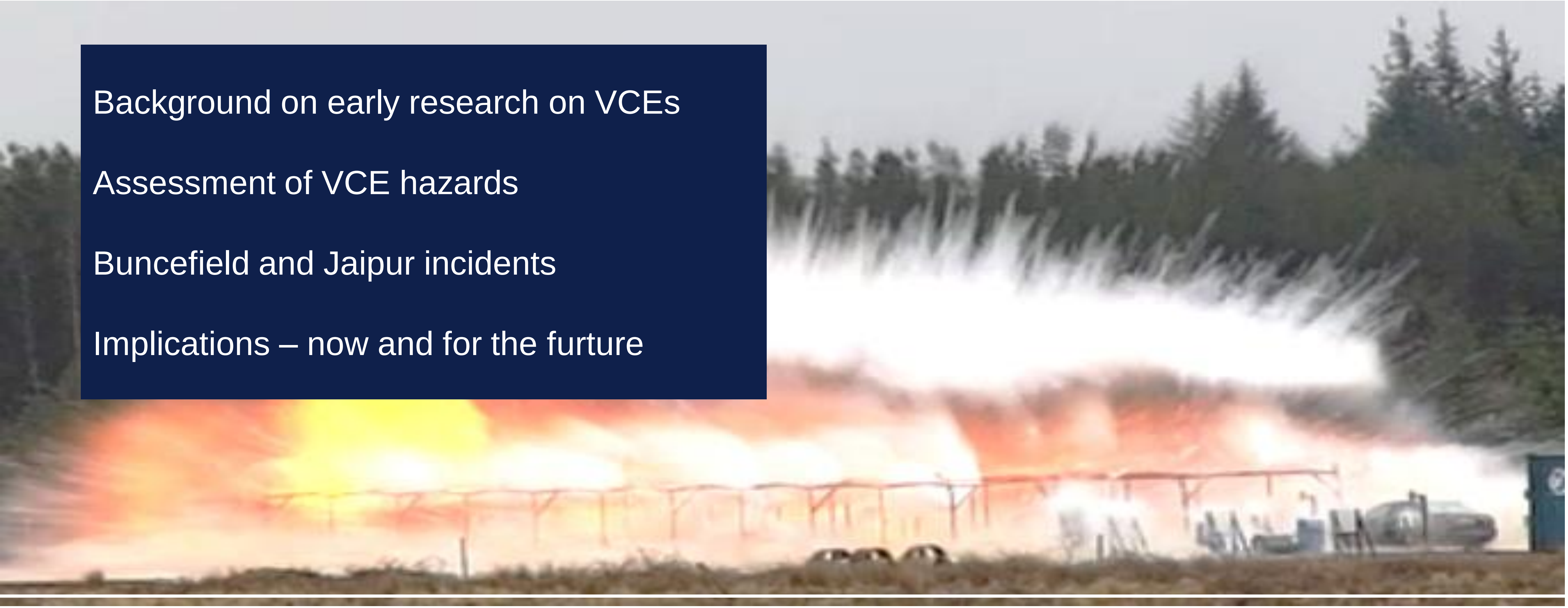
DNV

WHEN TRUST MATTERS

Buncefield & Jaipur Vapour Cloud Explosions

Mike Johnson

Overview



Background on early research on VCEs

Assessment of VCE hazards

Buncefield and Jaipur incidents

Implications – now and for the furture

My History

- Graduated from University of Cambridge with MA in Mathematics
- Joint British Gas Research & Development in 1978
- Initially developing methods for quantitative risk assessment of oil & gas operations

- In 1984, I moved to explosions research…

DNV Spadeadam

Leased from UK Ministry of Defence in 1977

- Continuously manned since that date

Remote & secure site

Conduct of potentially hazardous research and testing

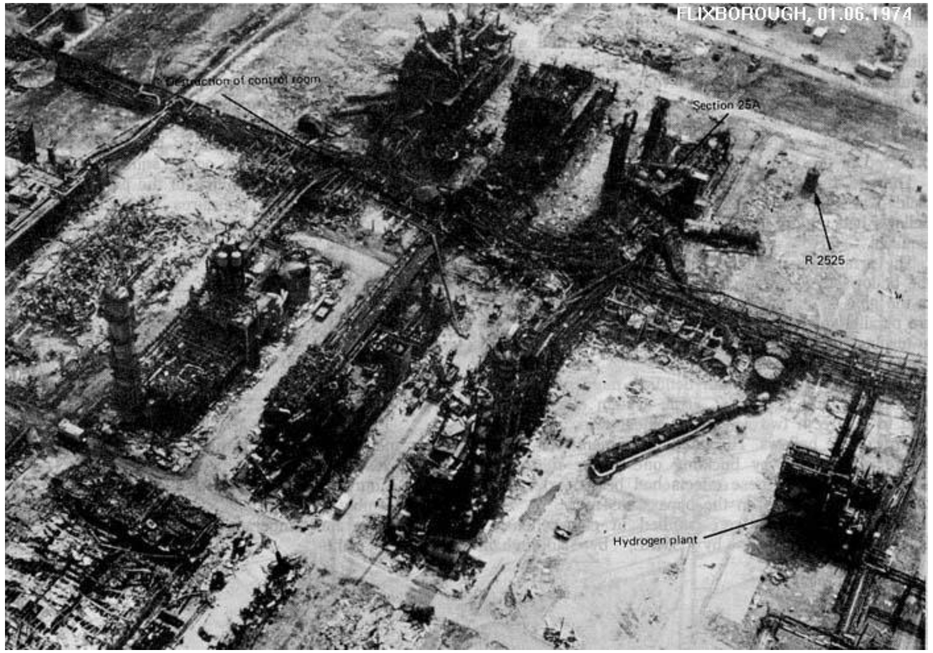
Generation of Pressure in Explosions

Confined Explosion

- Combustion produces hot combustion products
- Volume expansion is prevented by the confinement, so the pressure rises
- For common hydrocarbon-air mixtures, overpressure up to 8bar (governed by expansion ratio)
- Structural failure will generally occur well before this

‘Unconfined’ Vapour Cloud Explosions

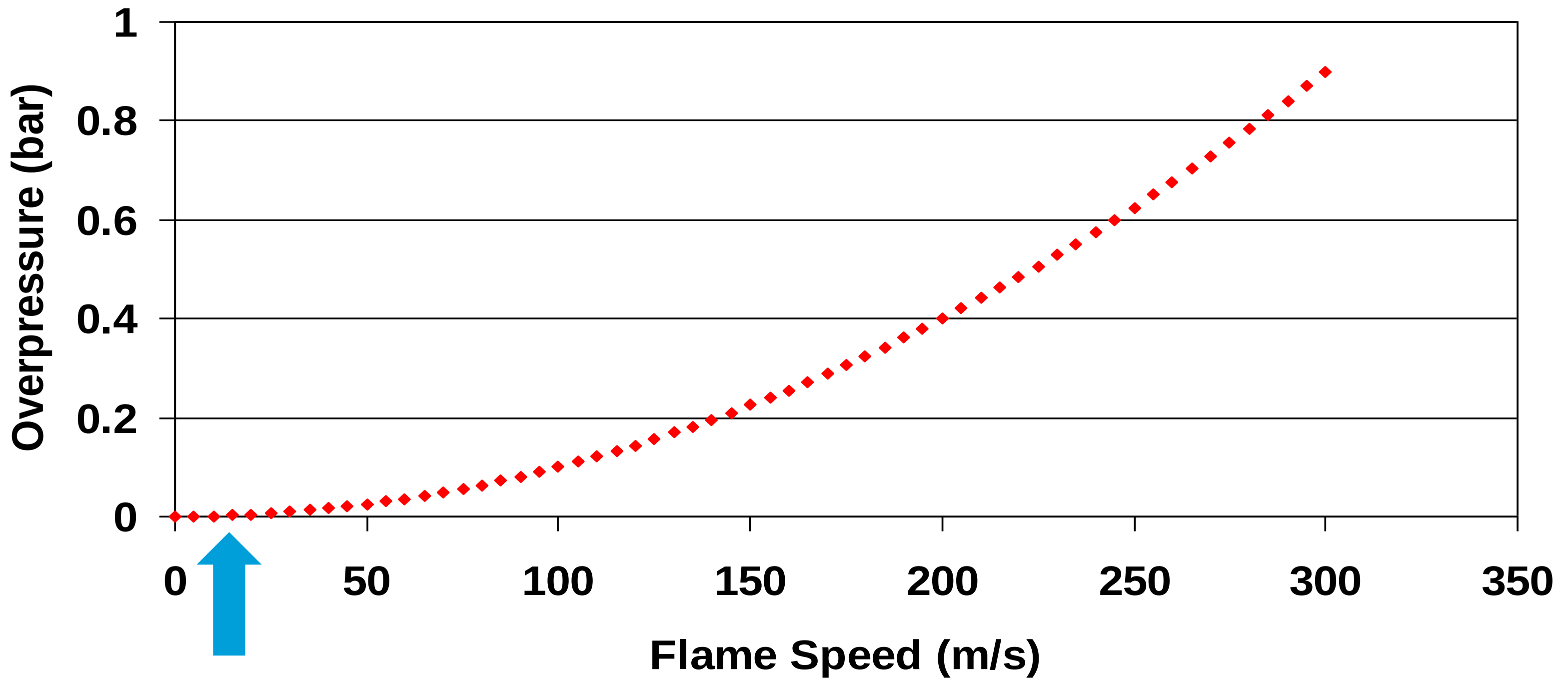
- Major explosions in the 2nd half of the 20th century where the gas/vapour cloud was not confined
- No understanding of the cause of damaging pressures
- A key incident for the UK was in Flixborough in 1974



Flixborough

- 40 tonnes cyclohexane released,
- Vapour cloud 100-200m diameter
- 28 fatalities
  - 18 in control room
  - 9 on site
  - 1 delivery driver
- Structural damage 8km away

