WHEN TRUST MATTERS

The Nature of Vapour Cloud Explosions

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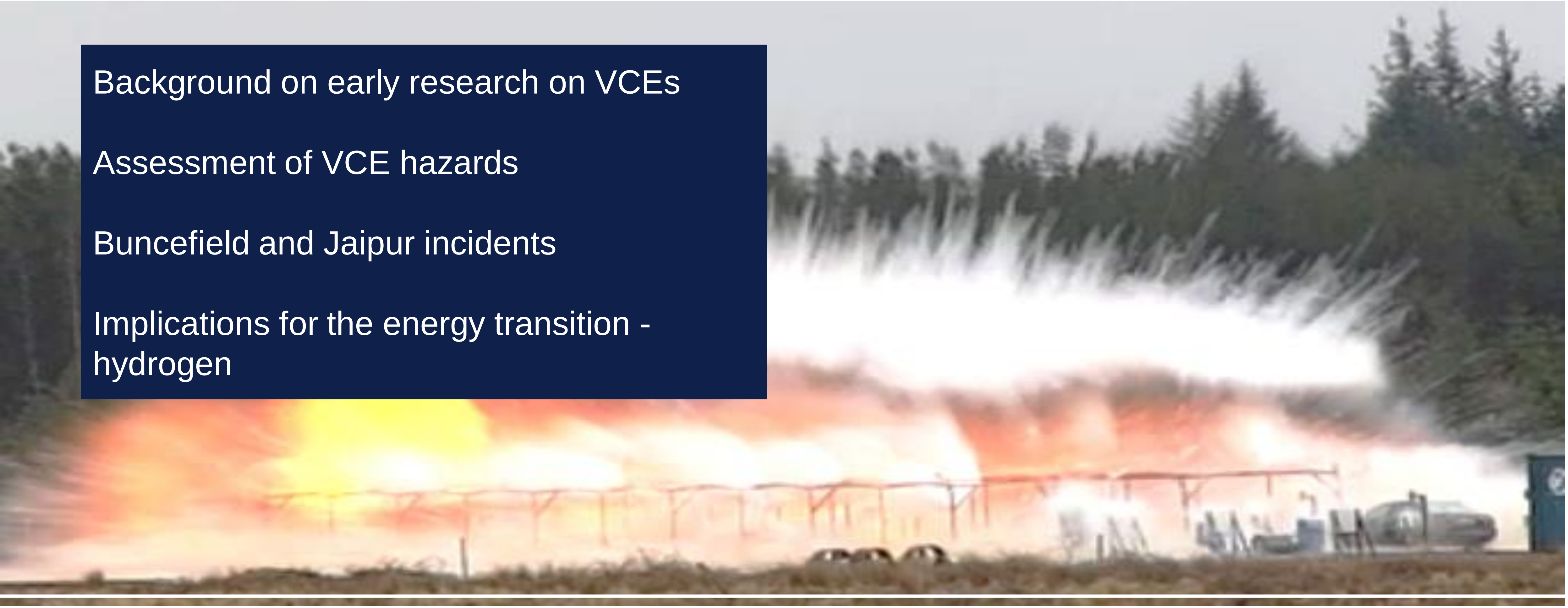
14 September 2022

