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Vapor Cloud Explosion (VCE) Historical Review

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Acknowledgement

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- Background
- Choice of VCE incidents for historical review
- Cloud development in major incidents
- Severity of VCEs (Blast damage)
- Preliminary findings

Background

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In Jan 2015, comments to the Draft Environmental Impact Statement for Jordan Cove LNG export site: "[the DEIS] ***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"*

Buncefield (2005)

Jaipur (2009)

Puerto Rico (2009)

Amuay (2012)

Study based on the assumption that severe VCEs will not occur in open areas for LNG (methane)

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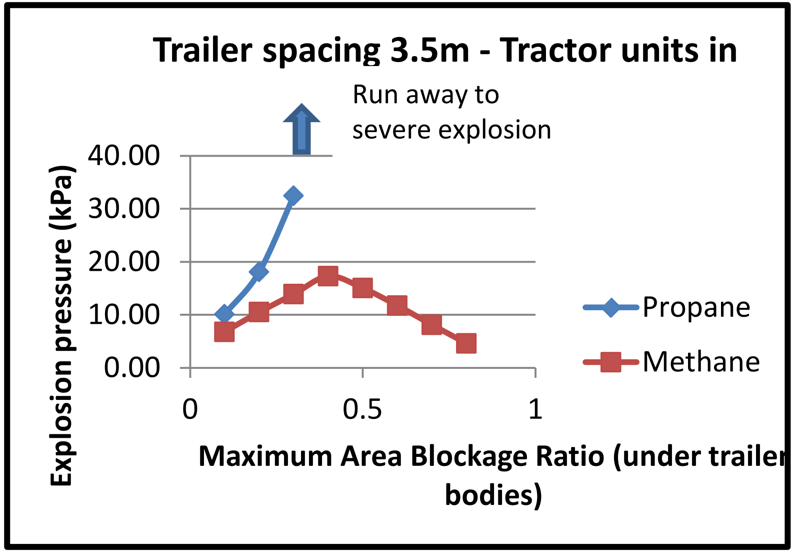
Flame acceleration along a line of tankers in a higher molecular weight hydrocarbon vapor cloud



Explosion modelling

Methane is not prone to flame acceleration

But there are inventories of higher hydrocarbons at LNG export sites

Refrigerants: typically of order 50 tonnes

Ethane Propane Isobutane Ethylene
Blends

Condensates: Many hundreds of tonnes

Pentanes Hexanes

What VCE incidents should we review?

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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.

VCE incidents reviewed
LPG (14), LNG (1), Gasoline (6) and Other (3) incidents

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Brenham, TX	LPG Storage
Newark, NJ	Gasoline storage
Big Spring, TX	Refinery (LPG)
San Juan, Puerto Rico	Gasoline storage
Skikda, Algeria	LNG facility
Buncefield, UK	Gasoline storage
Amuay, Venezuela	Refinery LPG storage
Jaipur	Gasoline storage
Austin , TX	LPG pipeline
North Blenheim, NY	LPG pipeline
Donnellson, IA	LPG pipeline
Ruff Creek, PA	LPG pipeline
Port Hudson, MO	LPG pipeline
St Herblain, France	Gasoline storage
Geismer, LA	Petrochemicals
Naples, Italy	Gasoline storage
La Mede, France	Refinery (LPG)
Baton Rouge, LA	Refinery (LPG)
Norco, LA	Refinery (LPG)
Pasadena, CA	HDPE
Flixborough, UK	Petrochemicals
Devers, TX	LPG Pipeline
Lively, TX	LPG Pipeline
Ufa, USSR	LPG Pipeline

Part 1: Findings on vapor cloud development

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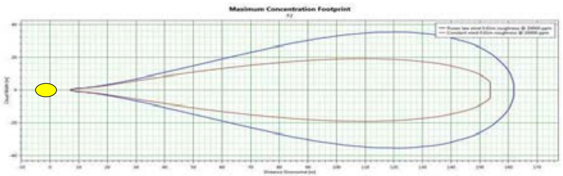
There are examples of vapor clouds that spread in all directions around the source and hard to find any that showed a burned area extending downwind.