Effect of Flame Speed

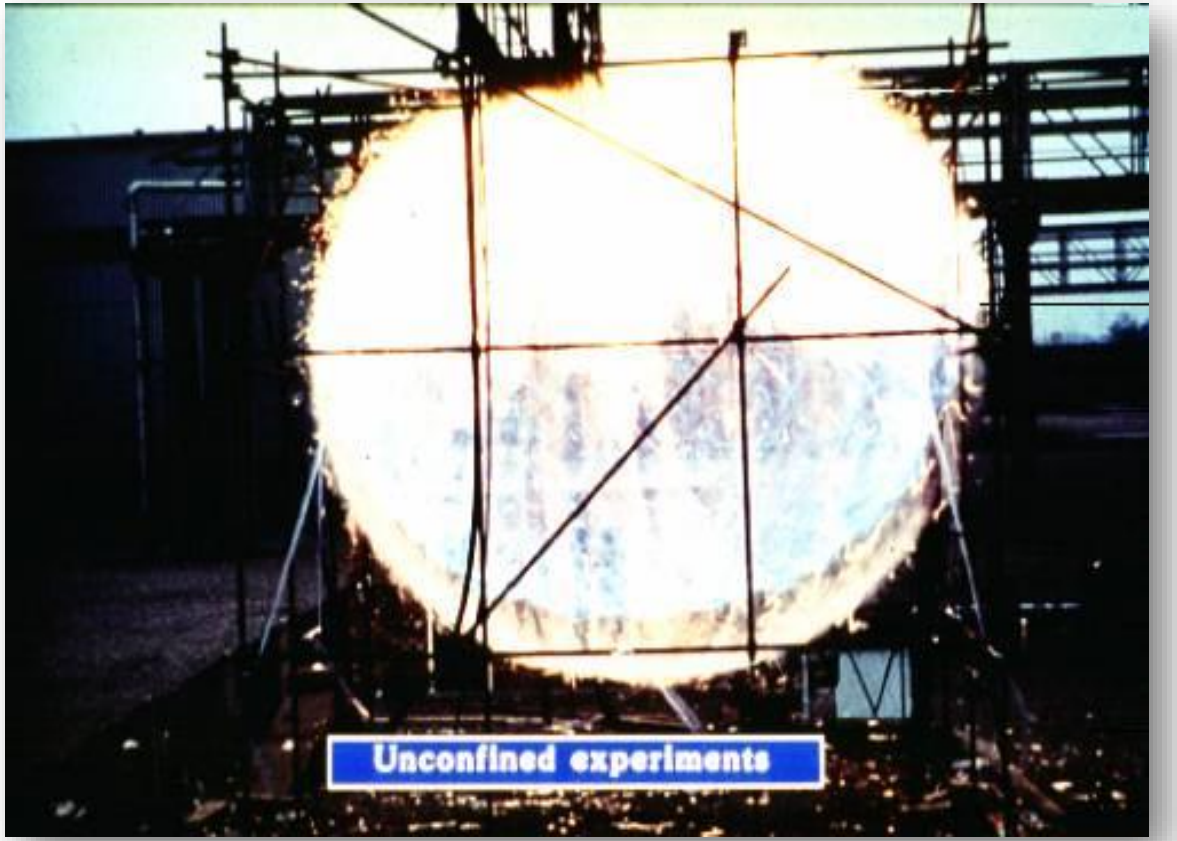


High flame speeds can generate overpressure

But laboratory experiments suggest maximum flame speed of 5-20ms^{-1} for typical hydrocarbons

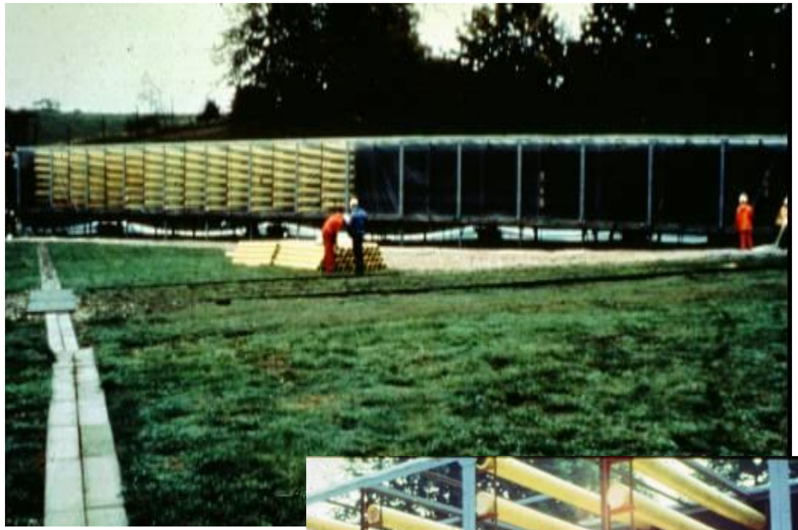
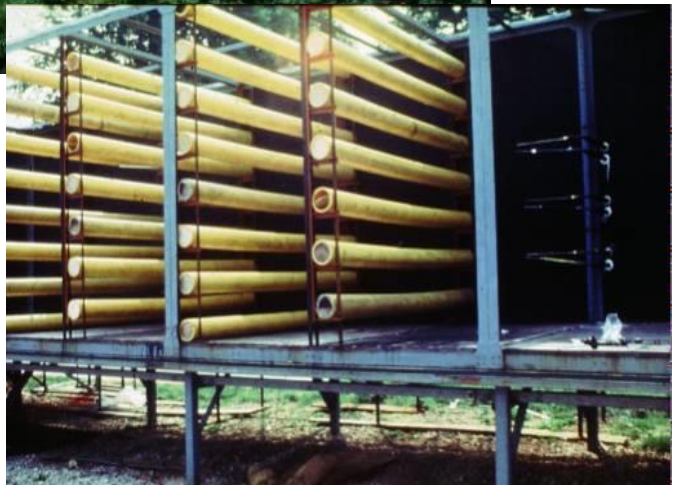
Large Unconfined Vapour Clouds

- Experiments involving large gas clouds showed that the size of the release alone was not sufficient explanation, flame speeds remained low

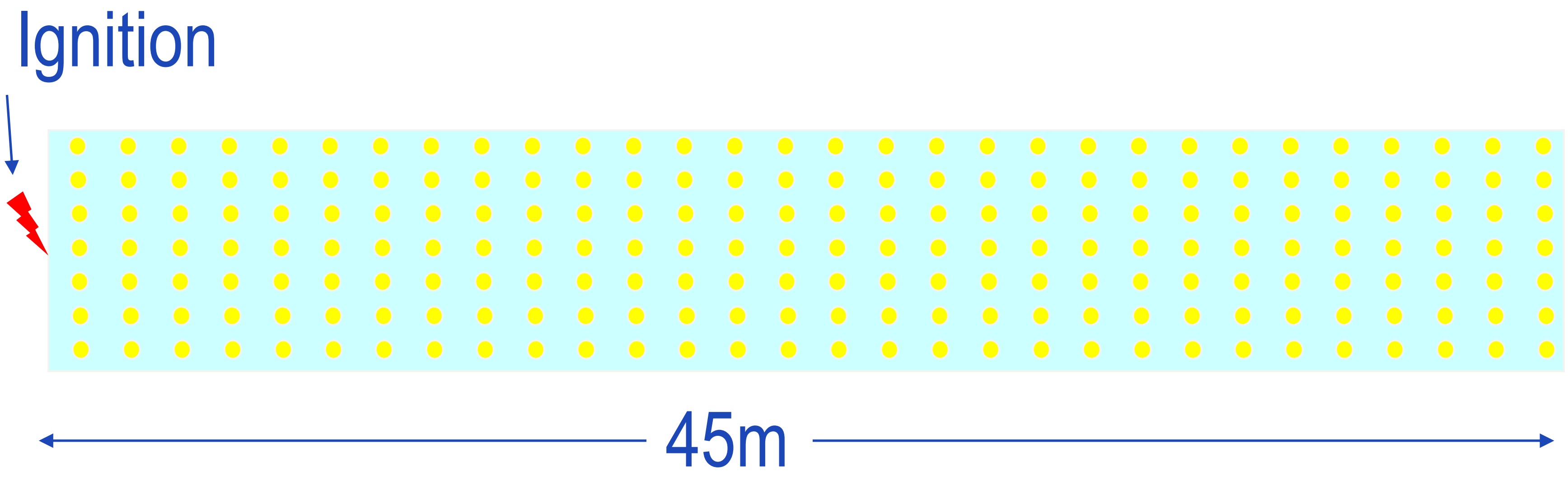


Effect of Process Congestion

- One characteristic was that clouds usually engulfed congested process areas
- Research examined the effect of pipework in the gas cloud
  - Conducted ~1980-1986
  - No computer models
  - Simple regular obstacle arrangement
  - Parameter variations easily specified

Experimental Arrangement



Flame Acceleration – Natural Gas

Maximum flame speed ~100m/s

Expansion of combustion products produces flow

Turbulence in flow increases the burning velocity

Flame acceleration

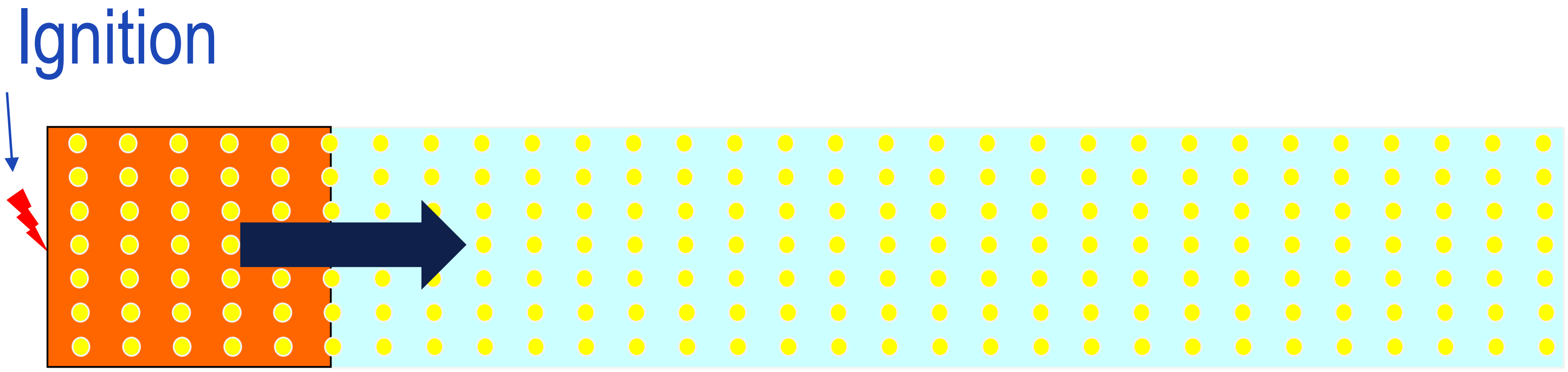
Flame Acceleration – Cyclohexane

Maximum flame speed ~230m/s

Maximum pressure ~700 mbar

Clear difference between fuels

Addition of Initial Confinement



All flow directed through obstacles - enhancing turbulence generation and increases in burning velocity