Overview



Background on early research on VCEs

Assessment of VCE hazards

Buncefield and Jaipur incidents

Implications for the energy transition - hydrogen

DNV Spadeadam

Leased from UK Ministry of Defence in 1977

- Continuously manned since that date

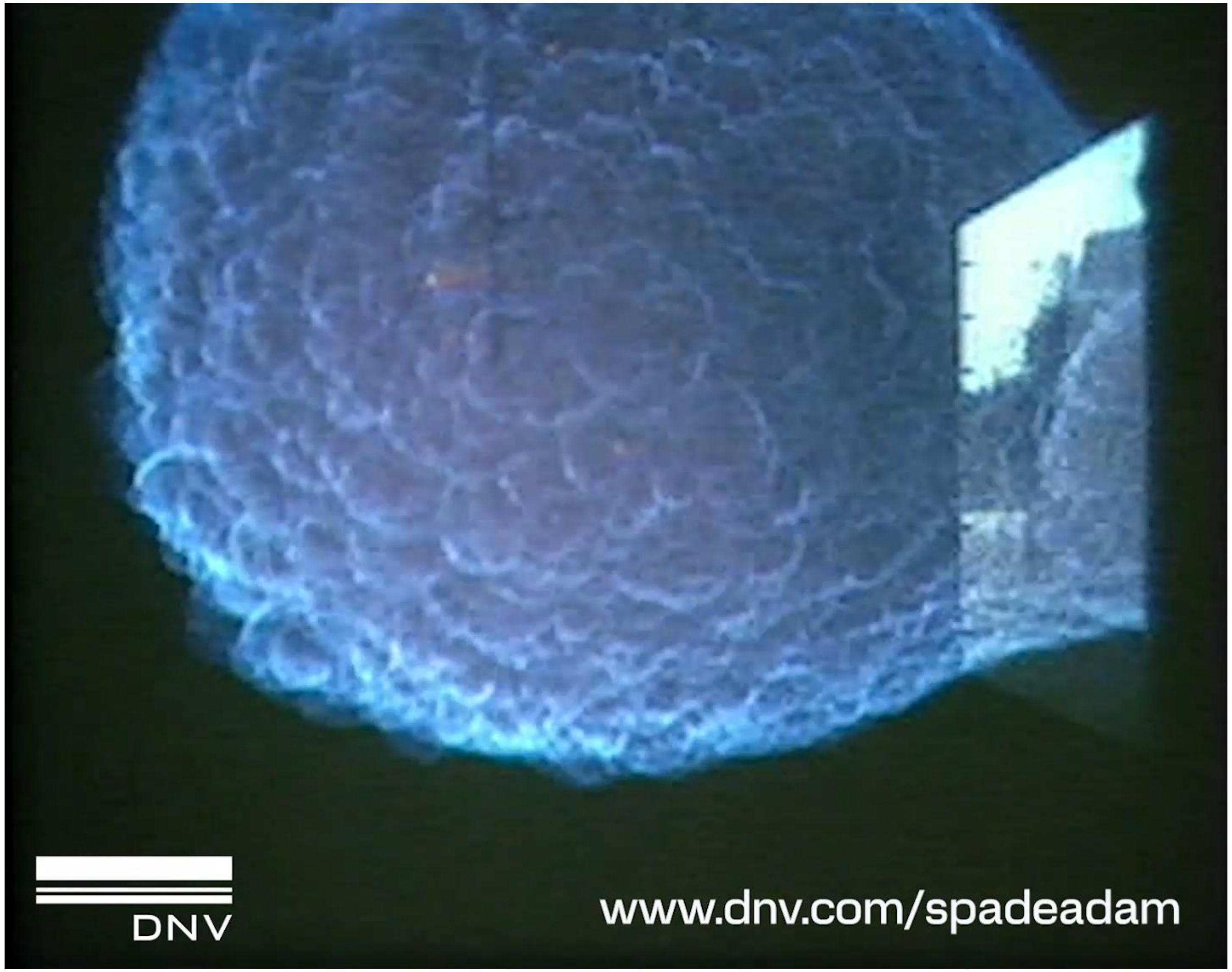
Remote & secure site

Conduct of potentially hazardous research and testing

Generation of Pressure in Explosions

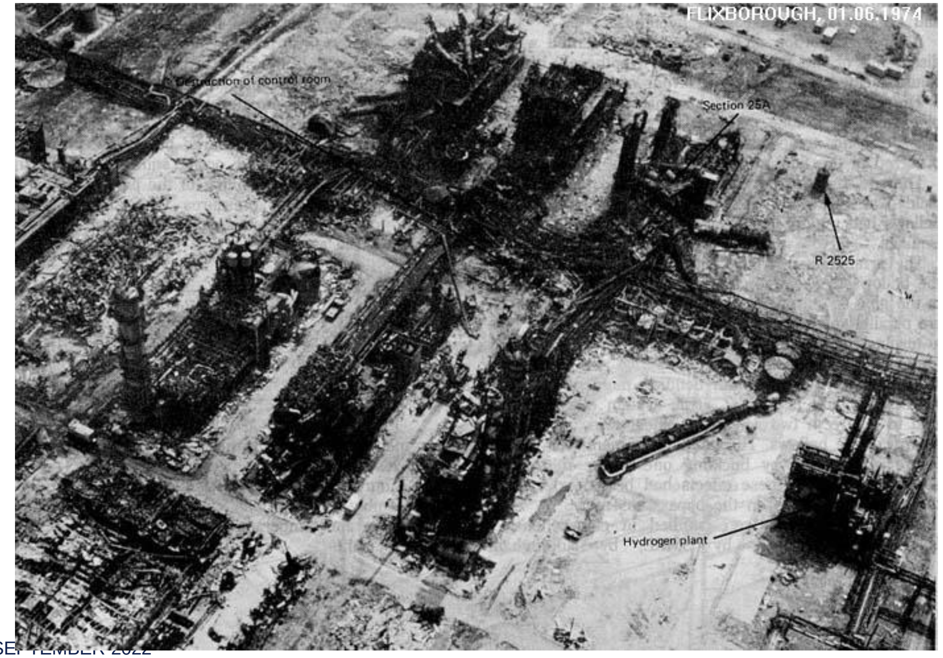
Confined Explosion

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



‘Unconfined’ Vapour Cloud Explosions

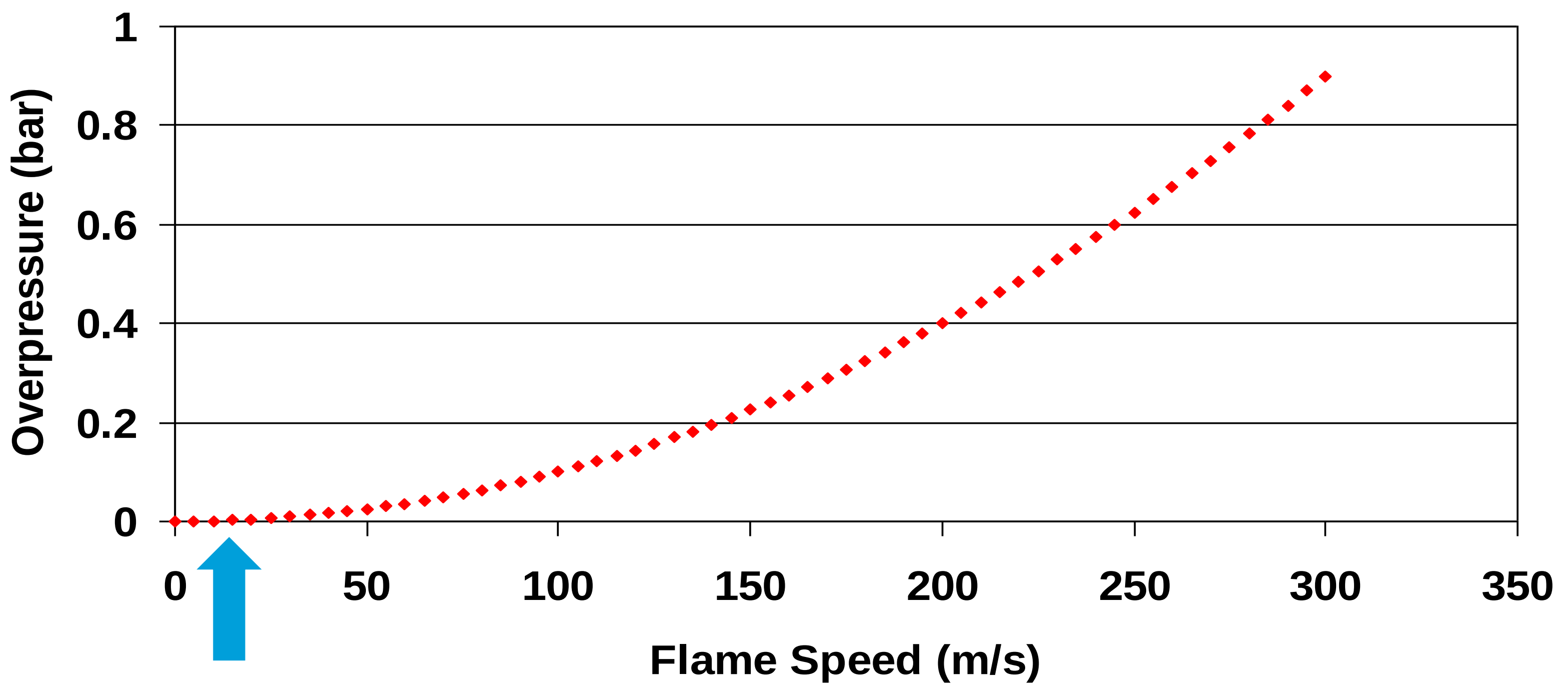
- Major explosions in the 2nd half of the 20th century where the gas/vapour cloud was not confined
- No understanding of the cause of damaging pressures
- A key incident for the UK was in Flixborough in 1974



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



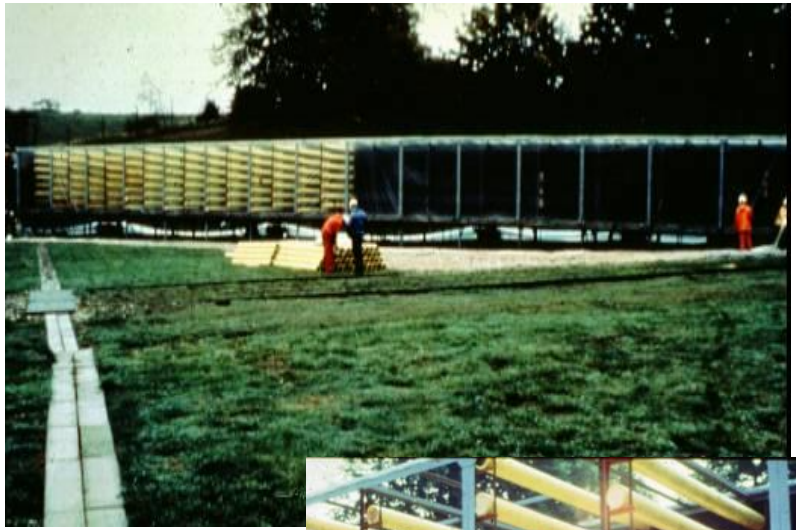
High flame speeds can generate overpressure

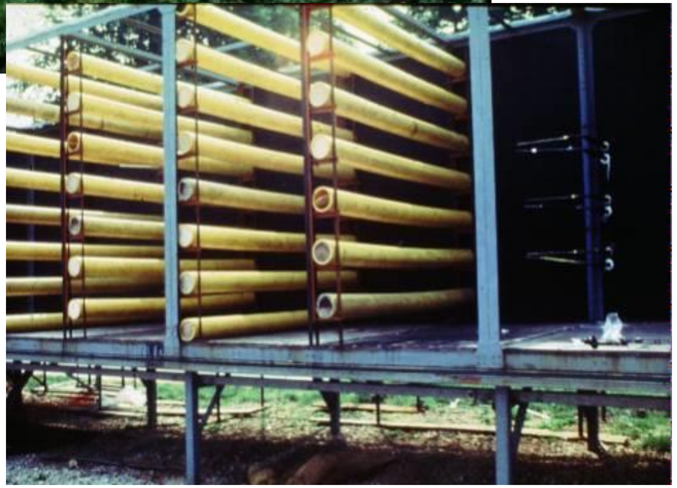
But laboratory experiments suggest maximum flame speed of 5-20ms^{-1} for typical hydrocarbons

Effect of Process Congestion

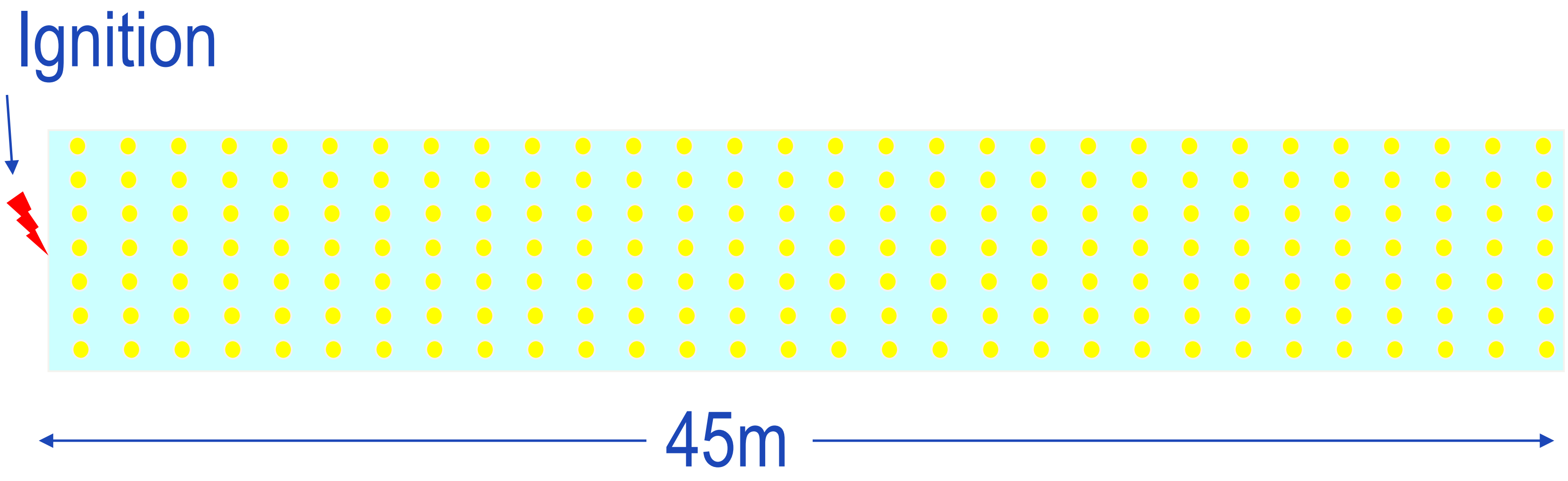
- Another characteristic was that clouds usually engulfed congested process areas