Five examples of cloud development in nil-wind conditions



Modelling of dispersion in a 2 m/s wind (Pasquill Stability Class F)

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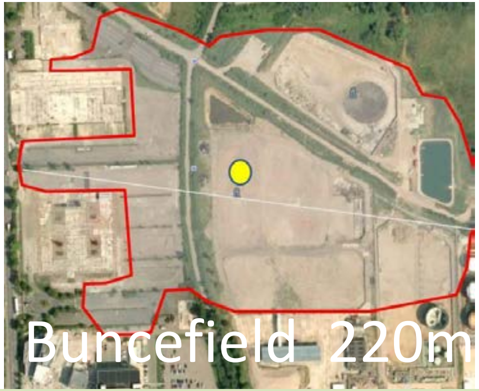
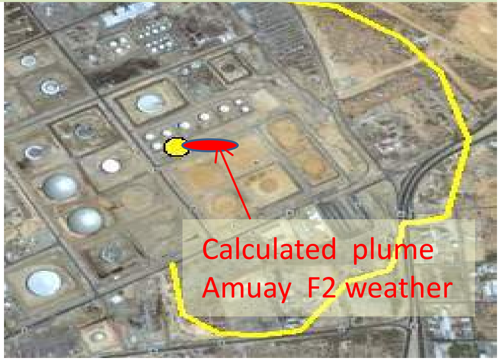


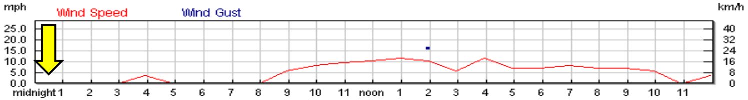
Average cloud radii



Data on dispersion conditions from…

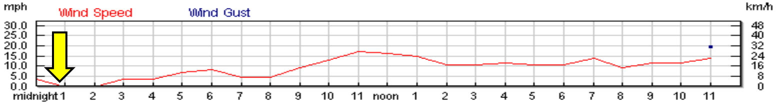
Meteorological data

Brenham, Texas (7:00am)



San Jan, Puerto Rico (00:23 am)

Big Spring , Texas



Newark, New Jersey (0:10 am)

Vapor cloud structure

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Summary of incidents reviewed (excluding pipeline failures)

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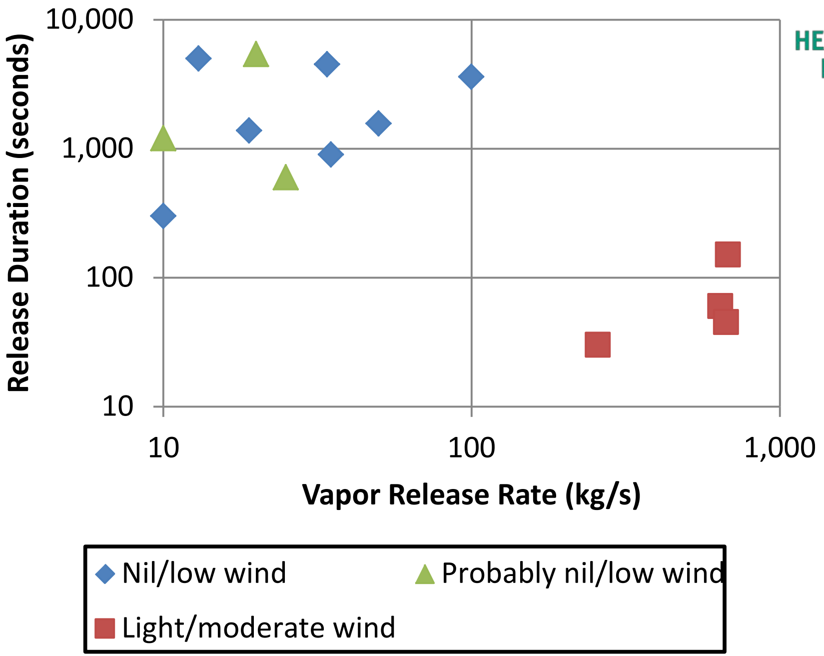
Incidents that occurred in nil/low–wind conditions		Vapor release rate (kg/s)	Duration prior to ignition (s)
Brenham, TX	LPG Storage	100	3600
Newark, NJ	Gasoline storage	35	>900
Big Spring, TX	Refinery	not known	not known
San Juan, Puerto Rico	Gasoline storage	50	1560
Skikda, Algeria	LNG facility	~10	<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