Natural Gas

Flame speed ~550m/s

Rapid initial flame acceleration

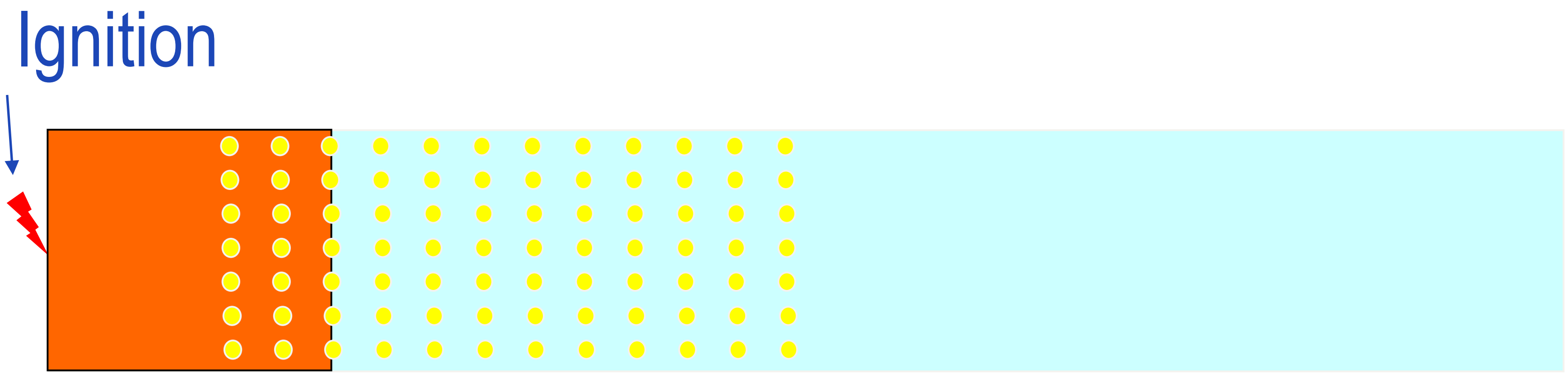
Supersonic deflagration

Still dependent on continued presence of process congestion

Confinement and Congestion

- Now with a much stronger initial confinement
- Allows repeated experiments

Cyclohexane and Propane



Cyclohexane

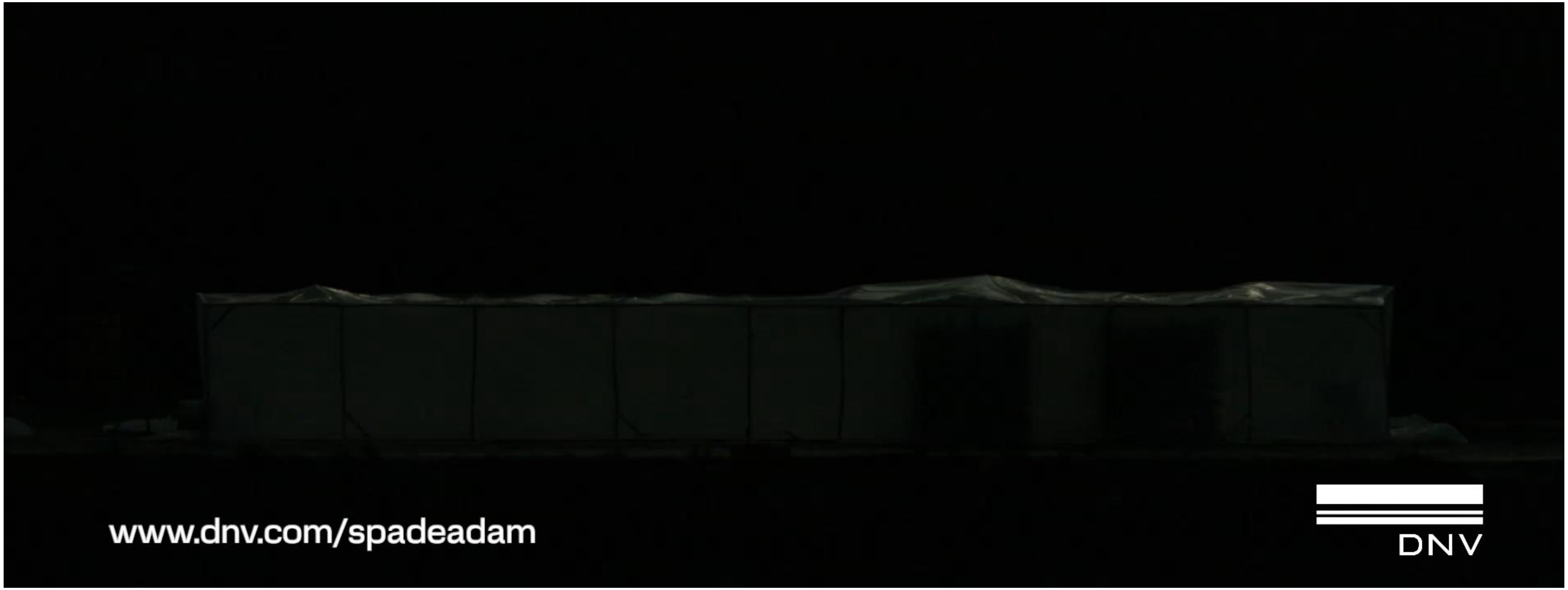
Transition from deflagration to detonation (DDT)

Detonation propagates at 1.8km/s with pressures of 20 bar

Deflagration to Detonation Transition (DDT)

20 bar shock wave compresses mixture to autoignition temperature

Combustion maintains shock wave – self sustaining and not dependent on congestion



Late 20th Century

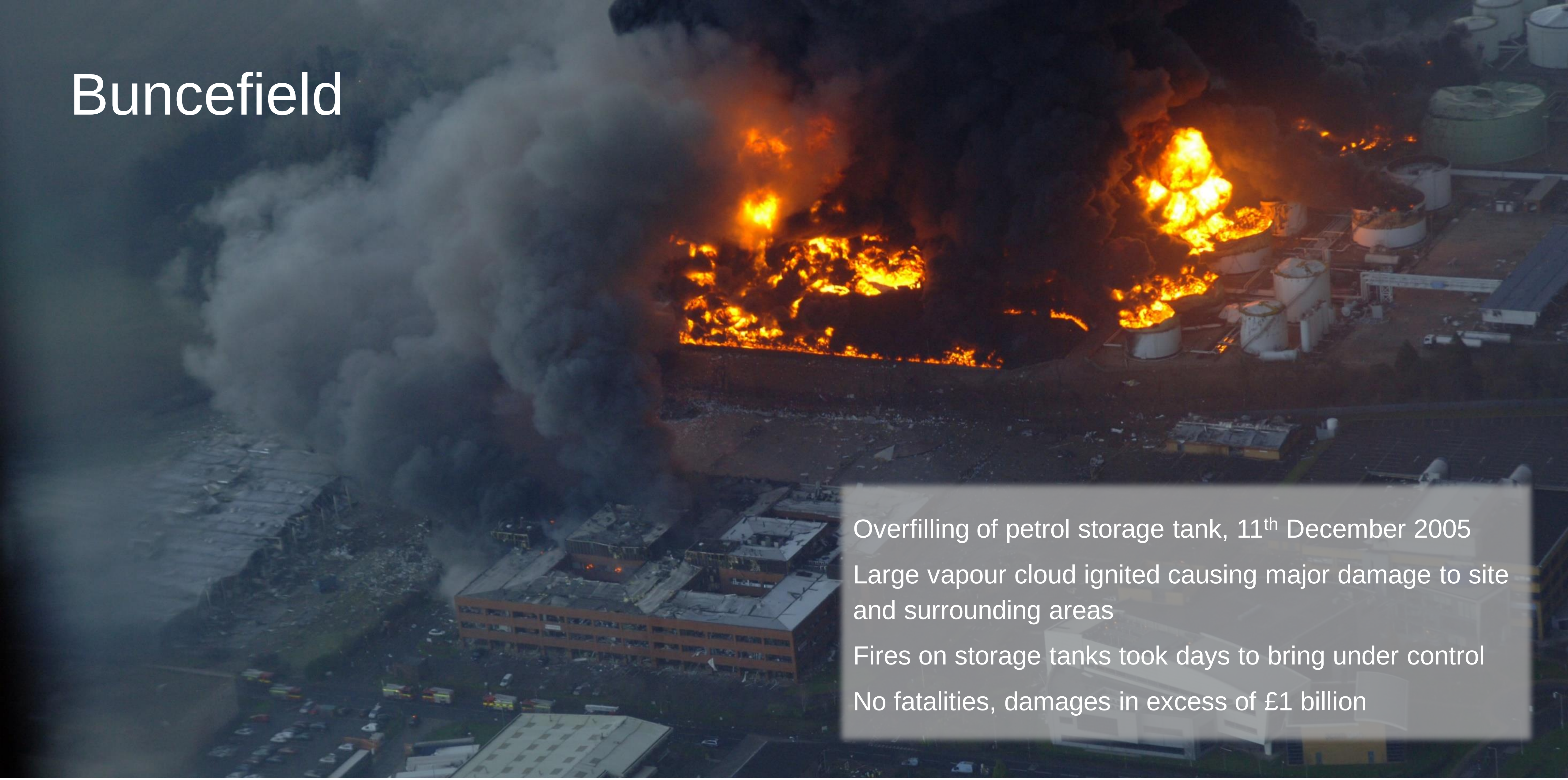
Results of experimental research published in 1988

DDT ignored by industry or considered unrealistic for common hydrocarbons

Industry adopted assessment based on deflagrations limited to process regions

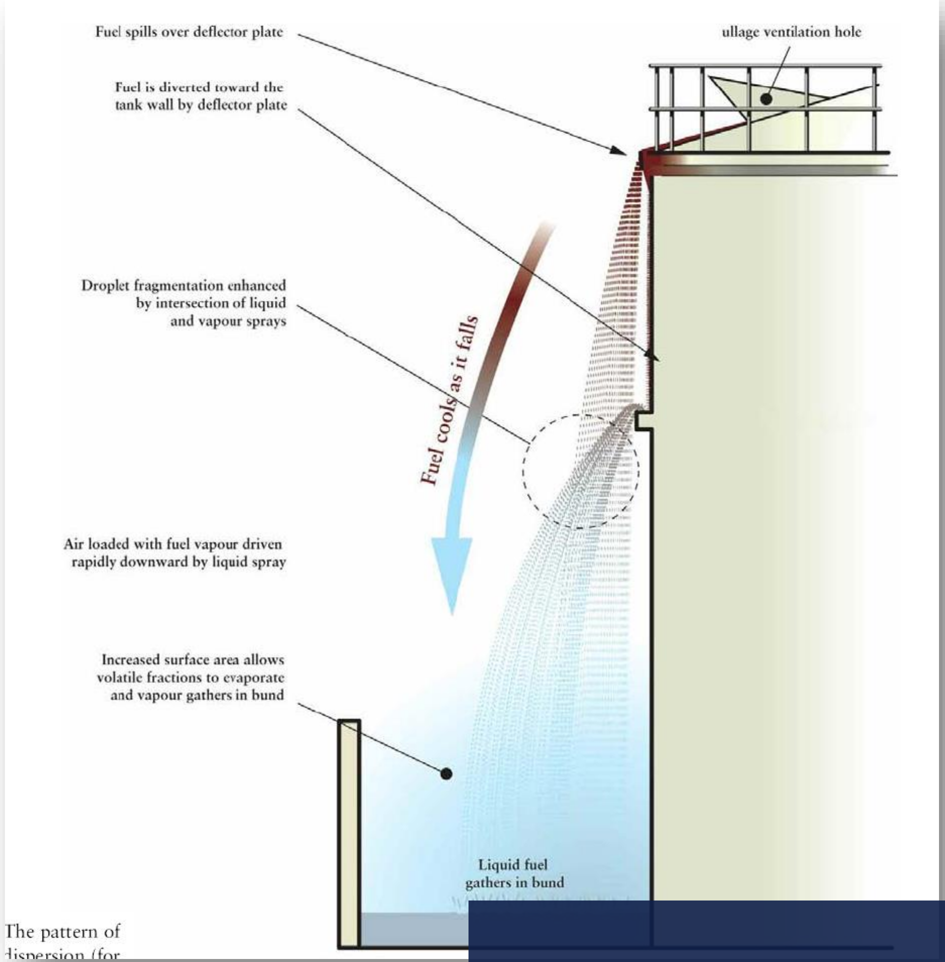
But……

Buncefield



- Overfilling of petrol storage tank, 11th December 2005
- Large vapour cloud ignited causing major damage to site and surrounding areas
- Fires on storage tanks took days to bring under control
- No fatalities, damages in excess of £1 billion