- 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

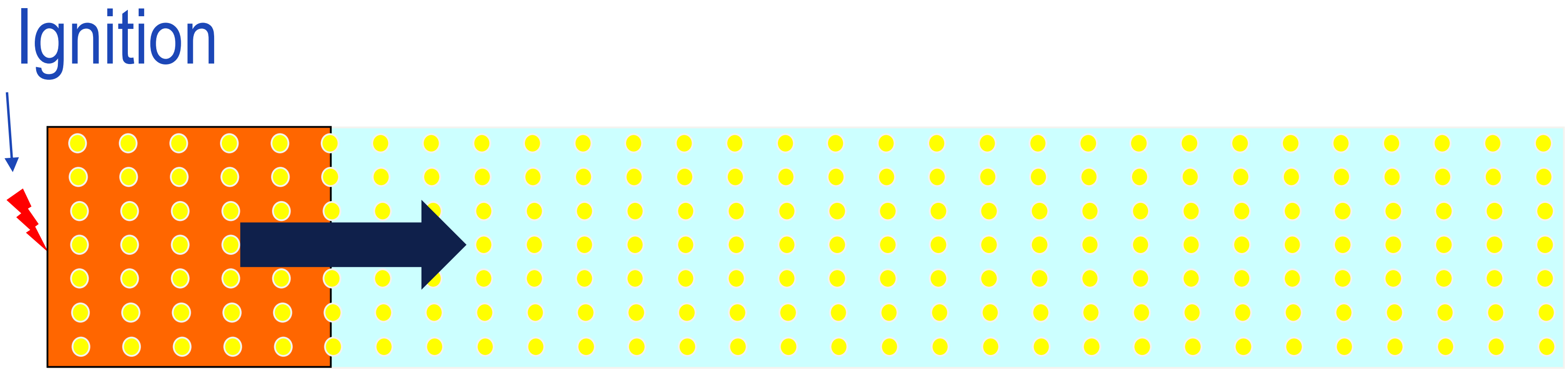
Flame Acceleration – Cyclohexane

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 burning velocity

Natural Gas

Flame speed ~550m/s

Rapid initial flame acceleration

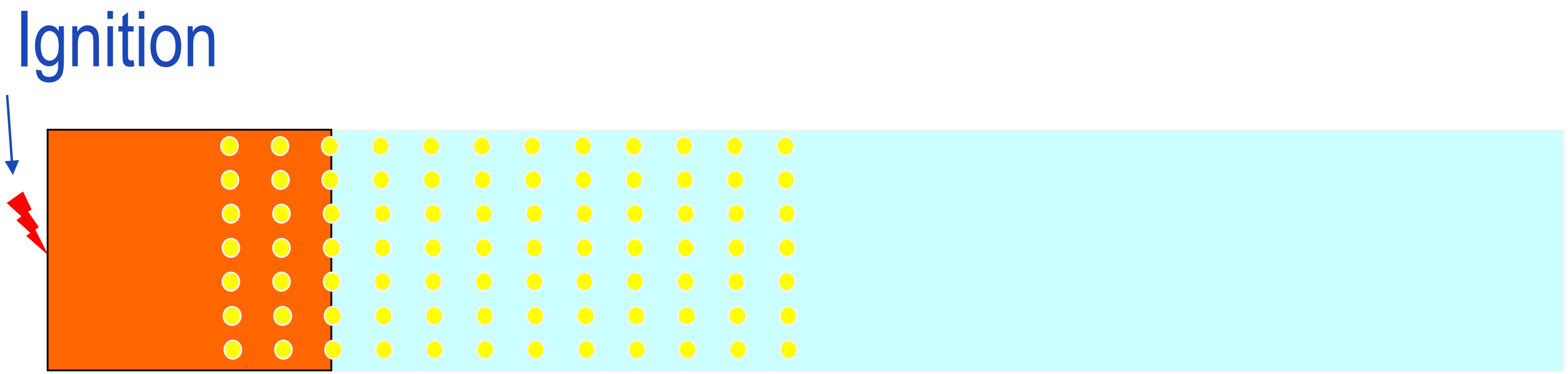
Supersonic deflagration

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

DNV

Late 20th Century

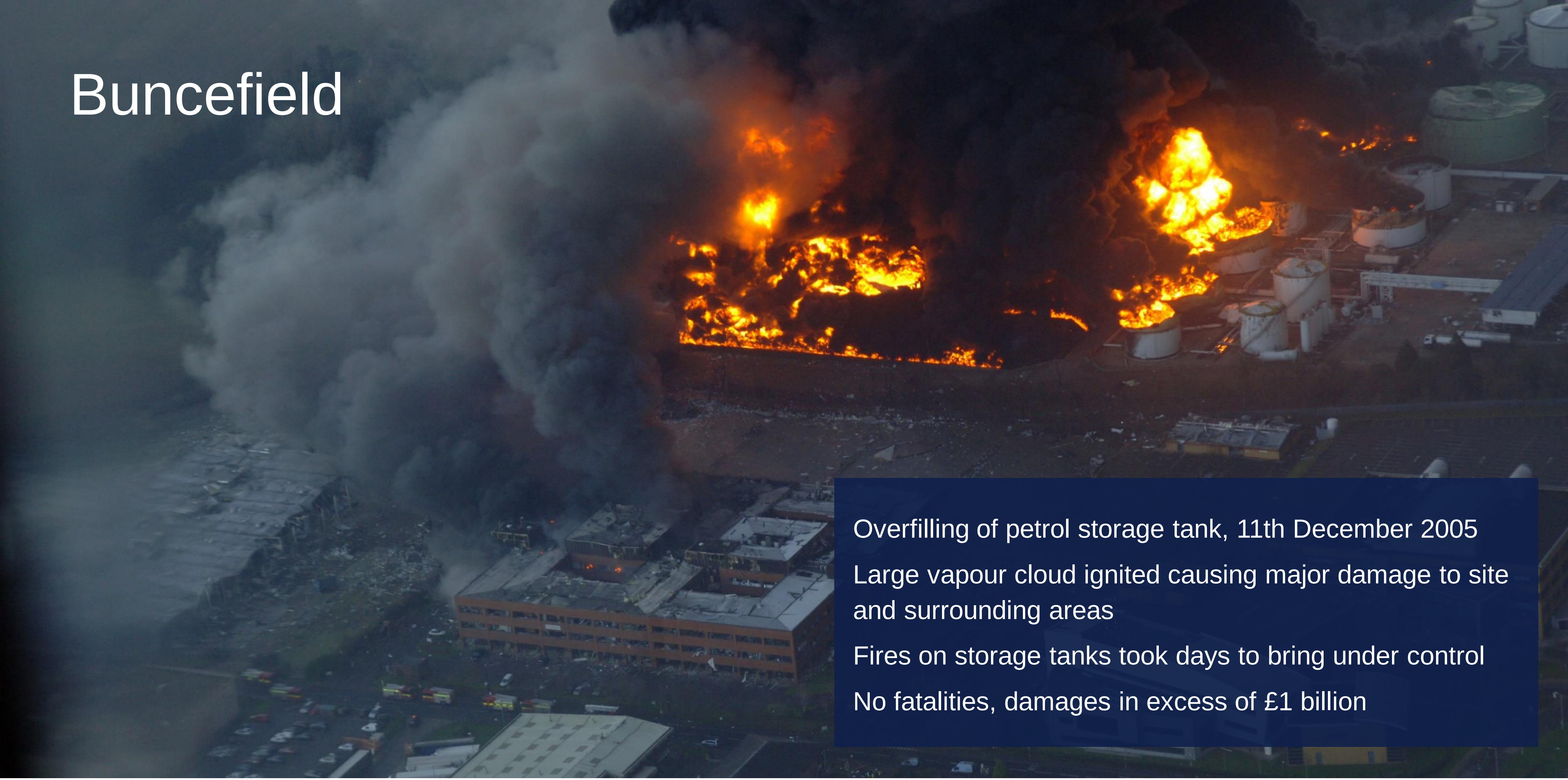
Results of experimental research published in 1988

DDT ignored by industry or considered unrealistic for common hydrocarbons

Industry adopted assessment based on deflagrations limited to process regions

But……

Buncefield



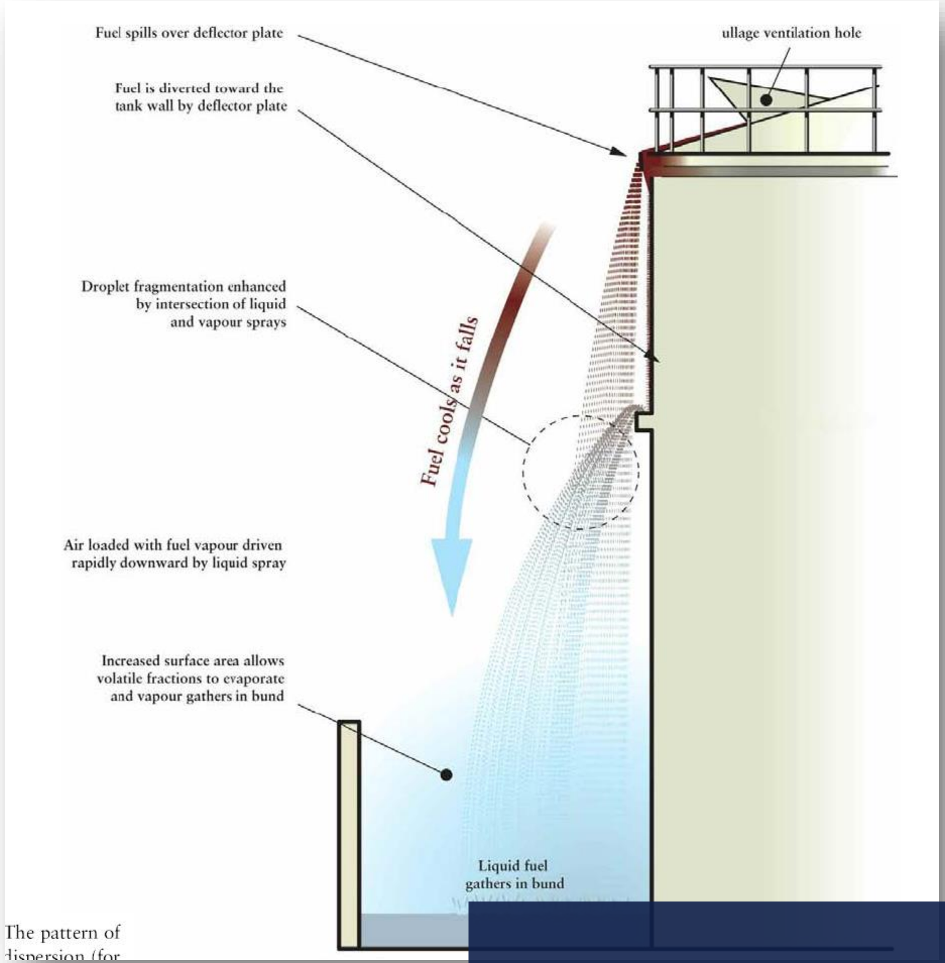
Overfilling of petrol storage tank, 11th December 2005

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

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 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