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



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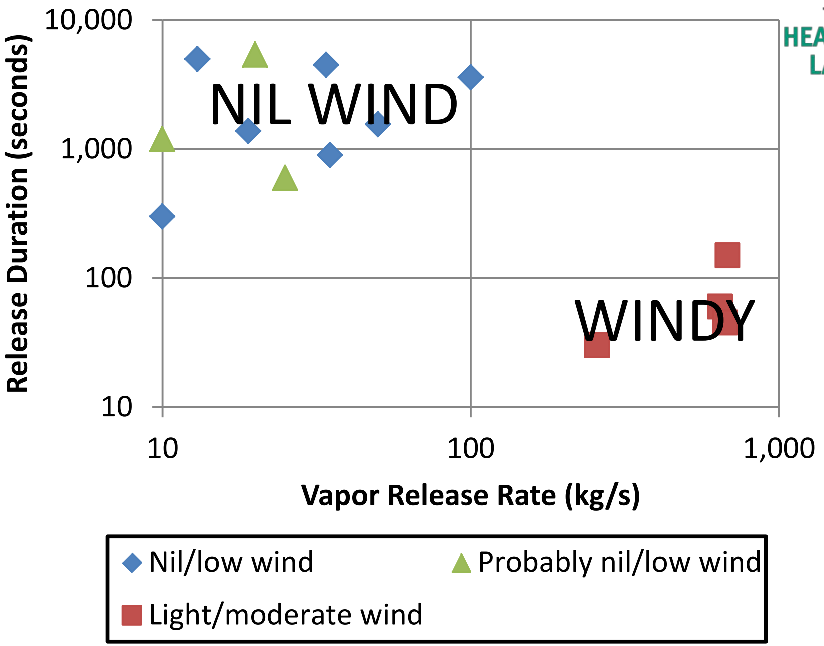

How do vapor clouds develop in nil-wind conditions?

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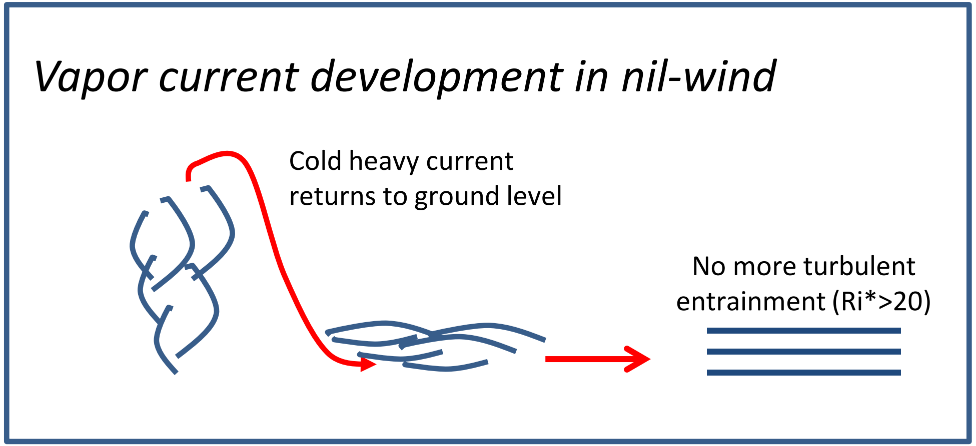
In nil-wind conditions, air is entrained close to the source. Away from the source, flow speeds fall to the point where turbulence in the heavy vapor current is suppressed. The low level flow of vapor is *laminar*.



Buncefield – a laminar vapor current

Part 2: Findings on explosion severity

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What happens in a severe vapor cloud explosion?