Vapour Cloud



Dispersion enhanced by break up of fuel into droplets as it fell from tank roof, generating large surface area for vapour evaporation

Vapour cloud extended offsite

Buncefield

- Vapour cloud formed over a period of about 25 minutes
- Ignition when fire water pumps were turned on

Buncefield

- Fires at Buncefield involved many storage tanks

- Burned for several days

Explosion Damage

- Severe explosion damage to buildings, vehicles etc
- Wherever vapour cloud was present, even in open areas

Jaipur

- Spillage of petrol from valve on outlet from tank 401A

Source of Spillage

- Source of leak was a ‘Blind Hammer Valve’ on the tank outlet
- Changing from blocked to open required a short period where the top is open to the atmosphere
- Valve upstream isolating the storage tank opened
- Fuel driven out of valve opening by tank hydraulic pressure

Jaipur – October 2009

1000Te of petrol spilled as a ‘geyser’ from the tank outlet pipe

Again break-up of liquid into droplets enhanced vapour generation

In calm conditions, vapour cloud spread to cover most of the site (an area 3 times that of the Buncefield cloud)

Characteristics of Buncefield and Jaipur Incidents

Very little process congestion on sites

Dense vapour cloud covering large area

Widespread severe blast damage through most of the vapour cloud

Does this indicate a detonation of the cloud?

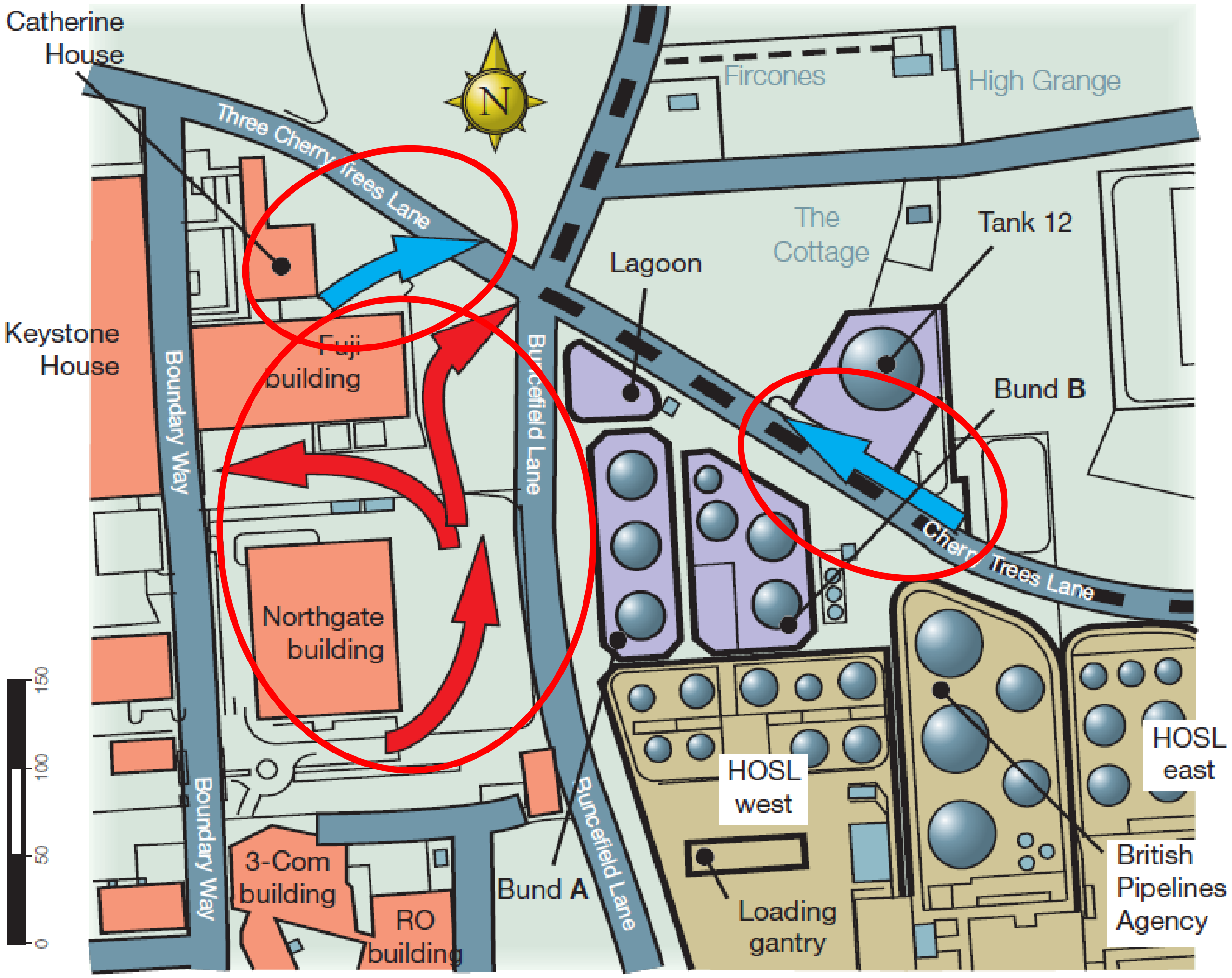
Directional Indicators

- Observed throughout clouds in Buncefield and Jaipur incidents
  - Bent or leaning lampposts
  - Trees scorched on one side
  - Branches on trees snapped and bent over in one direction
  - Scoured paintwork on one side of posts

Initial Investigation

- Early Buncefield report gave initial assessment of the directional indicators
- Suggested three explosion events!! (Indicated by the red and blue arrows)