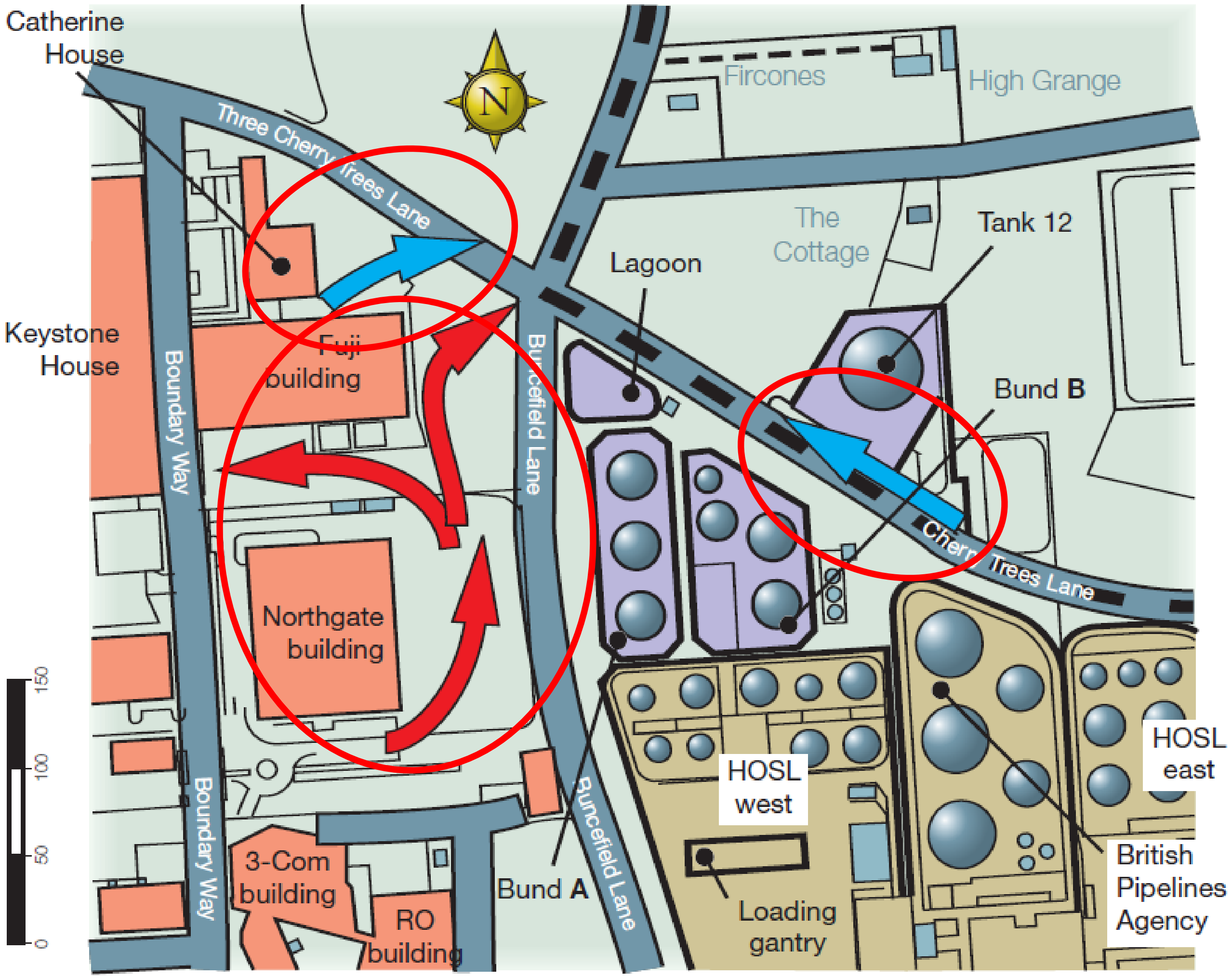



DNV

Initial Investigation

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

Assumed direction of explosion



DNV

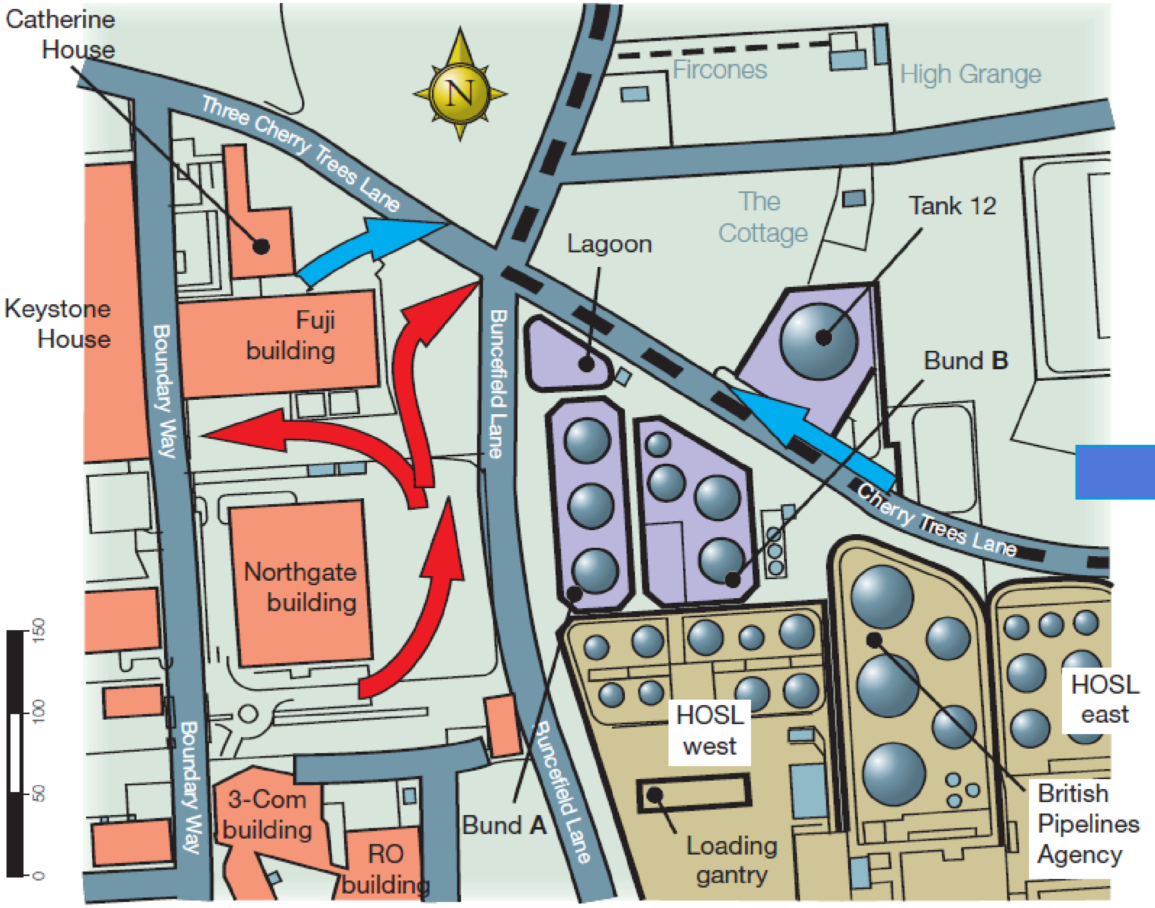
Directional Indicators

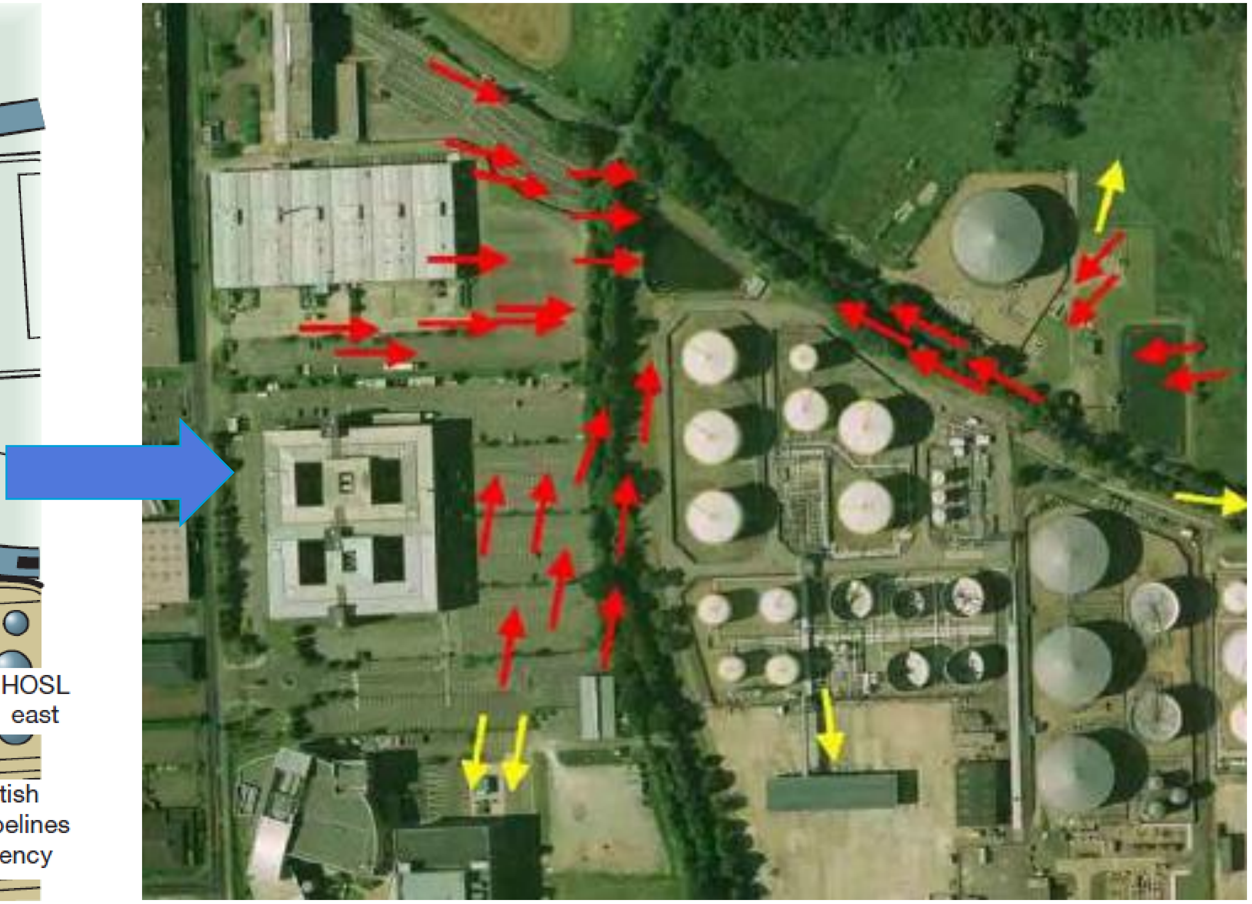
- Experimental work showed significant reverse flow

