# Large Scale Experimental Research of VCEs

## A Summary from One Viewpoint

Mike Johnson

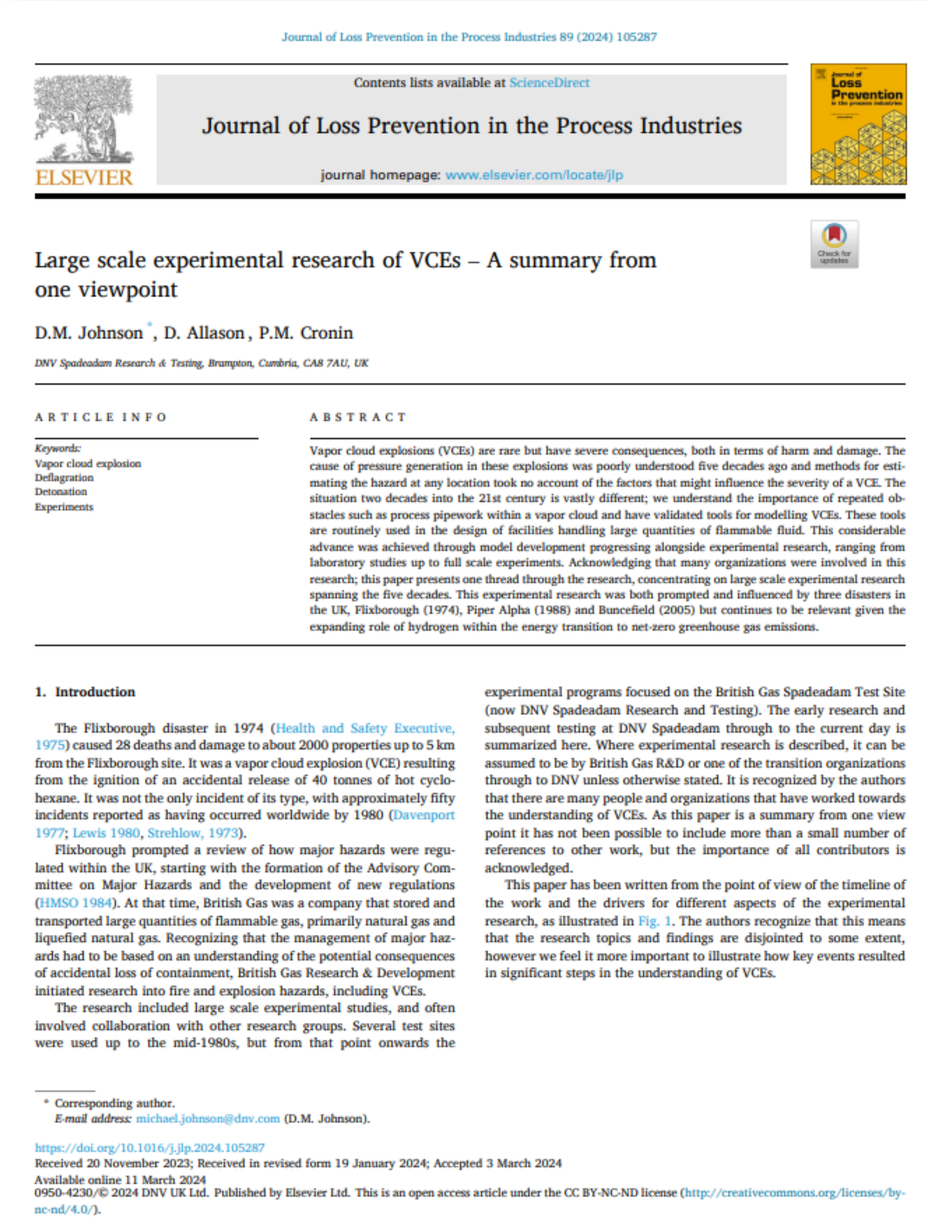
27 November 2025

This presentation is an overview of the work presented in a recent publication*

The paper provides a summary of over four decades of experimental research carried out at DNV Spadeadam[+]

* Gold publication – free to download

[+] And some precursor sites



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Large scale experimental research of VCEs – A summary from one viewpoint