Assumed direction of explosion

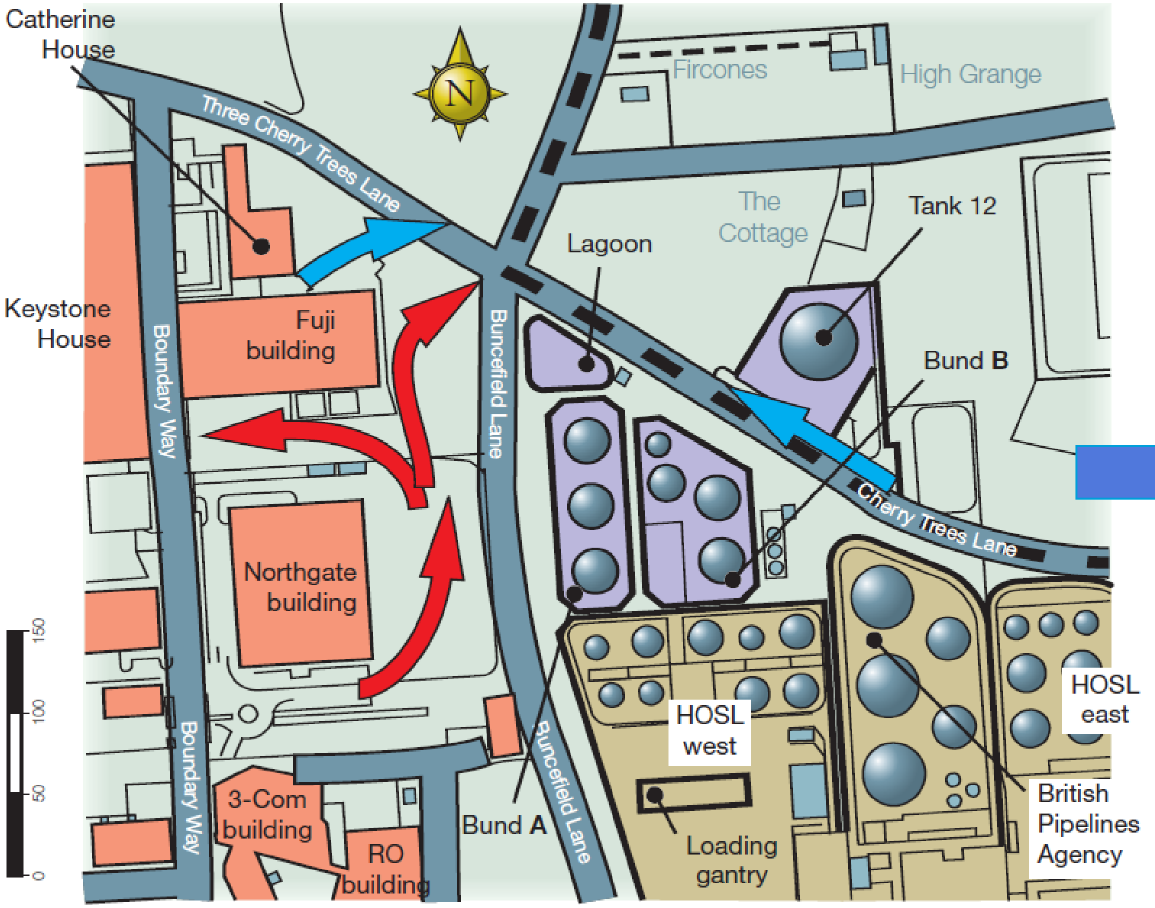


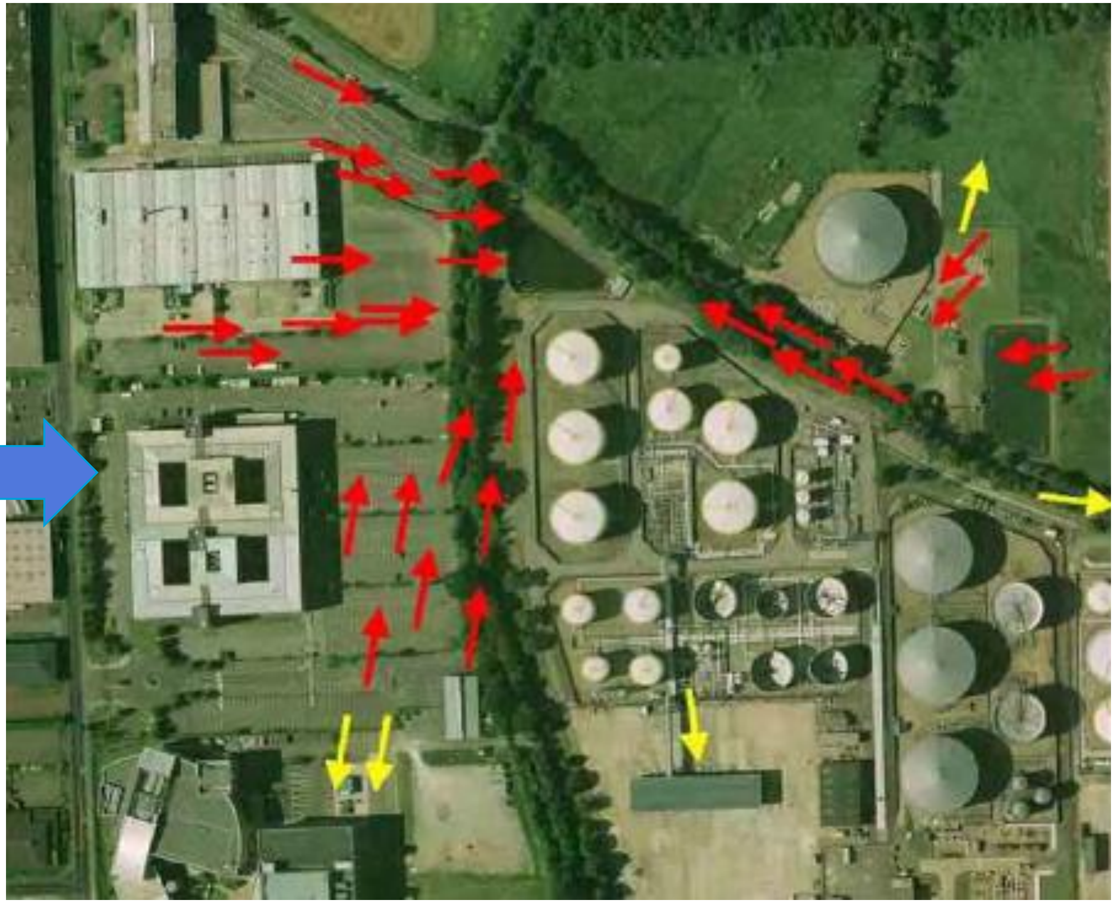
Directional Indicators

- Experimental work showed significant reverse flow
- Modelling confirmed net force in reverse direction

Re-interpret as opposite direction of explosion

Directional Indicators - Buncefield



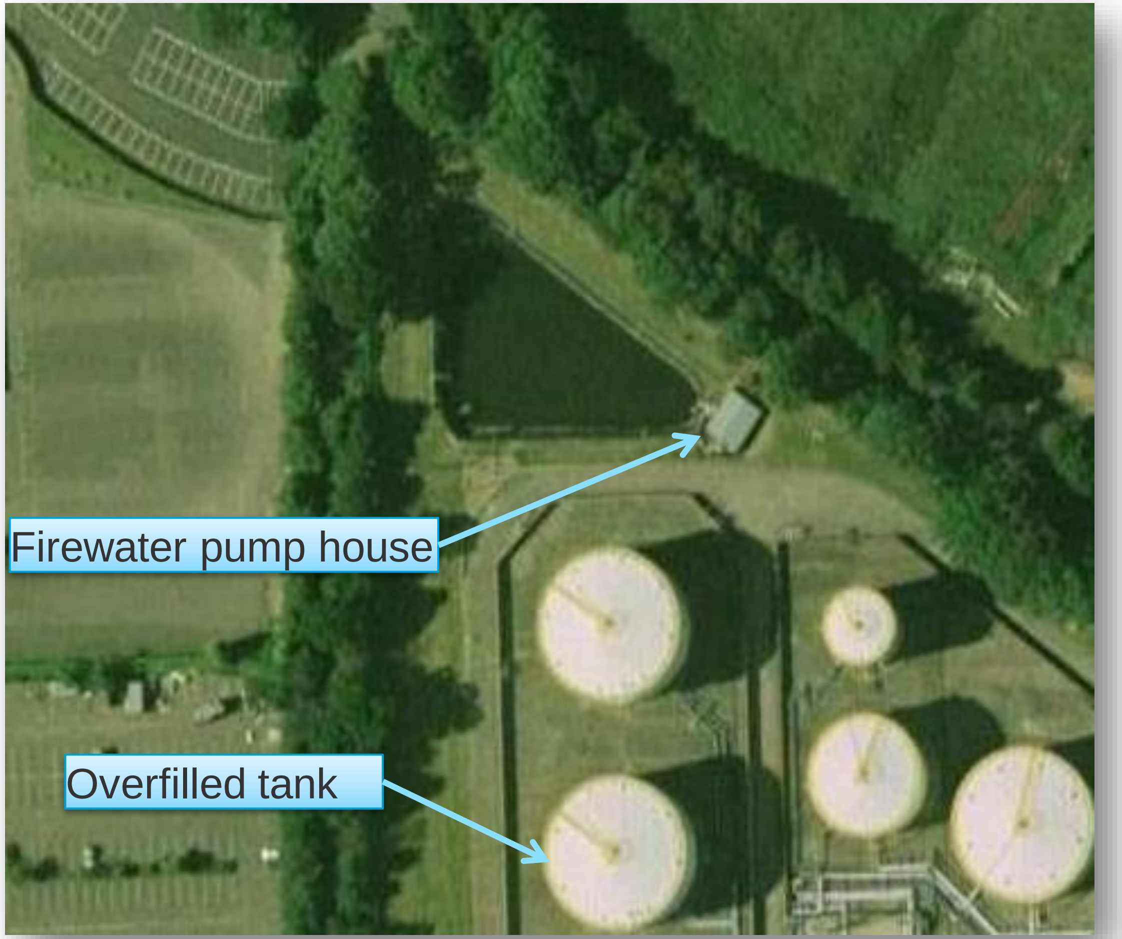


Red inside cloud, Yellow outside cloud

Red arrows point to location of DDT

Cause of Flame Acceleration and DDT at Buncefield

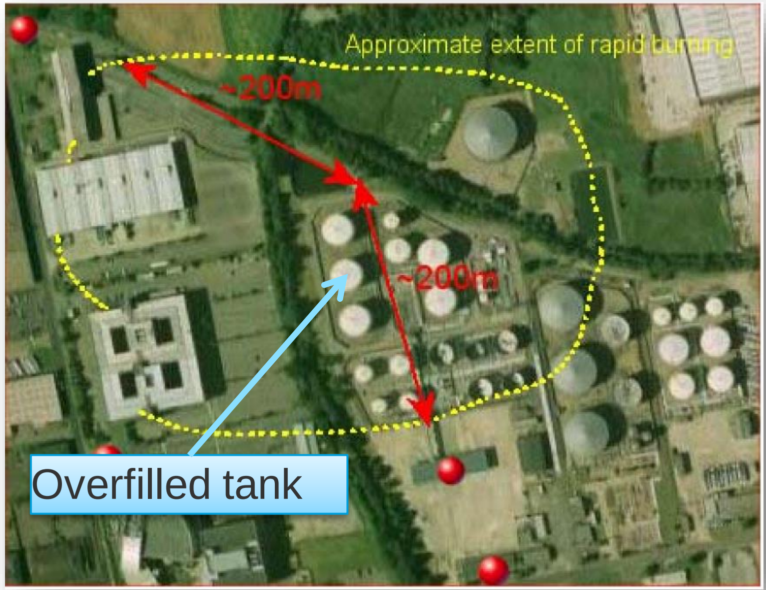
- Site had very little pipework congestion
- However there was dense undergrowth and trees along the site boundary
- Could the congestion cause flame acceleration?

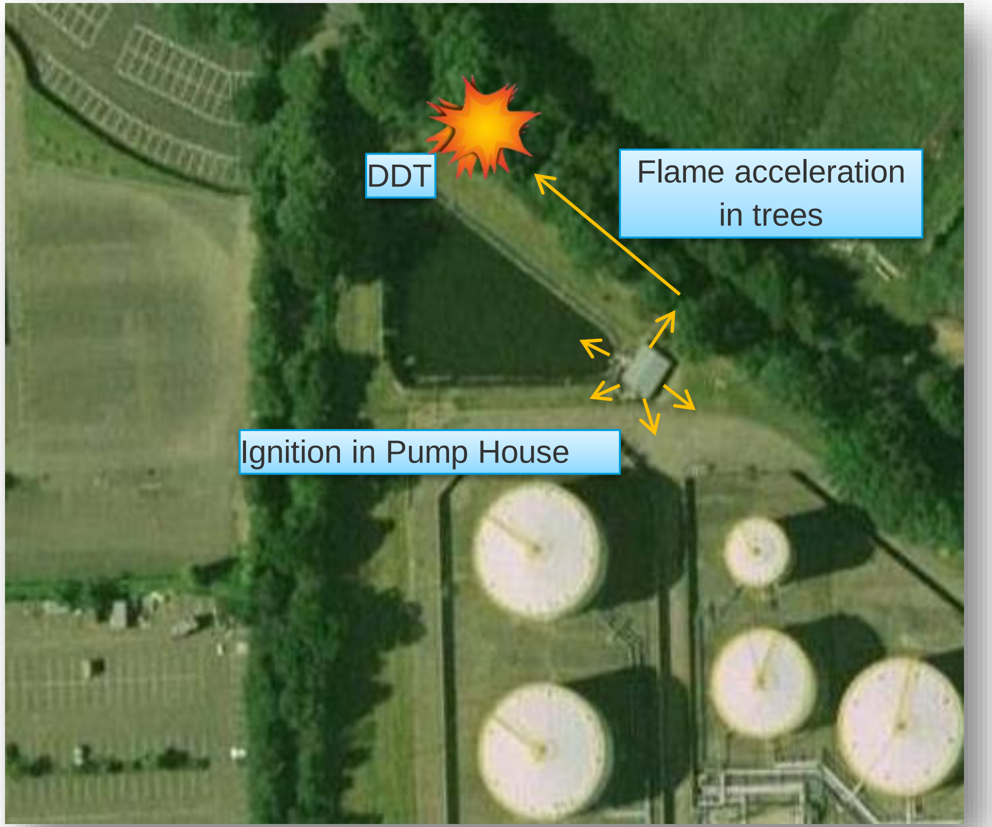


Cause of Flame Acceleration and DDT at Buncefield

- Experiments in tree congestion:
  - **Low density:**
    - Reaches limiting flame speed at sub-sonic
    - Low pressures
  - **High Density:**
    - Continuous flame acceleration to DDT
    - Short distance of flame propagation – as little as 12m from point of ignition
    - Sustained when flame emerged from vegetation