- Modelling confirmed net force in reverse direction

Re-interpret as opposite direction of explosion

Directional Indicators - Buncefield



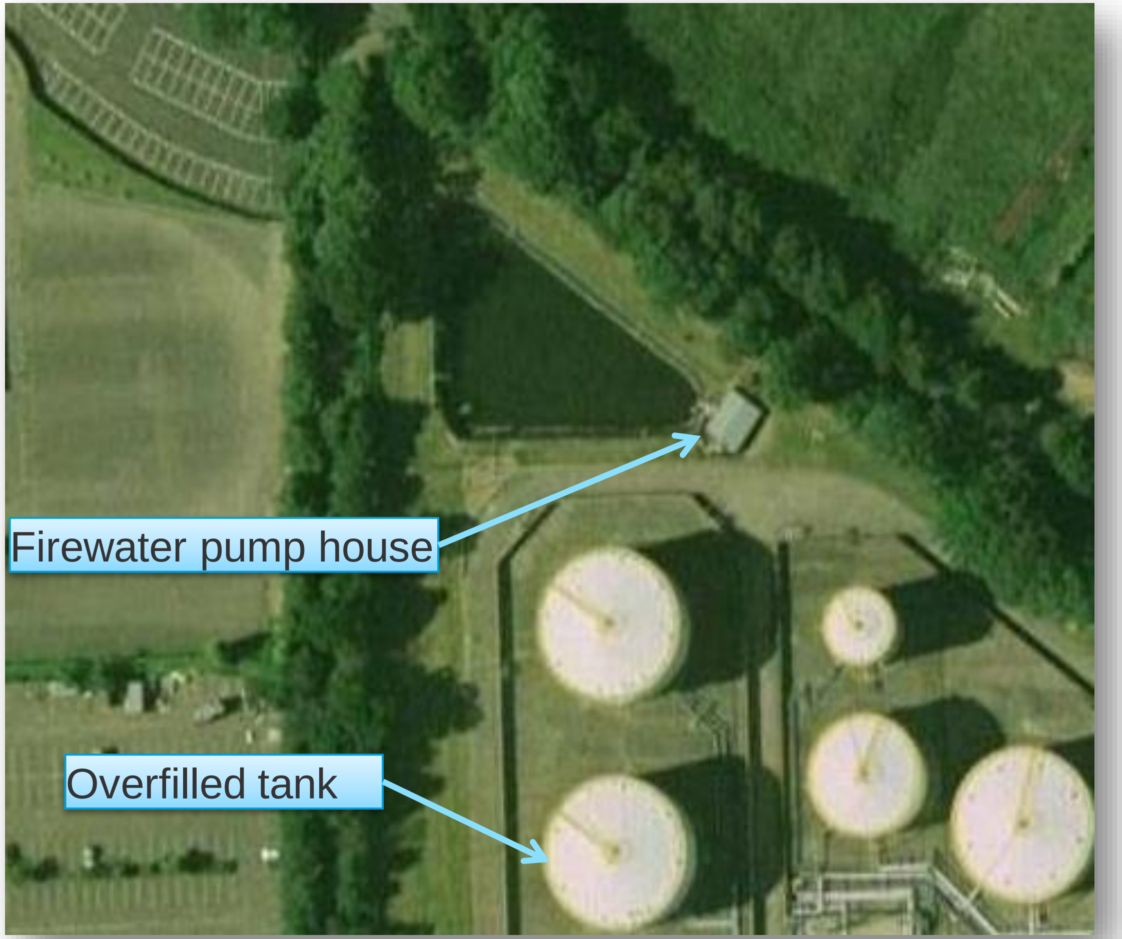


Red inside cloud, Yellow outside cloud

Red arrows point to location of DDT

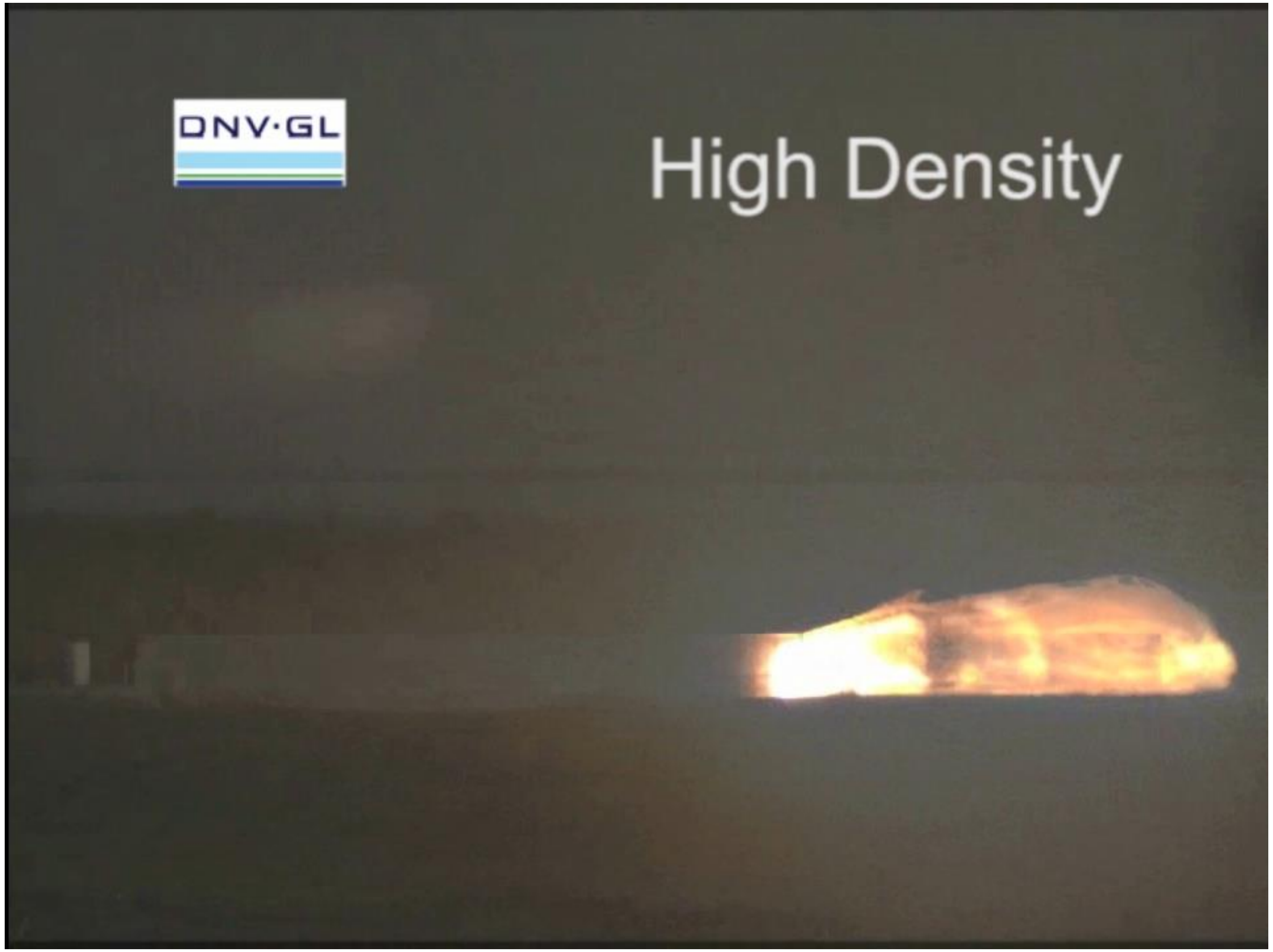
Cause of Flame Acceleration and DDT at Buncefield

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

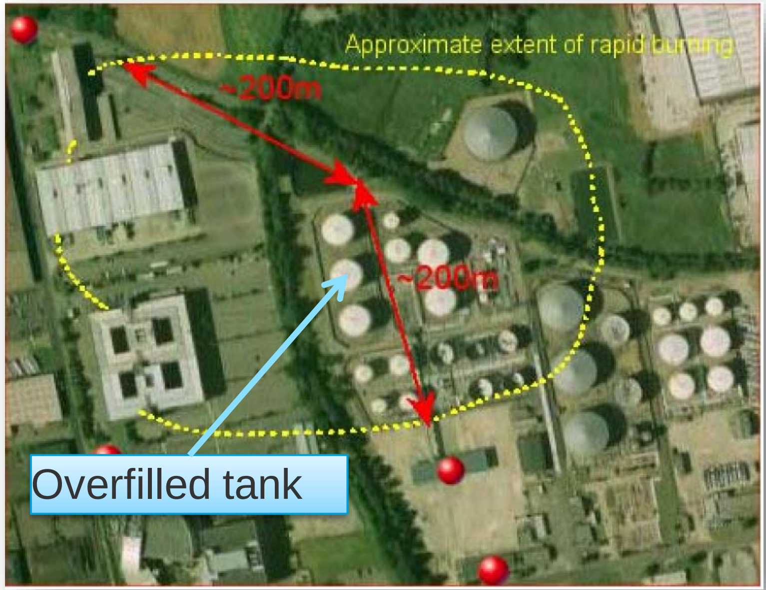


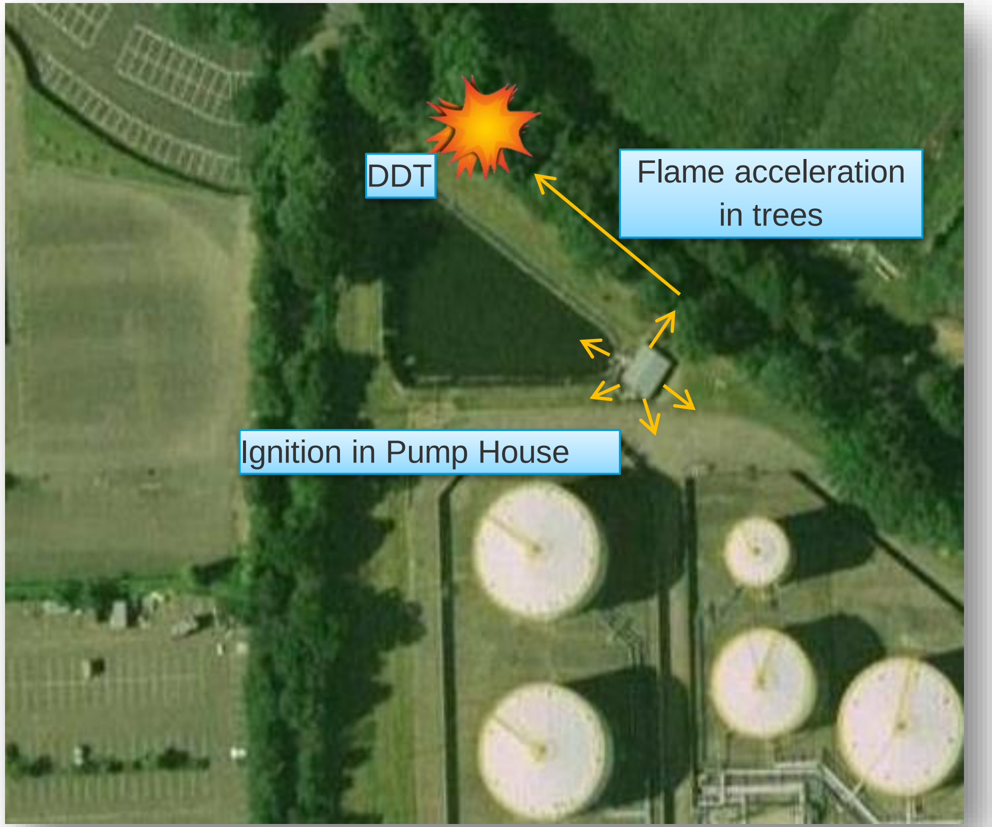
Cause of Flame Acceleration and DDT at Buncefield

- 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
- Indicates location of DDT
- Most likely due to flame venting from an explosion in a building