Multimedia packages have been developed to present images from the incidents at:

- Buncefield
- Jaipur
- Flixborough
- San Juan

Part of the San Juan package

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Part of the Jaipur package

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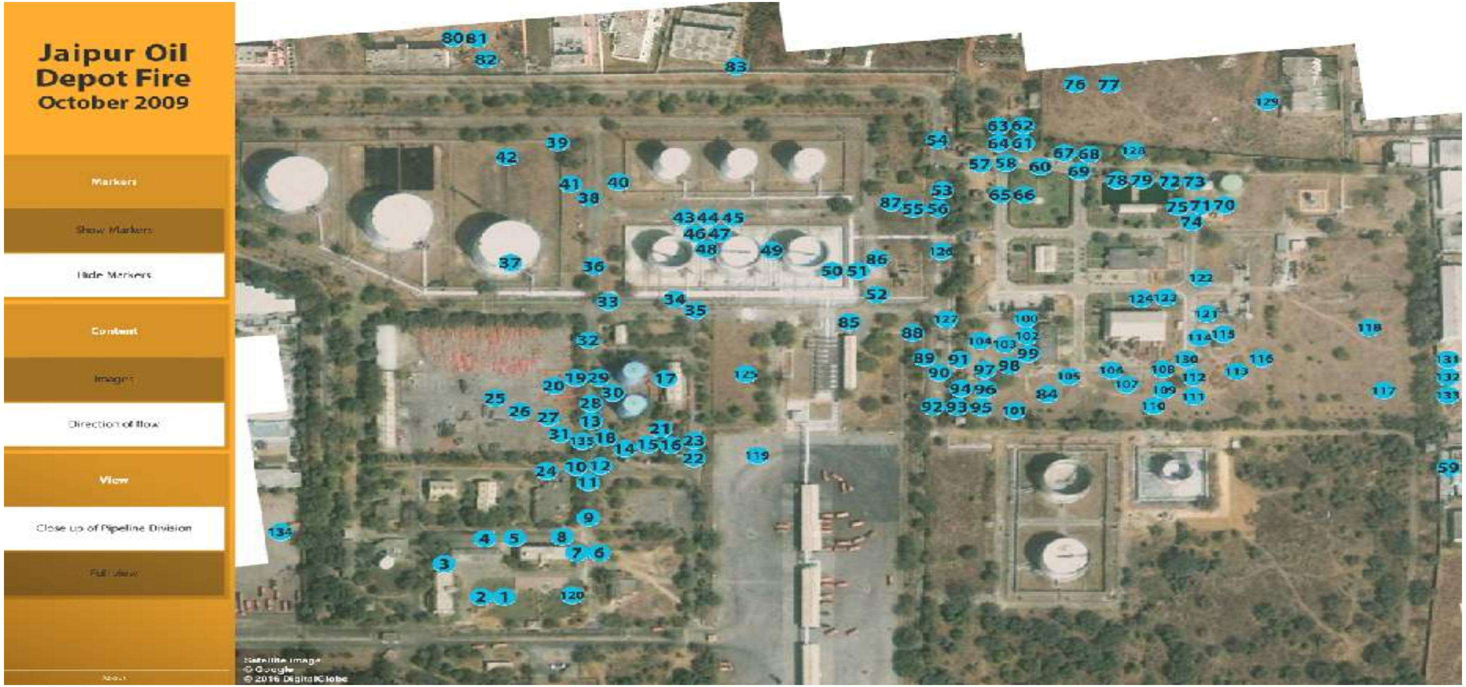

Part of the Buncefield package

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Part of the Flixborough package

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What happens in a severe vapor cloud explosion?

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For bomb blast damage varies continuously with distance from the device.

For the vapor cloud explosions reviewed here that extended into open areas, the extent of blast damage is similar across *all of the area* covered by the cloud.

Cars

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Empty tanks

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Full tanks:(Efficiently set on fire in the area covered by the vapor cloud)

San Juan

Buncefield

Amuay

Drums

Jaipur

Test (2 bar)

Buncefield

Test (2 bar)

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Buildings

Buncefield

Amuay

Jaipur

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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 have relatively similar effects, 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)

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Preliminary Observation

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In all but one of the incidents reviewed, when a very large cloud was formed, there was a severe explosion.