Buncefield


Approximate extent of rapid burning
~200m
~200m
Overfilled tank


DDT
Flame acceleration in trees
Ignition in Pump House

Directional Indicators - Jaipur

- Large red arrows show summary of many directional indicator measurements
- Point towards a single source, as in Buncefield
- <u>Indicates location of DDT</u>
- Most likely due to flame venting from an explosion in a building

Damage to Cars – Short Duration Shock Loadings

Outside the Cloud

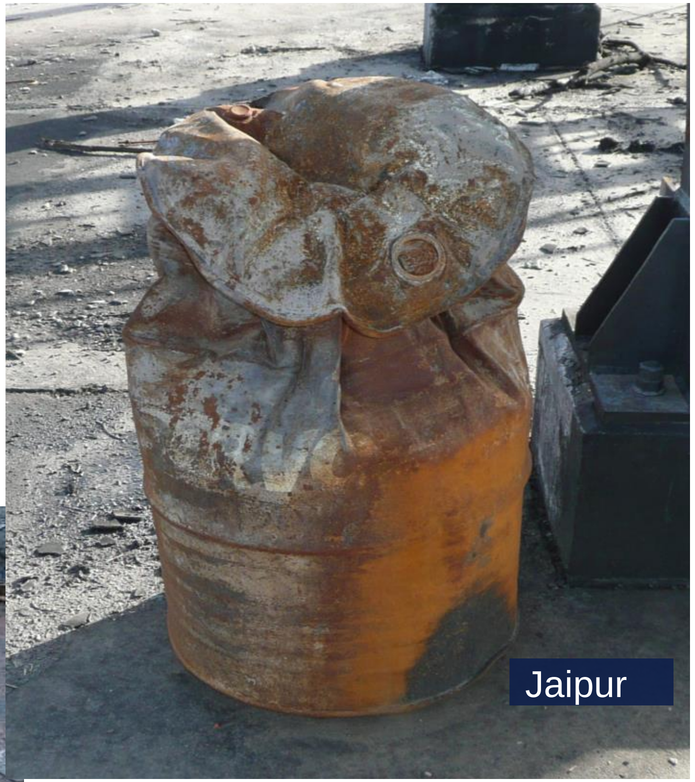
Inside the Cloud

Damage to Oil Drums

Shock loading up to 4.4bar

Deflagration loading up to 1.8bar

Inside the Cloud



Jaipur

Other Vapour Cloud Explosion Incidents

- Recent publication of a review of VCE incidents*

- Evidence consistent with DDT in most major VCEs
  - Pressure damage
  - Directional indicators

Skikda, Algeria, 2004

Paraguaná Refinery Complex, 2012

Flixborough 1974

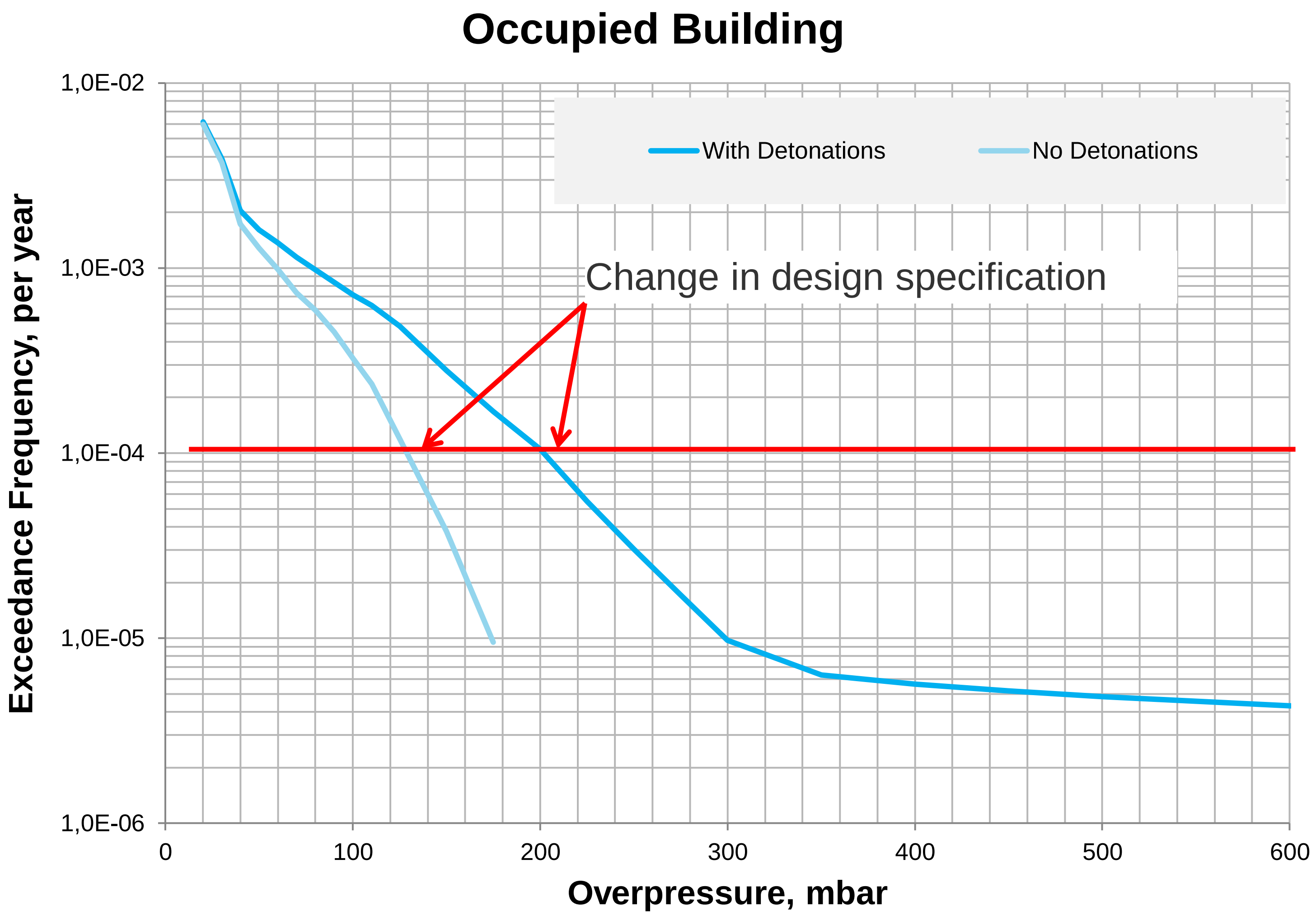
** G. Chamberlain, E. Oran, A. Pekalski, Detonations in industrial vapour cloud explosions, Journal of Loss Prevention in the Process Industries, Volume 62, November 2019, 103918*

So is this Very Bad News?

- First reaction can be ‘*I can’t design against for a 20bar detonation pressure*’
- So it looks like very bad news

- However, current good practice will minimise the risk:
  - Prevention or minimising release or spill is even more important
  - Separation of occupied buildings from process area (minimises effect on design strength)
  - Reducing potential for flame acceleration
  - Maintaining safety critical systems to original design intent

Risk Based Building Design



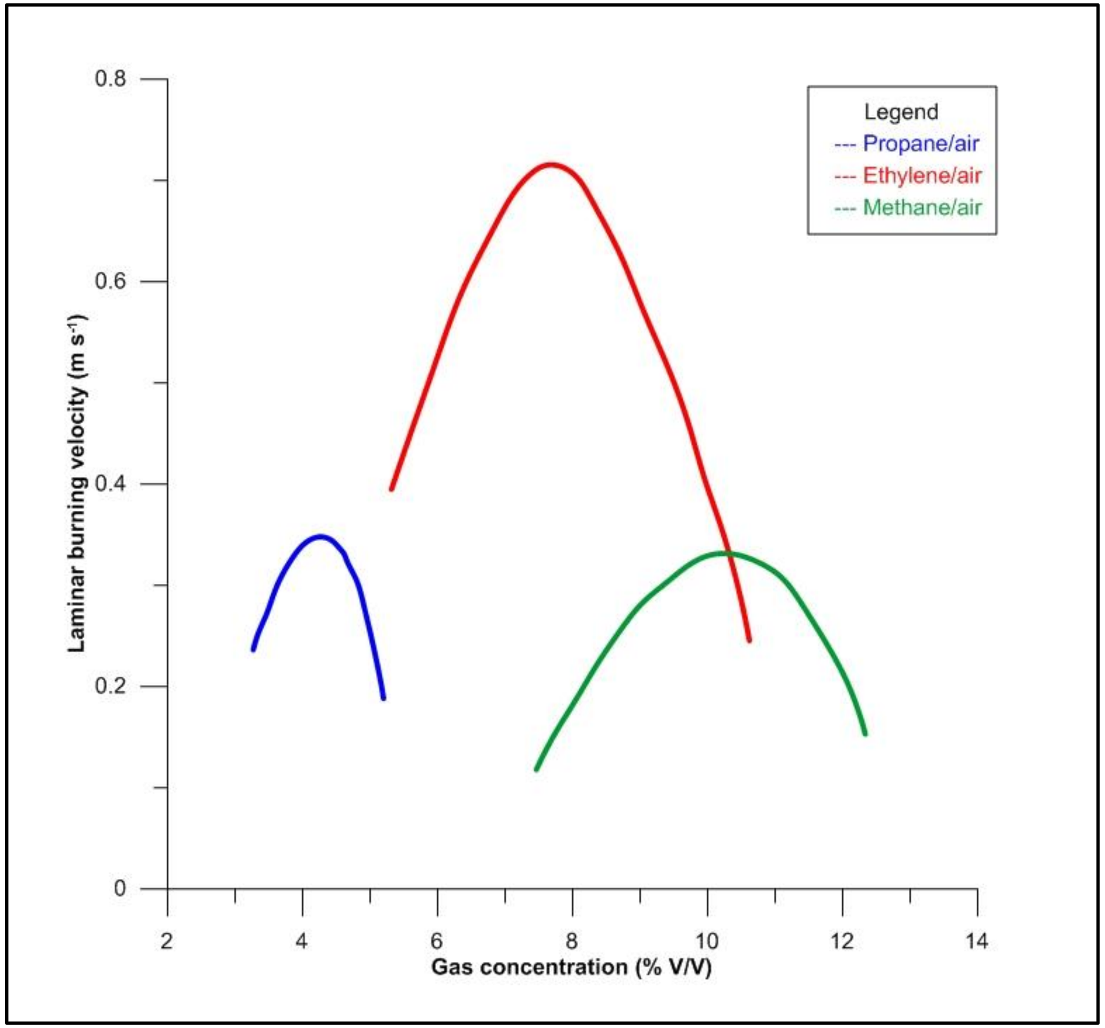
And the future?