Damage to Cars – Short Duration Shock Loadings

Outside the Cloud

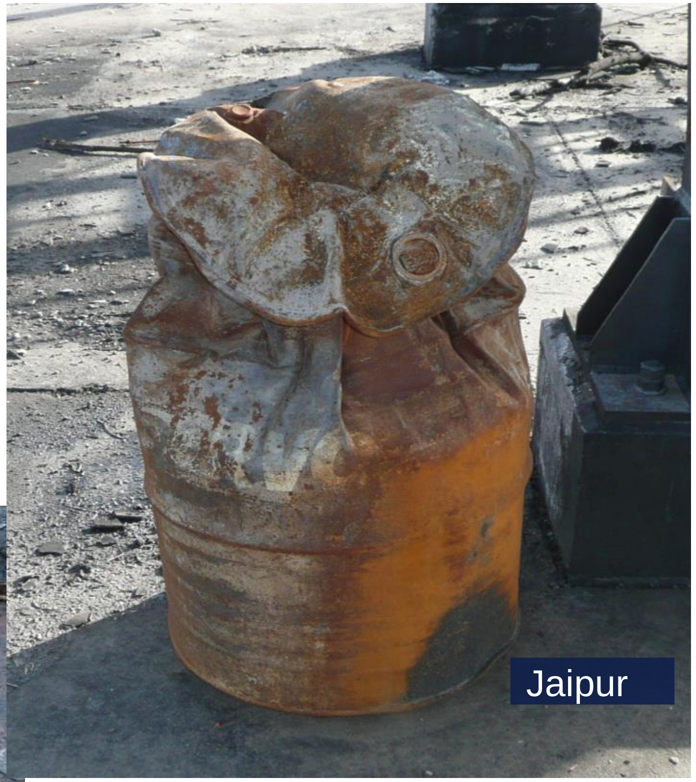
Inside the Cloud

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

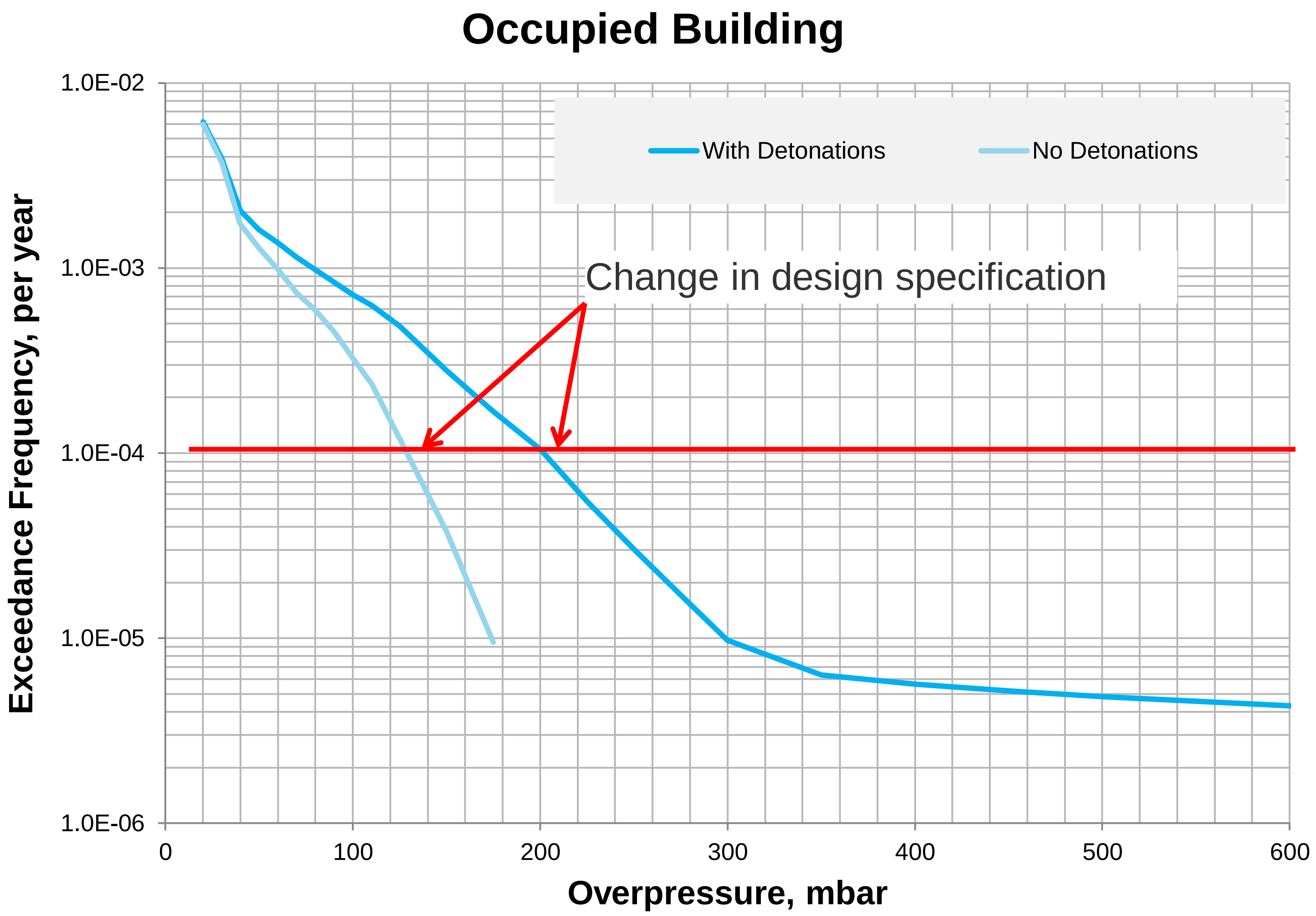
** G. Chamberlain, E. Oran, A. Pekalski, Detonations in industrial vapour cloud explosions, Journal of Loss Prevention in the Process Industries, Volume 62, November 2019, 103918*

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

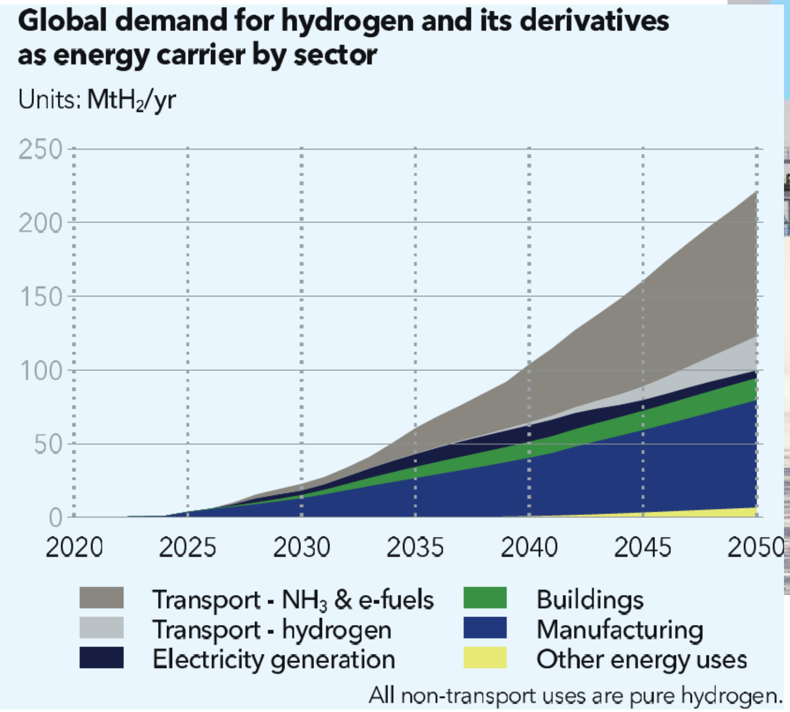
Risk Based Building Design

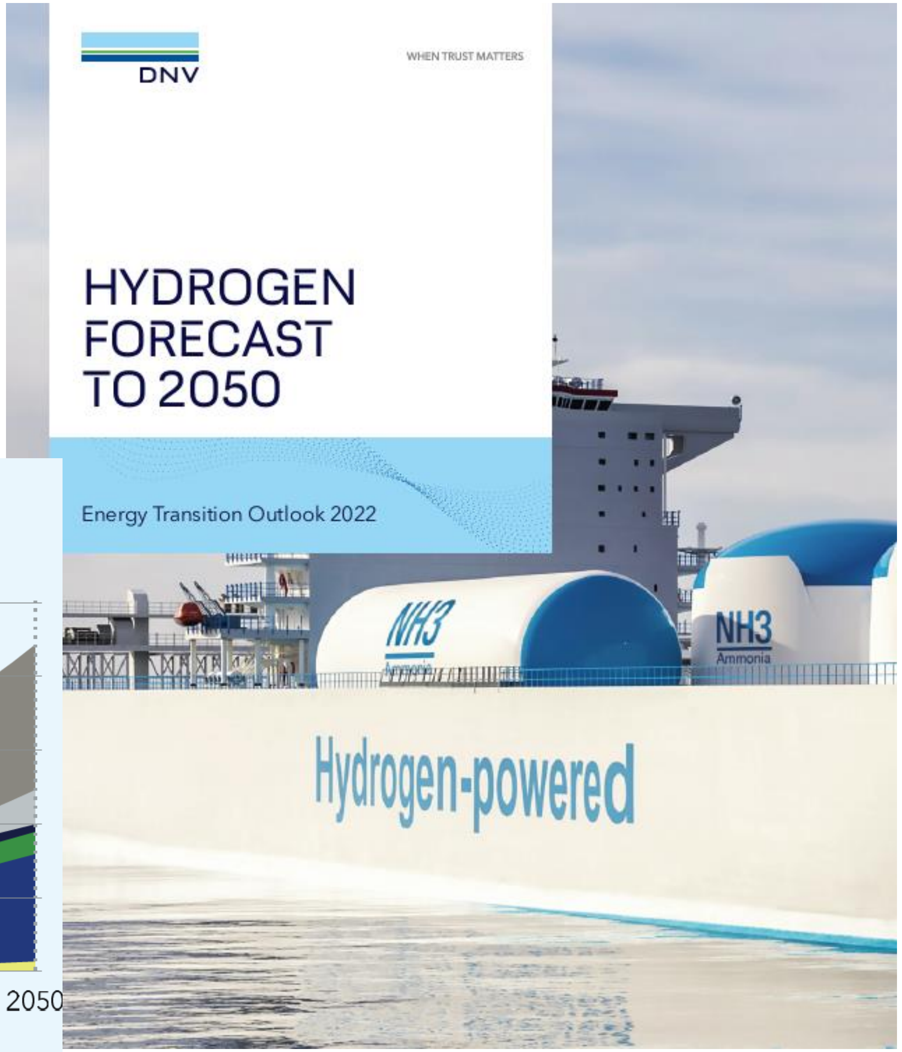


Energy Transition

Hydrogen Development

- DNV recent publication of Energy Transition Outlook on Hydrogen
- Significant growth in use to 2050





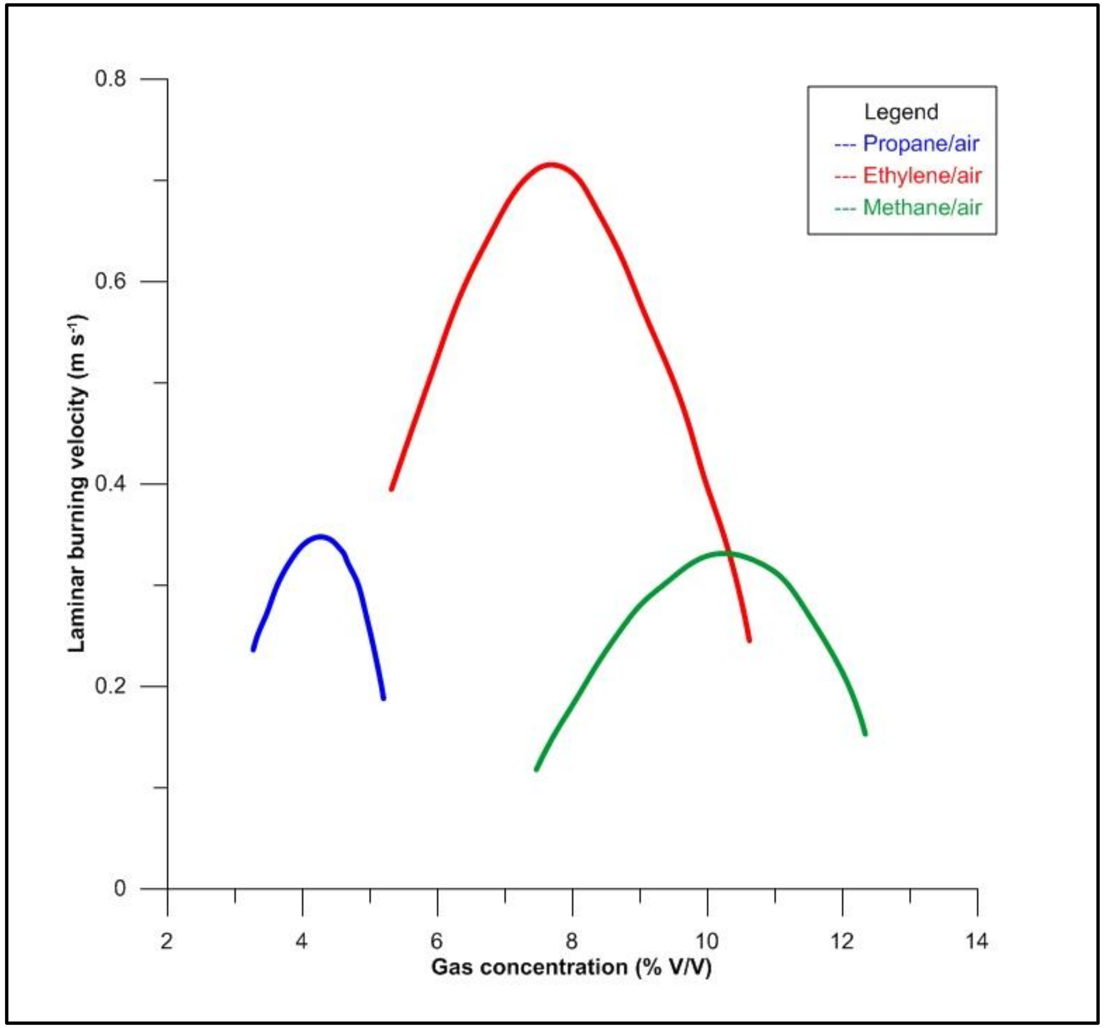
This is plot of the burning velocity for 3 common hydrocarbons