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

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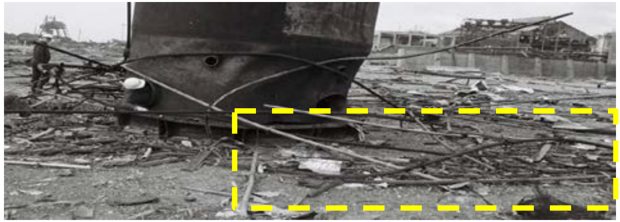
Detonations
Overpressure: 15-20 bar

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



Flixborough

Detonations produce continuously curved steel posts and tubes

Experimental detonation

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Severe (episodic) deflagrations
Overpressure 2-5 bar

Examples: San Juan, Buncefield, Jaipur etc.

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

Severe explosion appears to have extended across the whole cloud - from the point of transition.

Severe deflagrations do not leave continuously curved posts

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Case History – San Juan 23rd October 2009

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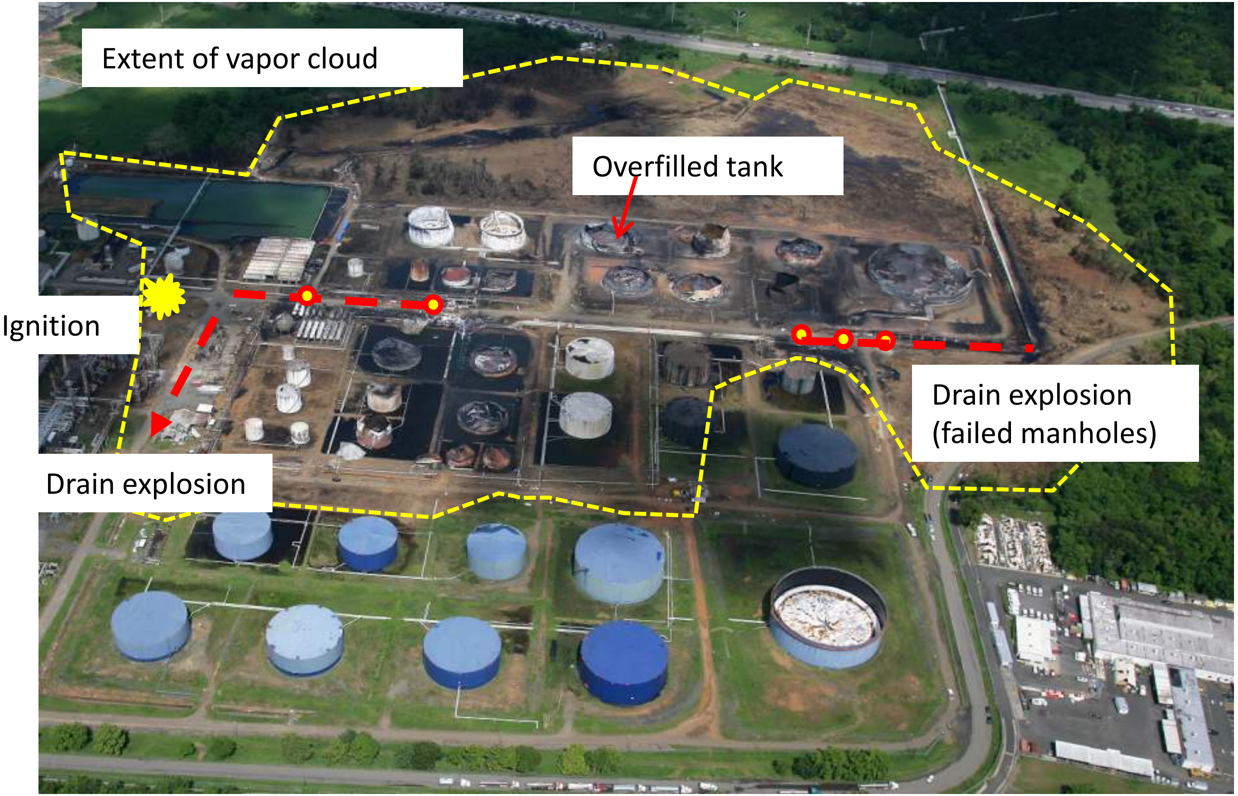

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CCTV views allowed progress of the flame to be monitored