One fuel property that governs reactivity is burning velocity

This is the speed a flame burns through the mixture ahead of it

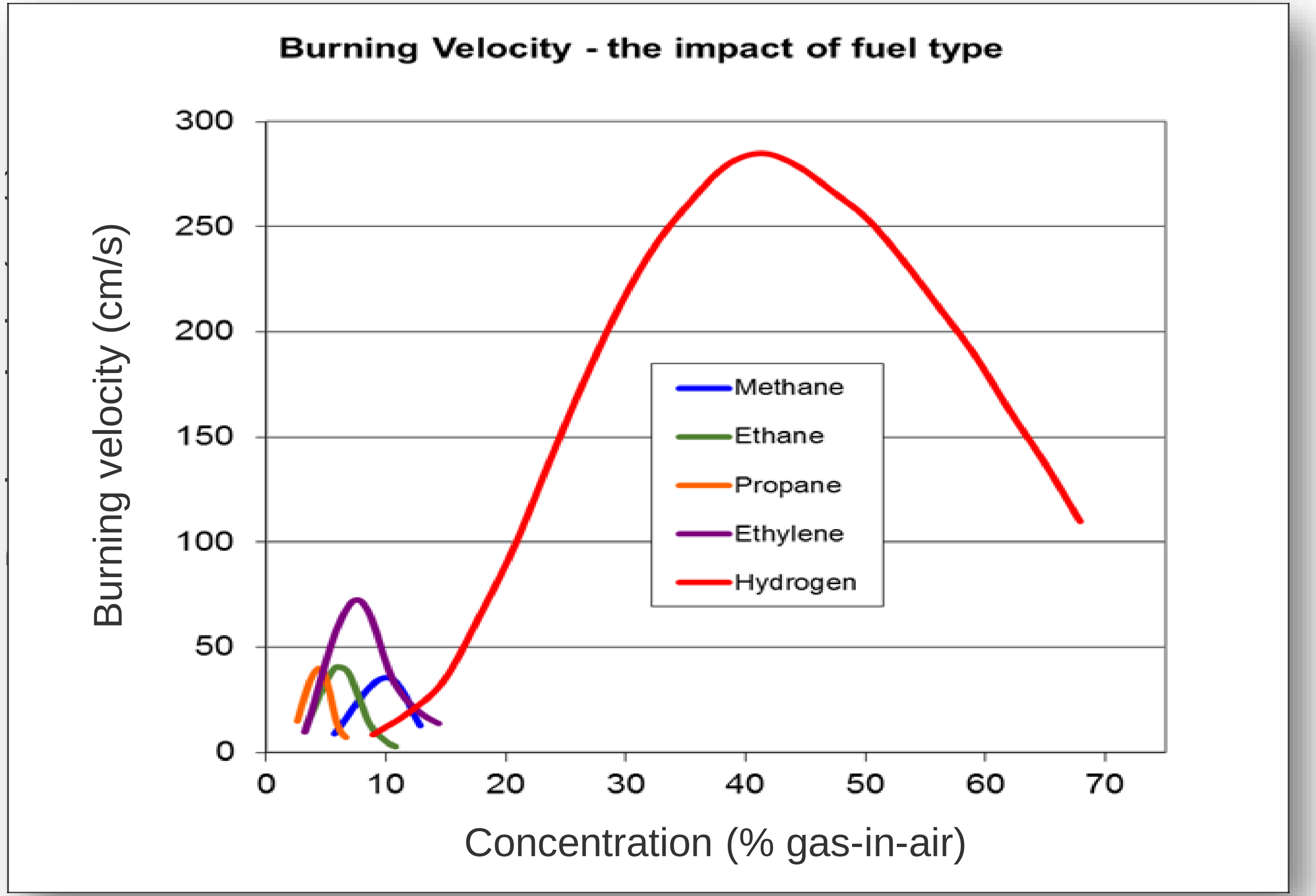
This is the plot of burning velocity for 3 common hydrocarbons across their flammable range

So what about hydrogen – which may have a significant role in the energy transition?



Burning Velocity Comparison with Hydrogen

- Hydrogen has a much higher burning velocity than hydrocarbons

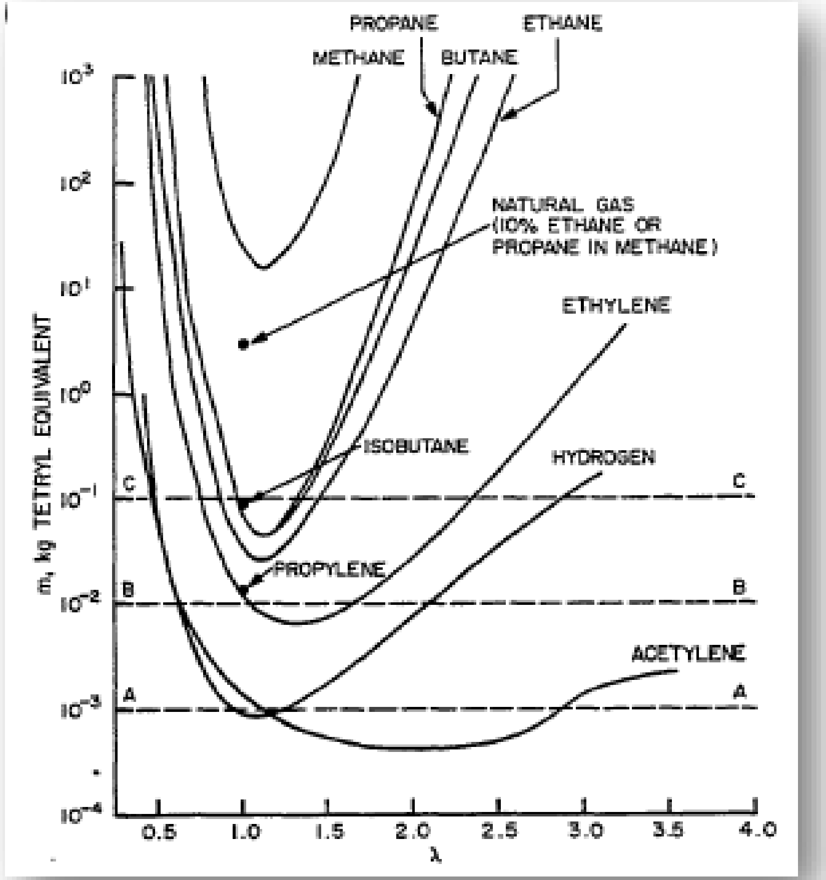


Explosion Detonation Initiation

- Initiation of detonation quantified by explosive mass required to initiate a detonation

Fuel	Minimum Mass tetryl (g)
Methane	16,000
Propane	37
Ethylene	5.2
Acetylene	0.4
Hydrogen	0.8

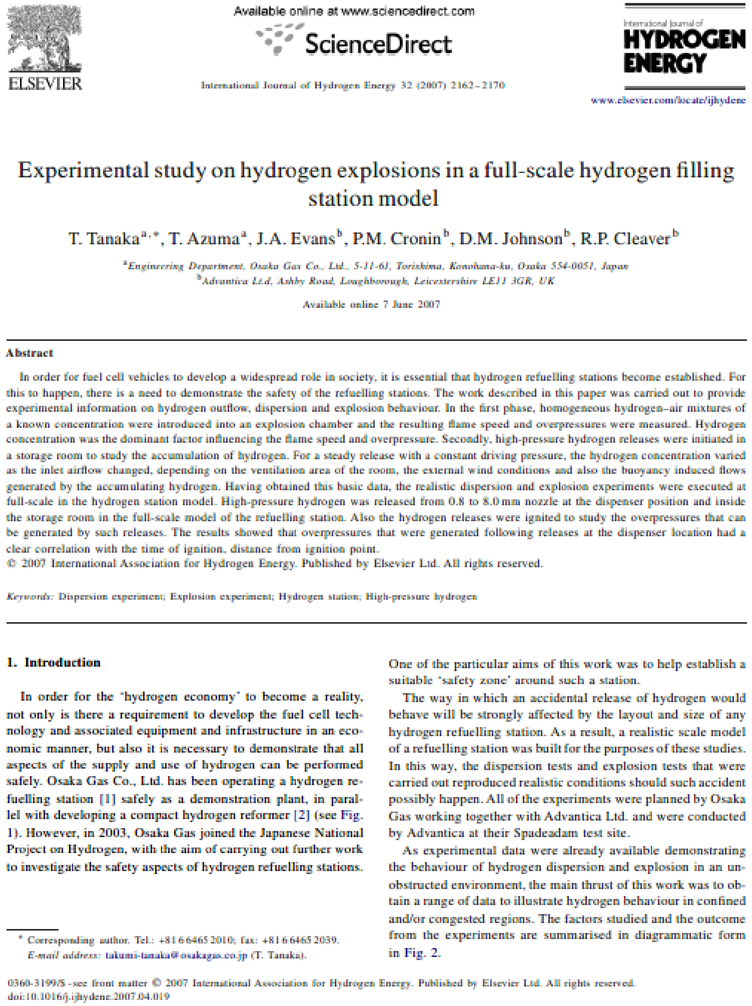
- Natural Gas detonations ~*NEVER* happen
- Hydrogen detonations are entirely credible, if not likely



Concentration limits to the initiation of unconfined detonation in fuel/air mixtures, DC Bull, Transactions of the Institute of Chemical Engineers, Volume 57, Number 4, Pages 219-2271979 (λ indicates the concentration relative to stoichiometric)

Japanese National Project on Hydrogen

- DNV Spadeadam contracted to conduct experimental research related to hydrogen refuelling stations
- Tests with 100% hydrogen with pressures up to 400 bar
  - Dispersion, gas build-up, explosions
  - Idealised arrangements
  - Full scale mock-up of refuelling station



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International Journal of Hydrogen Energy 32 (2007) 2162–2170

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Experimental study on hydrogen explosions in a full-scale hydrogen filling station model

T. Tanaka[a,*], T. Azuma[a], J.A. Evans[b], P.M. Cronin[b], D.M. Johnson[b], R.P. Cleaver[b]

[a]Engineering Department, Osaka Gas Co., Ltd., 5-11-61, Torishima, Konohana-ku, Osaka 554-0051, Japan

[b]Advantica Ltd, Ashby Road, Loughborough, Leicestershire LE11 3GR, UK

Available online 7 June 2007

Abstract

In order for fuel cell vehicles to develop a widespread role in society, it is essential that hydrogen refuelling stations become established. For this to happen, there is a need to demonstrate the safety of the refuelling stations. The work described in this paper was carried out to provide experimental information on hydrogen outflow, dispersion and explosion behaviour. In the first phase, homogeneous hydrogen–air mixtures of a known concentration were introduced into an explosion chamber and the resulting flame speed and overpressures were measured. Hydrogen concentration was the dominant factor influencing the flame speed and overpressure. Secondly, high-pressure hydrogen releases were initiated in a storage room to study the accumulation of hydrogen. For a steady release with a constant driving pressure, the hydrogen concentration varied as the inlet airflow changed, depending on the ventilation area of the room, the external wind conditions and also the buoyancy induced flows generated by the accumulating hydrogen. Having obtained this basic data, the realistic dispersion and explosion experiments were executed at full-scale in the hydrogen station model. High-pressure hydrogen was released from 0.8 to 8.0 mm nozzle at the dispenser position and inside the storage room in the full-scale model of the refuelling station. Also the hydrogen releases were ignited to study the overpressures that can be generated by such releases. The results showed that overpressures that were generated following releases at the dispenser location had a clear correlation with the time of ignition, distance from ignition point.