- Methane
- Propane
- Ethylene

Generally, the higher the burning velocity, the more severe the explosion

Depends on fuel type and concentration

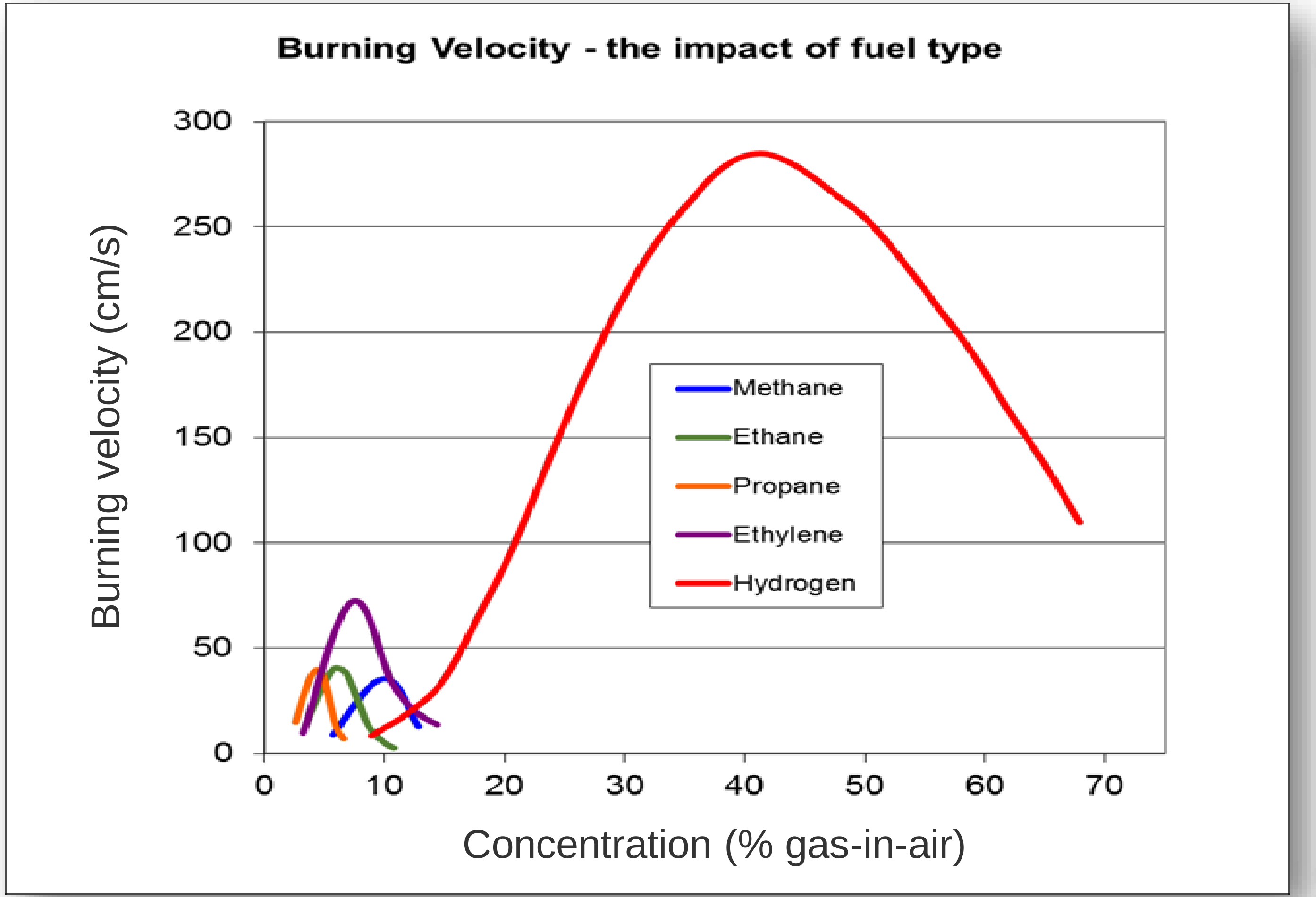
So what about hydrogen?



Key Hydrogen Properties - Burning Velocity

Hydrogen has a much higher burning velocity than hydrocarbons

Again, the higher the burning velocity, <u>the more severe the explosion</u>



Methane & Hydrogen Explosion Comparison

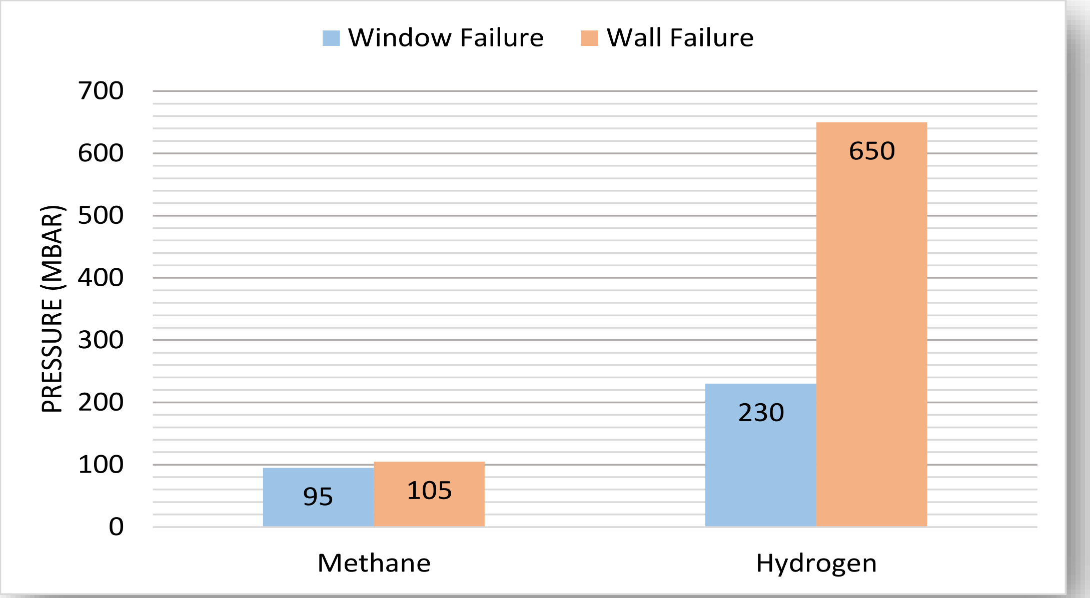
Methane and Hydrogen releases at same pressure and with same hole size

Methane (10%vol layer)

Hydrogen (20%vol layer)

Confined Explosion

- Videos aligned to window failure but pressures very different



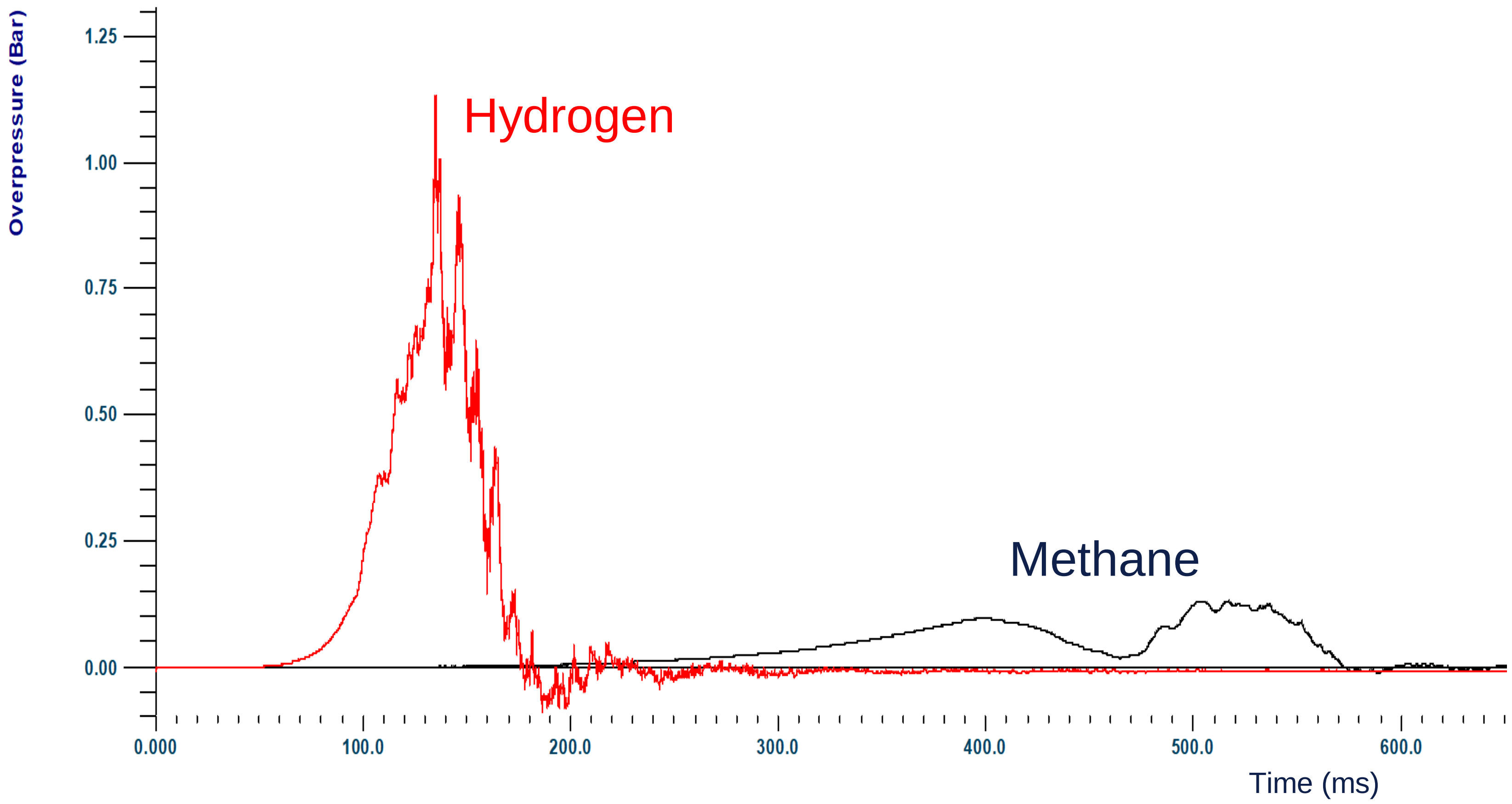
- Pressures in hydrogen experiment far exceeded the minimum required failure pressure of window and wall.
- Why?