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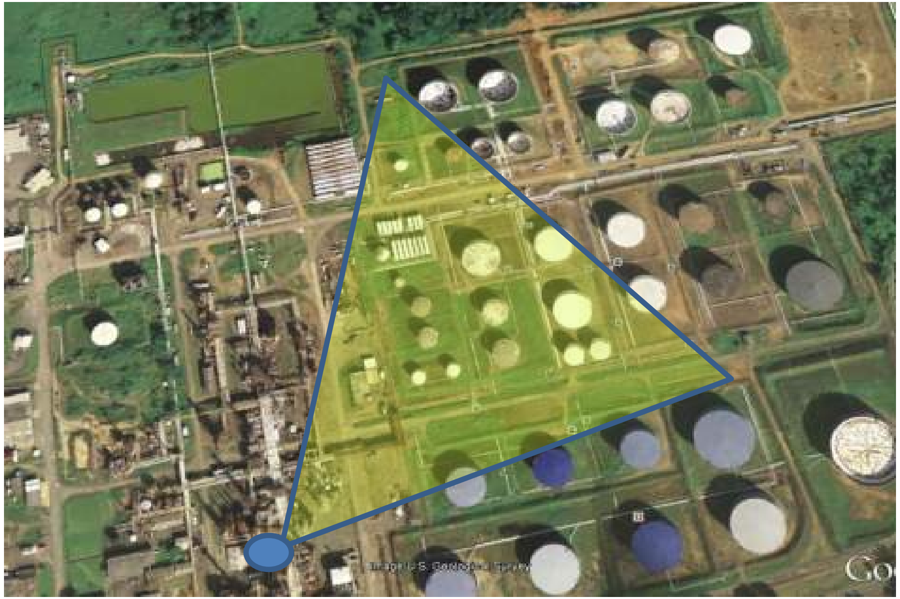
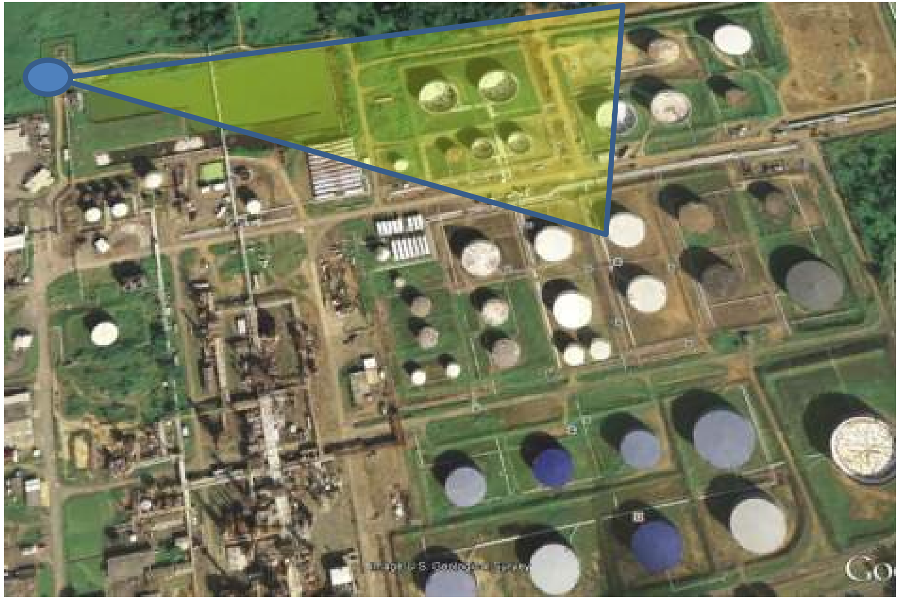