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ABSTRACT

Vapor cloud explosions (VCEs) are rare but have severe consequences, both in terms of harm and damage. The cause of pressure generation in these explosions was poorly understood five decades ago and methods for estimating the hazard at any location took no account of the factors that might influence the severity of a VCE. The situation two decades into the 21st century is vastly different; we understand the importance of repeated obstacles such as process pipework within a vapor cloud and have validated tools for modelling VCEs. These tools are routinely used in the design of facilities handling large quantities of flammable fluid. This considerable advance was achieved through model development progressing alongside experimental research, ranging from laboratory studies up to full scale experiments. Acknowledging that many organizations were involved in this research; this paper presents one thread through the research, concentrating on large scale experimental research spanning the five decades. This experimental research was both prompted and influenced by three disasters in the UK, Flixborough (1974), Piper Alpha (1988) and Buncefield (2005) but continues to be relevant given the expanding role of hydrogen within the energy transition to net-zero greenhouse gas emissions.

**1. Introduction**

The Flixborough disaster in 1974 (Health and Safety Executive, 1975) caused 28 deaths and damage to about 2000 properties up to 5 km from the Flixborough site. It was a vapor cloud explosion (VCE) resulting from the ignition of an accidental release of 40 tonnes of hot cyclohexane. It was not the only incident of its type, with approximately fifty incidents reported as having occurred worldwide by 1980 (Davenport 1977; Lewis 1980, Strehlow, 1973).

Flixborough prompted a review of how major hazards were regulated within the UK, starting with the formation of the Advisory Committee on Major Hazards and the development of new regulations (HMSO 1984). At that time, British Gas was a company that stored and transported large quantities of flammable gas, primarily natural gas and liquefied natural gas. Recognizing that the management of major hazards had to be based on an understanding of the potential consequences of accidental loss of containment, British Gas Research & Development initiated research into fire and explosion hazards, including VCEs.

The research included large scale experimental studies, and often involved collaboration with other research groups. Several test sites were used up to the mid-1980s, but from that point onwards the experimental programs focused on the British Gas Spadeadam Test Site (now DNV Spadeadam Research and Testing). The early research and subsequent testing at DNV Spadeadam through to the current day is summarized here. Where experimental research is described, it can be assumed to be by British Gas R&D or one of the transition organizations through to DNV unless otherwise stated. It is recognized by the authors that there are many people and organizations that have worked towards the understanding of VCEs. As this paper is a summary from one view point it has not been possible to include more than a small number of references to other work, but the importance of all contributors is acknowledged.

This paper has been written from the point of view of the timeline of the work and the drivers for different aspects of the experimental research, as illustrated in Fig. 1. The authors recognize that this means that the research topics and findings are disjointed to some extent, however we feel it more important to illustrate how key events resulted in significant steps in the understanding of VCEs.