Internal Pressures

- Peak rate of pressure rise:
  - Hydrogen ~10 mbar/ms
  - Methane ~ 0.5 mbar/ms

- Time taken for structural failure is critical for hydrogen

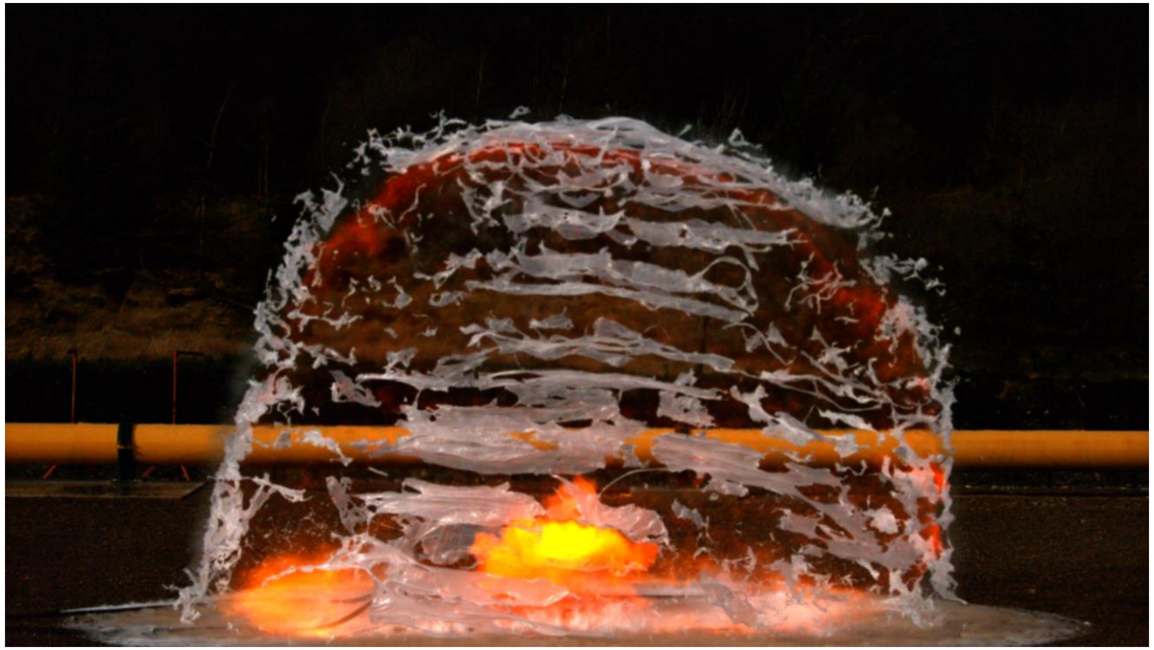
- Results in much higher pressures being generated



Deflagration to Detonation Transition (DDT)

Detonation

- Shock wave of 20 bar compresses fuel mixture to auto-ignition temperature
- Immediate combustion of fuel provides energy to maintain the shock wave
- Self sustaining and will propagate through the flammable mixture at 1800 m/s



Detonability

- Detonation occurs when sufficient energy is concentrated in a small volume
- Can achieve this with high explosives

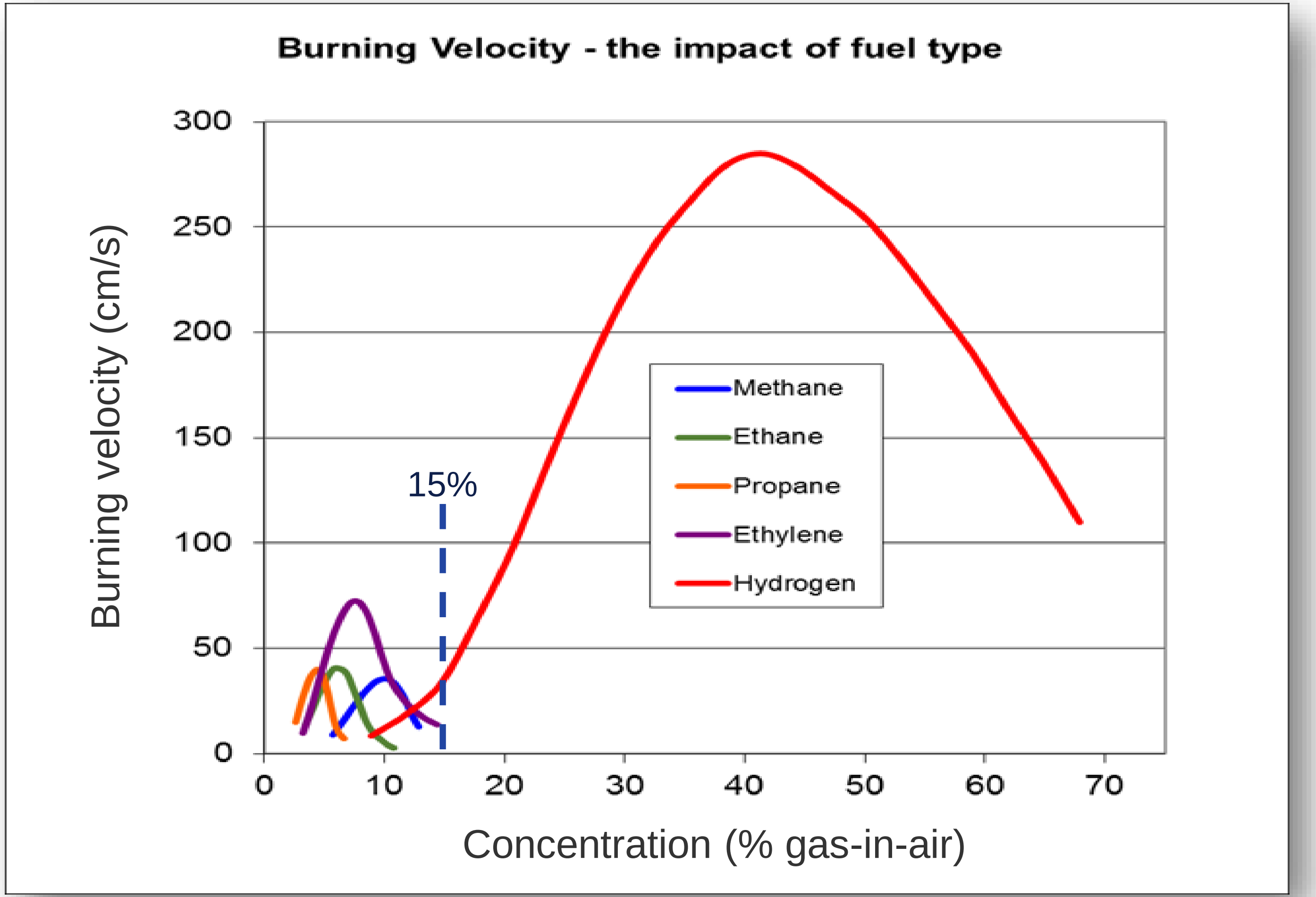
Fuel	Minimum Mass tetryl (g)
Hydrogen	**0.8**
Methane	16,000
Propane	37
Ethylene	5.2

- Natural Gas detonations ~NEVER happen
- Hydrogen detonations are entirely credible – factor of 20,000 reduction in energy required (compared to methane)

Managing Explosion Risk

Remember this?

If the hydrogen concentration is kept below ~15% then no worse than natural gas



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

Design to Operations

- Incidents often occur because operation deviates from the original design intent

- With hydrogen we can be close to a cliff edge of more severe consequences

- The original design intent for safety processes and systems needs to be maintained in operations

Hydrogen Research @ DNV Spadeadam

- Recent and current projects conducting hydrogen research at DNV Spadeadam

Hy4Heat

h21

FutureGrid

LTS Futures

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

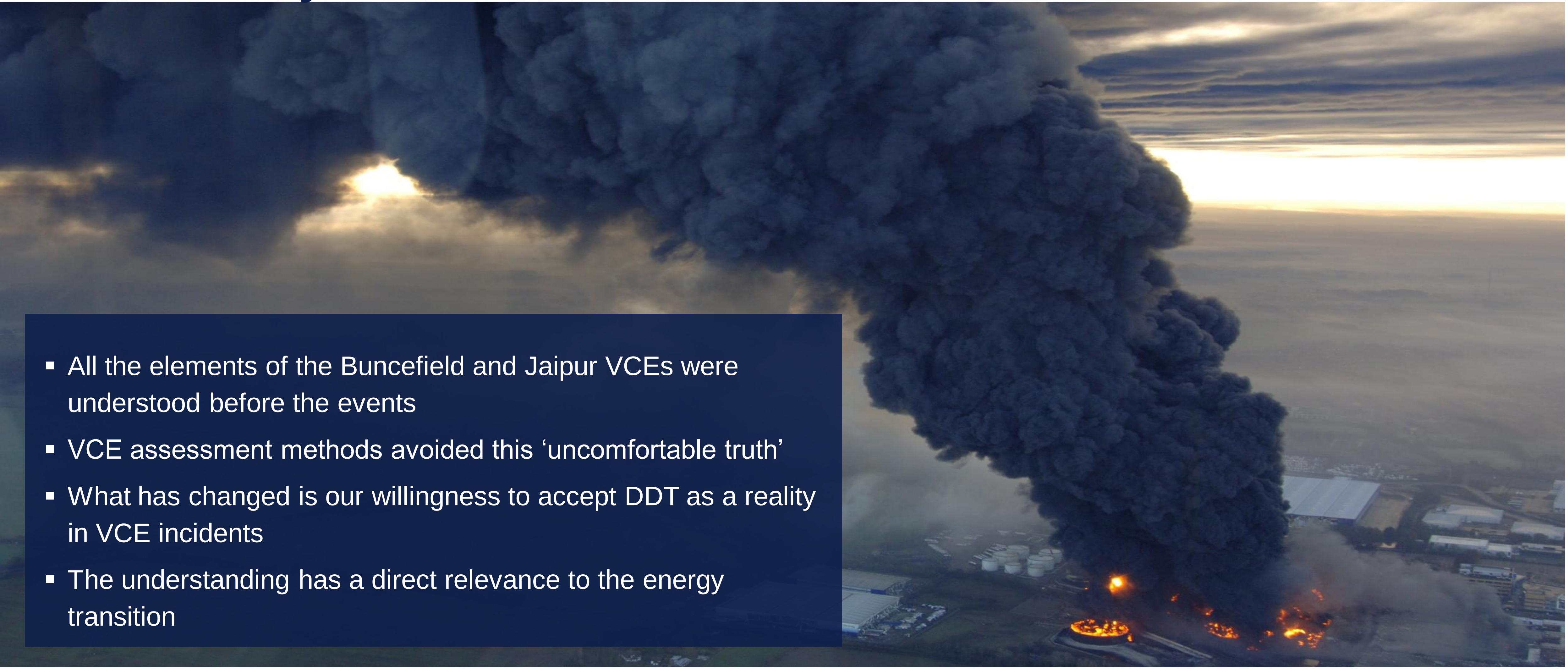
BY JEFF NISEWANGER *on* JUNE 11, 2019 · (1)

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/

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
- The understanding has a direct relevance to the energy transition

Thank you

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