion

Transition to high pressure explosion

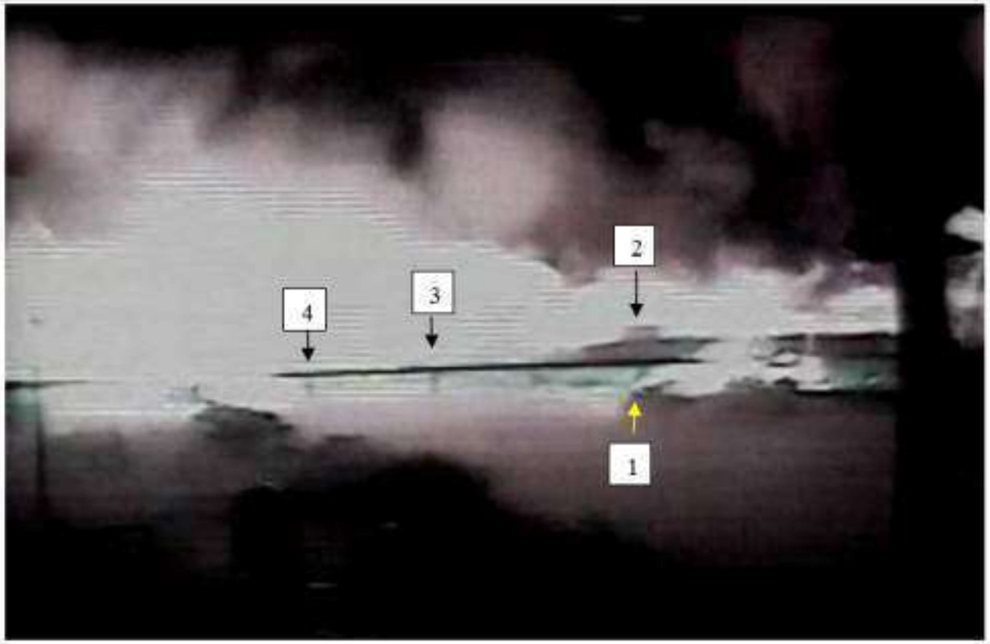
A sequence of violent explosions followed – crossing the open area around the overfilled tank (where the cloud was deepest)



The explosion covered about 140 m in 700 ms - corresponding to a sub-sonic rate of advance (200 m/s).

But individual episodes of violent combustion produced high overpressures

The locations of some explosion episodes can be pin-pointed by triangulating from the two camera views



Transition occurred in an area where there were intersecting pipe racks

Alternative views of the transition area

The transition area does not include the kind of dense semi-confined pipework normally associated with transition to a severe explosion (DDT).

Plant areas like this will be found on most chemical sites – including LNG export sites.

This goes some way to explaining why transition has occurred so frequently for very large flammable clouds.

Summary

1. Nil-wind scenarios dominate risk for releases under 50 kg/s and contribute significantly to the risk for release rates up to about 250 kg/s.

2. For clouds that accumulate in nil-wind conditions the fuel concentration hardly changes from close to the source to the outer edge.

3. Vapour clouds that have accumulated from sustained small leaks have caused major incidents with cloud spread, blast damage and multiple fatalities up to >700m from source.

4. If a very large, homogenous cloud accumulates (and the concentration is somewhere near an equivalence ratio of 1) then transition to a severe explosion is likely for gasoline or LPG.