Keywords: Dispersion experiment; Explosion experiment; Hydrogen station; High-pressure hydrogen

1. Introduction

In order for the 'hydrogen economy' to become a reality, not only is there a requirement to develop the fuel cell technology and associated equipment and infrastructure in an economic manner, but also it is necessary to demonstrate that all aspects of the supply and use of hydrogen can be performed safely. Osaka Gas Co., Ltd. has been operating a hydrogen refuelling station [1] safely as a demonstration plant, in parallel with developing a compact hydrogen reformer [2] (see Fig. 1). However, in 2003, Osaka Gas joined the Japanese National Project on Hydrogen, with the aim of carrying out further work to investigate the safety aspects of hydrogen refuelling stations. One of the particular aims of this work was to help establish a suitable 'safety zone' around such a station.

The way in which an accidental release of hydrogen would behave will be strongly affected by the layout and size of any hydrogen refuelling station. As a result, a realistic scale model of a refuelling station was built for the purposes of these studies. In this way, the dispersion tests and explosion tests that were carried out reproduced realistic conditions should such accident possibly happen. All of the experiments were planned by Osaka Gas working together with Advantica Ltd. and were conducted by Advantica at their Spadeadam test site.

As experimental data were already available demonstrating the behaviour of hydrogen dispersion and explosion in an unobstructed environment, the main thrust of this work was to obtain a range of data to illustrate hydrogen behaviour in confined and/or congested regions. The factors studied and the outcome from the experiments are summarised in diagrammatic form in Fig. 2.

* Corresponding author. Tel.: +81 6 6465 2010; fax: +81 6 6465 2039.
E-mail address: takumi-tanaka@osakagas.co.jp (T. Tanaka).

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doi:10.1016/j.ijhydene.2007.04.019

Effect of Burning Velocity

- Fuel concentration also affects the burning rate and, as a consequence, the maximum pressure
- Illustrate with tests in a mock H_2 refuelling station

8% H_2

26% H_2

Public Perception

- Maintaining public confidence will be important
- There is a need to understand the explosion potential of hydrogen in many different environments

HOME › GENERAL › RECENT EXPLOSIONS SHUTDOWN HYDROGEN VEHICLE REFUELING IN NORCAL AND NORWAY

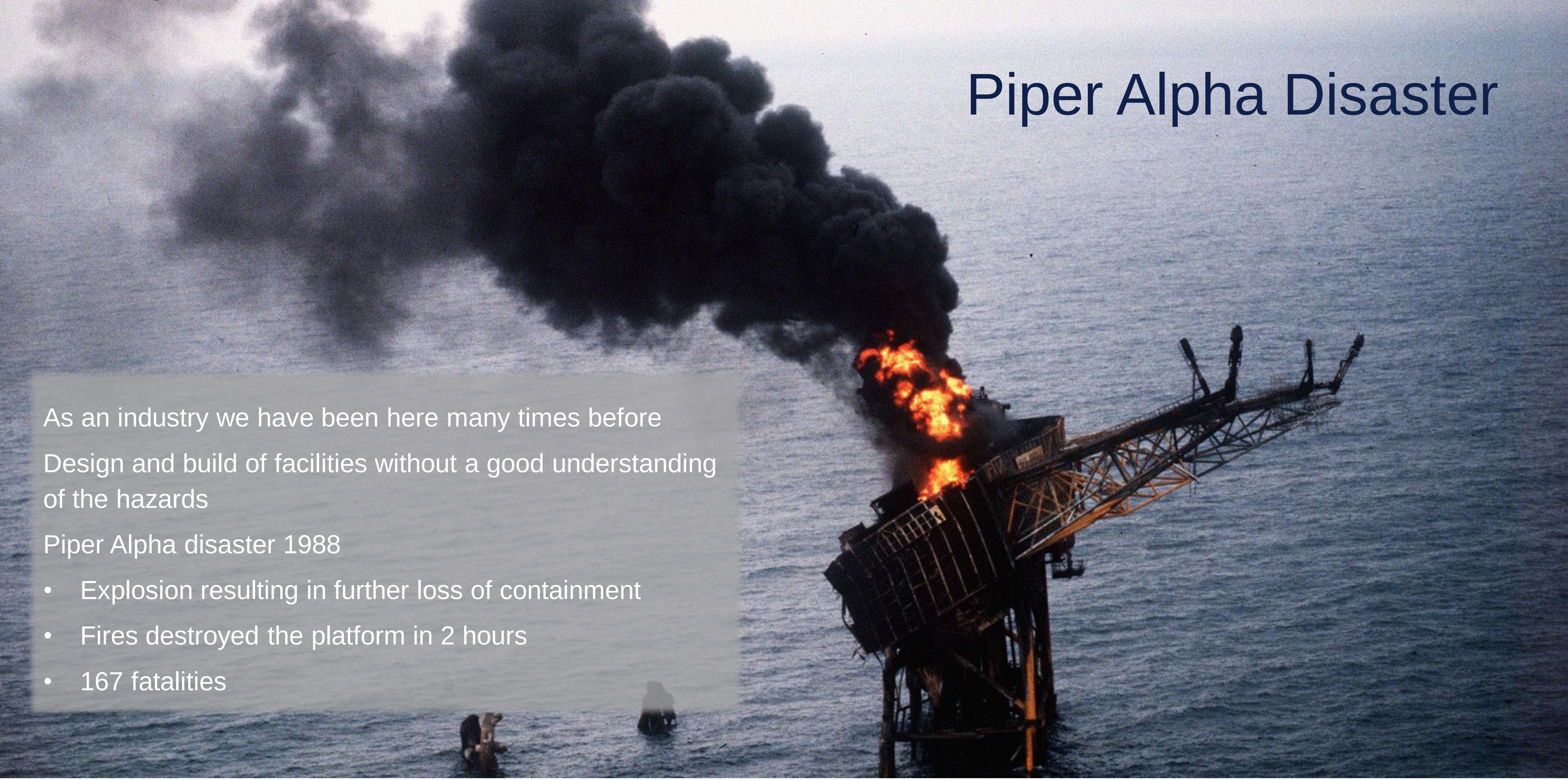
Recent explosions shutdown hydrogen vehicle refueling in NorCal and Norway

BY JEFF NISEWANGER *on* JUNE 11, 2019 · (1)

Explosions at a hydrogen fueling depot in Northern California and at a retail station in Norway have left owners of fuel cell cars in those regions without their usual source of refueling.

Monday's explosion in Sandvika, Norway near Oslo occurred at a hydrogen station operated by the company Uno-X adjacent to a major shopping center at around 5:30pm local time. As a result, some of the company's other fuel cell stations have been taken offline until an investigation reveals more information about the cause of the explosion.

https://electricrevs.com/2019/06/11/recent-explosions-shutdown-hydrogen-vehicle-refueling-in-norcal-and-norway/



Piper Alpha Disaster

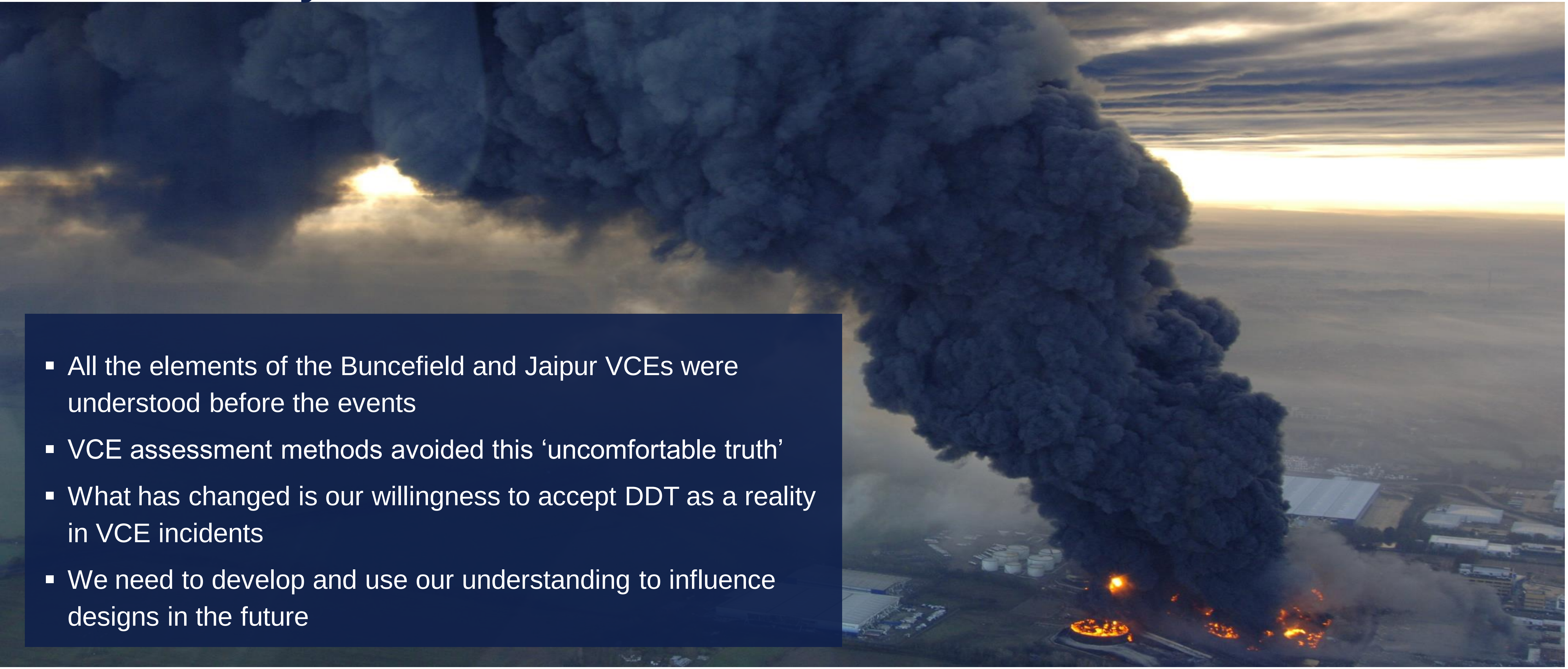
As an industry we have been here many times before

Design and build of facilities without a good understanding of the hazards

Piper Alpha disaster 1988

- Explosion resulting in further loss of containment
- Fires destroyed the platform in 2 hours
- 167 fatalities

Summary



- All the elements of the Buncefield and Jaipur VCEs were understood before the events
- VCE assessment methods avoided this ‘uncomfortable truth’
- What has changed is our willingness to accept DDT as a reality in VCE incidents
- We need to develop and use our understanding to influence designs in the future

Thank you

michael.johnson@dnv.com

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