Camera 1



Camera 2

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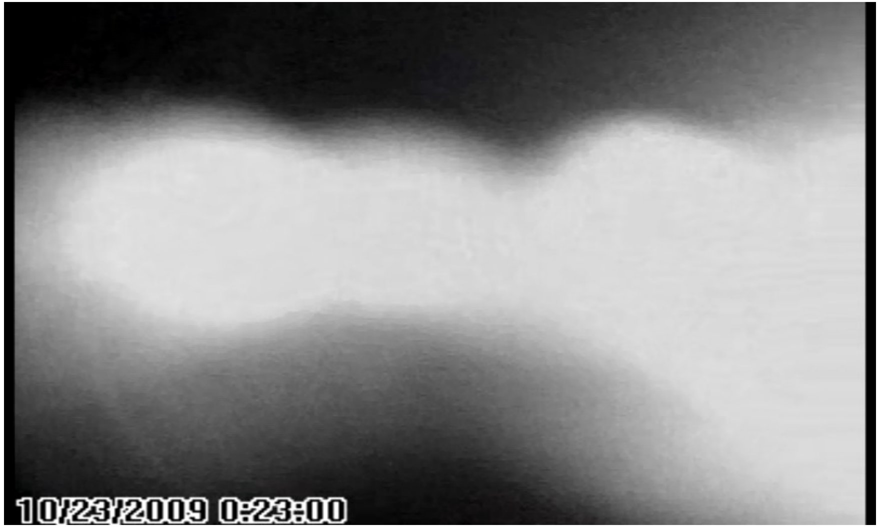
For the first 3 - 4 seconds the images are blurred and overexposed



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

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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

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

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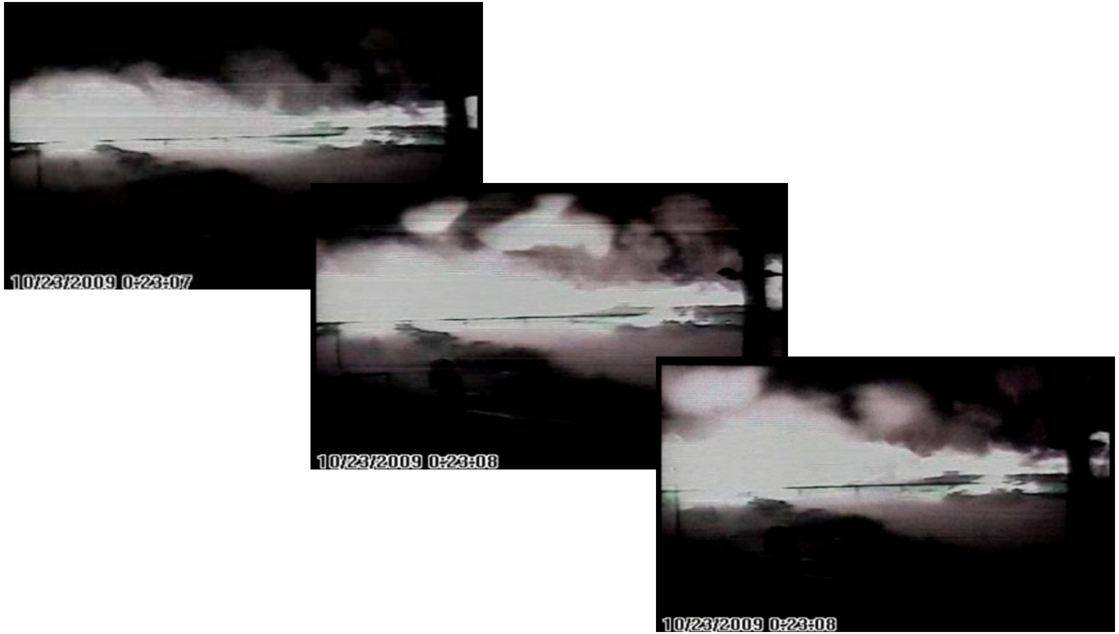
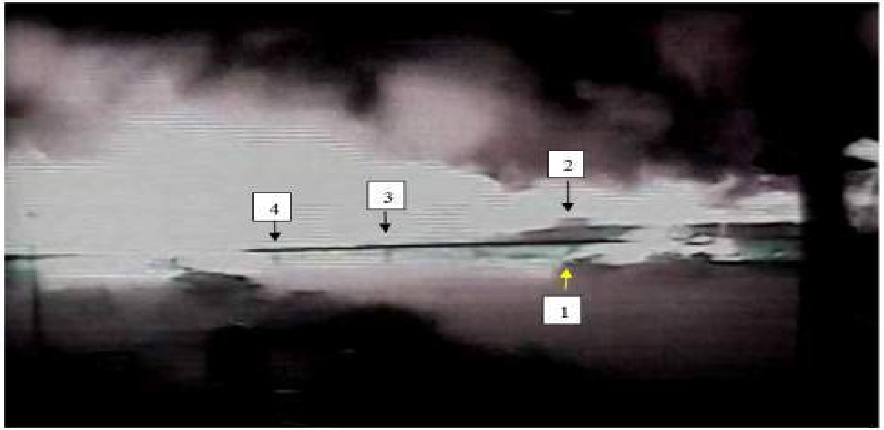
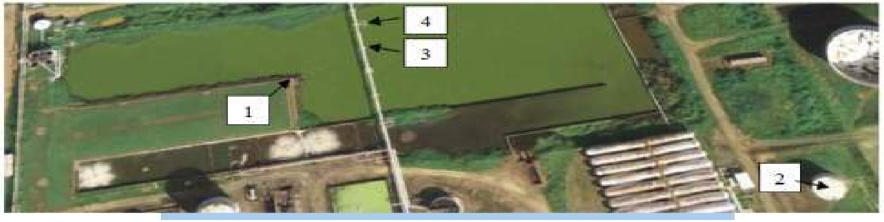