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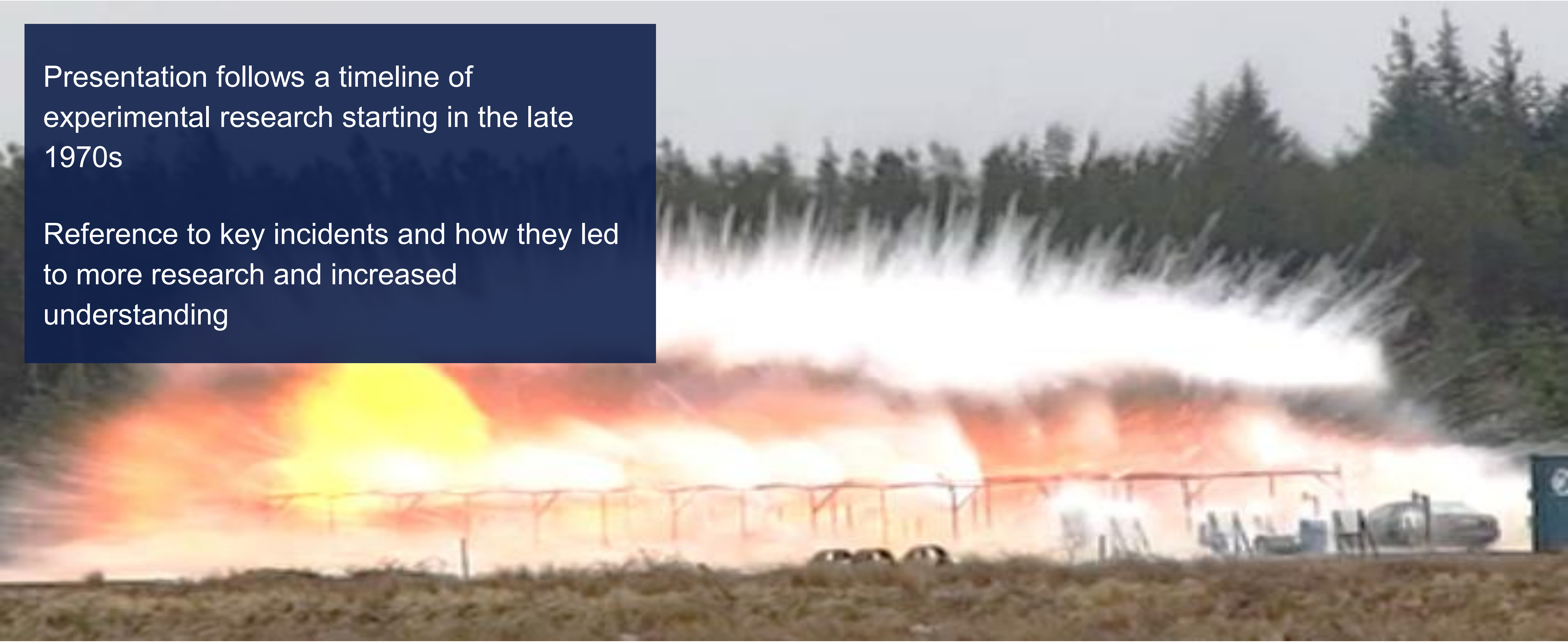
# Overview



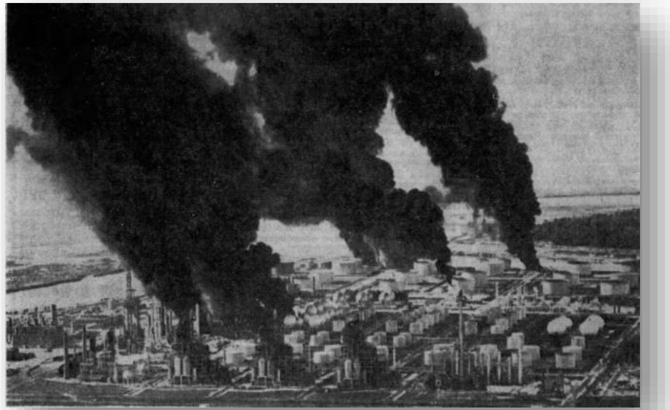
Presentation follows a timeline of experimental research starting in the late 1970s

Reference to key incidents and how they led to more research and increased understanding

# Vapour Cloud Explosions

- Timeline up to mid 1970s:
  - Severe explosions following ignition of large vapour clouds (~50 reported by 1980)
- In the early 1970's the mechanism for generating these severe explosions was not understood