The explosion covered about 140 m in 700 ms - corresponding to a sub-sonic rate of advance (200 m/s).

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





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Transition occurred in an area where there were intersecting pipe racks

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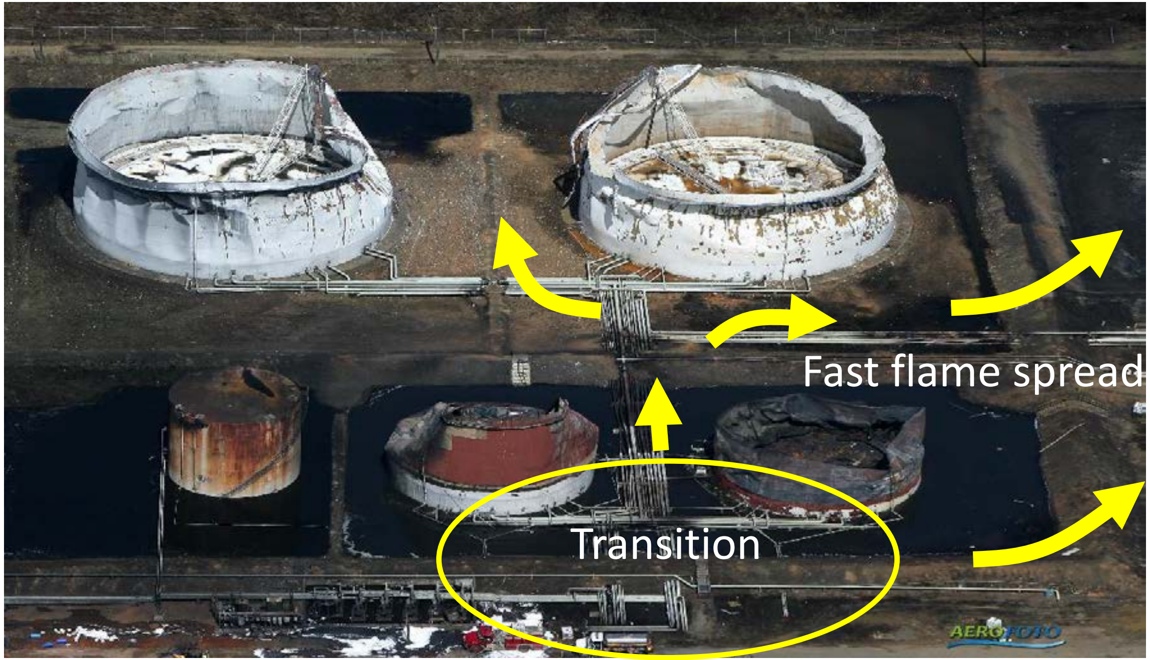

Alternative views of the transition area

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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.

This may explain why transition has occurred so frequently for very large flammable clouds.

Summary

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1. Based on the incidents reviewed, nil-wind scenarios appear to be significant risk contributors for releases up to about 250 kg/s.

2. For clouds that accumulated in nil-wind conditions, the fuel concentration appeared to hardly change 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 appears to be likely for gasoline or LPG.