Lake Charles, Louisiana, 1967



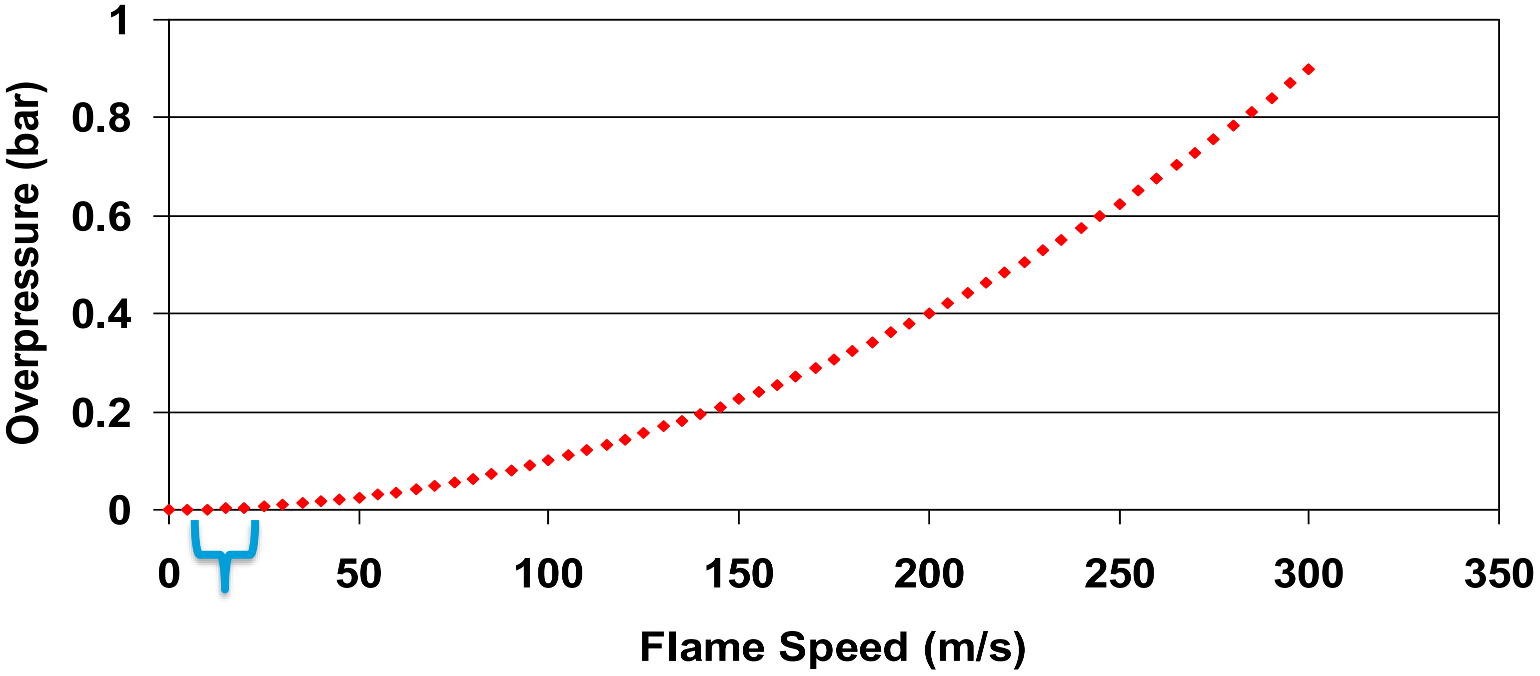
Port Hudson, Missouri, 1970

Flixborough, UK 1974

Pernis, Netherlands, 1968

# Effect of Flame Speed

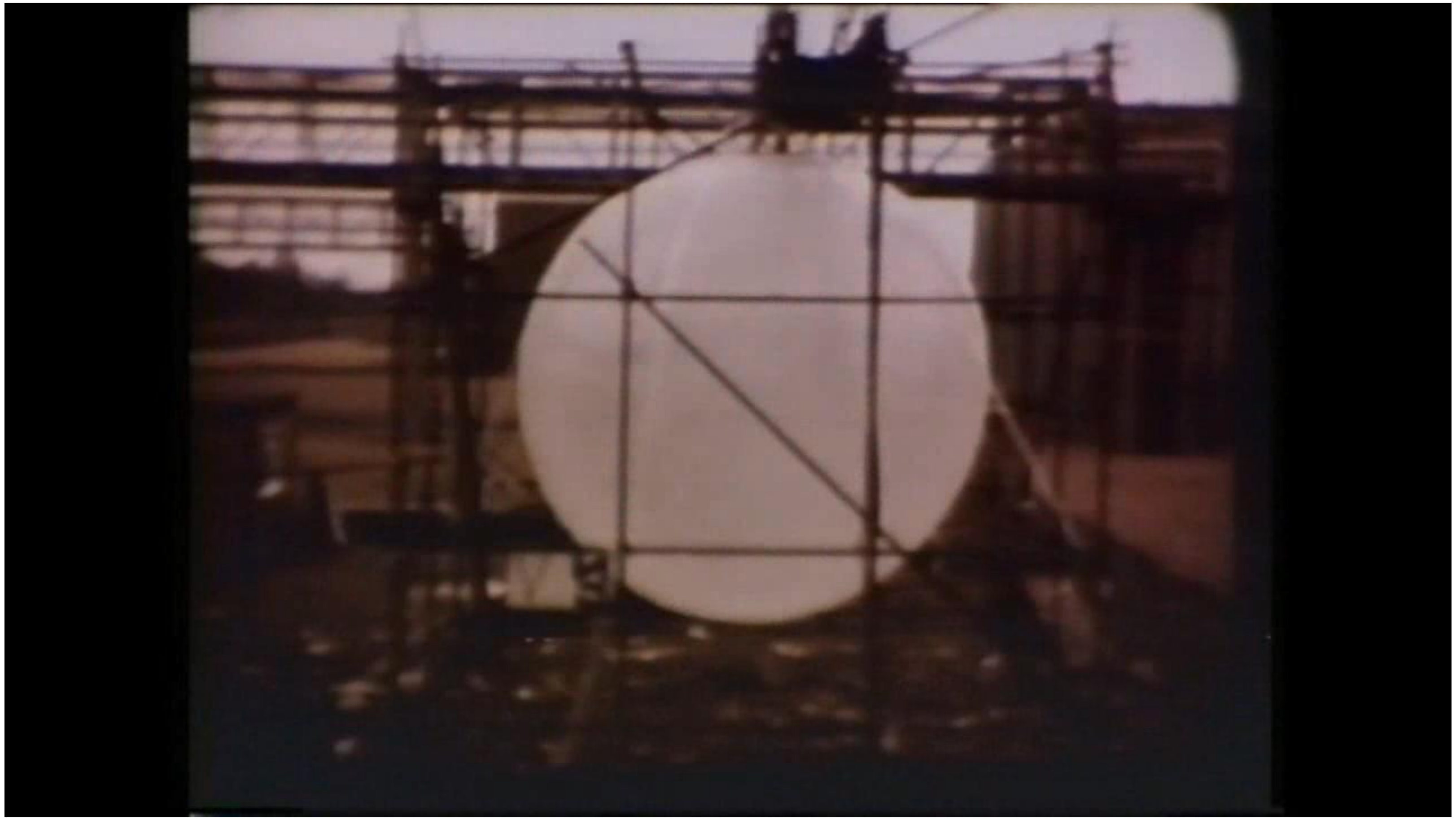
- High flame speeds can generate overpressure
- But laboratory experiments indicated flame speeds of 5-20ms$^{-1}$ for typical hydrocarbons
- What causes flame acceleration?
- Is it just because the clouds are much bigger than lab-scale experiments?



# Large Unconfined Vapour Clouds

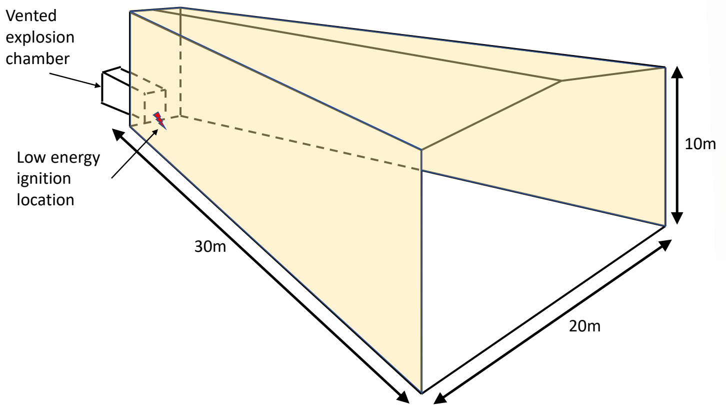
- No, it isn't just scale

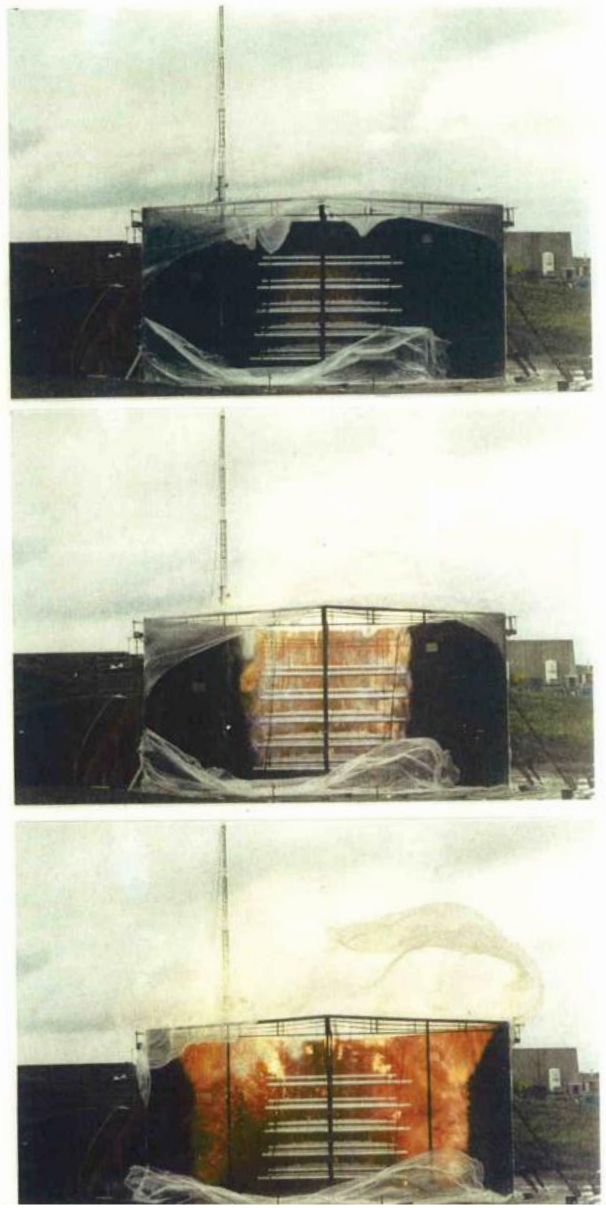
- Experiments involving large gas clouds showed that the size of the release alone was not sufficient explanation



# Effect of Process Congestion

- A characteristic of many incidents (though not all) was that the cloud engulfed congested process areas
- No understanding, no models, so experiments are needed
  - Large scale
  - Idealised geometries
- 1st experiments at Spadeadam led by Shell Thorton R&D
  - 30-degree sector, 30m radius, 10m height
  - Some ignited by high energy vented explosion
  - Flame acceleration observed
  - Significantly enhanced by vented explosion



- Around the same time, we had experiments in a long pipework region (up to 45m)
- Compared fuel types, with the intention to build a 90 degree version of the Shell rig
- Then we added some confinement to the first 9m of the test rig in a natural gas experiment
- Plans had to change!!  Built a stronger rig at Spadeadam to replicate the natural gas result and study other fuels
- Carried out experiments with cyclohexane and propane
- Deflagration to detonation transition (DDT) in both cases

# Reduced Scale Experiments

- Large scale experiments are expensive and take time to conduct
- But the physics of the explosions is scale dependant
  - Flame speeds and pressures are less if geometric scale is reduced
- Research carried out see if $O_2$ enrichment of the fuel-air mixture could correct for the scale effects
- Reproduced 45m and Shell results in 1/5$^{th}$ linear scale rigs
  - 45m reduced scale tests initially unreliable
  - We will come back to this

# Experiments for Model Development

- With understanding of the mechanisms, there is the potential for model development
- Projects MERGE & EMERGE (from late 1980's)
  - EU co-funded projects involving several European organisations, led by TNO PML
  - Small (TNO), medium and large-scale experiments (Spadeadam)
  - Modelling groups used data for explosion model development


# VCE Consequence Prediction – late 1980s

- Industry settled on assessing consequences based on deflagrations congested regions
- The concept of DDT in ‘real’ VCEs with common hydrocarbons was not accepted.
- Reasons given why DDT not considered relevant?

*“Detonation would not be sustained in open cloud”*

*“Conditions required would never be realised in a real incident”*

*“Damage from DDT would be much more severe than observed”*

***“How can I possibly design against a detonation!!”***





DNV

# Piper Alpha Disaster 1988

Explosion resulting in escalation & sustained fires

Platform destroyed in less than 3 hours

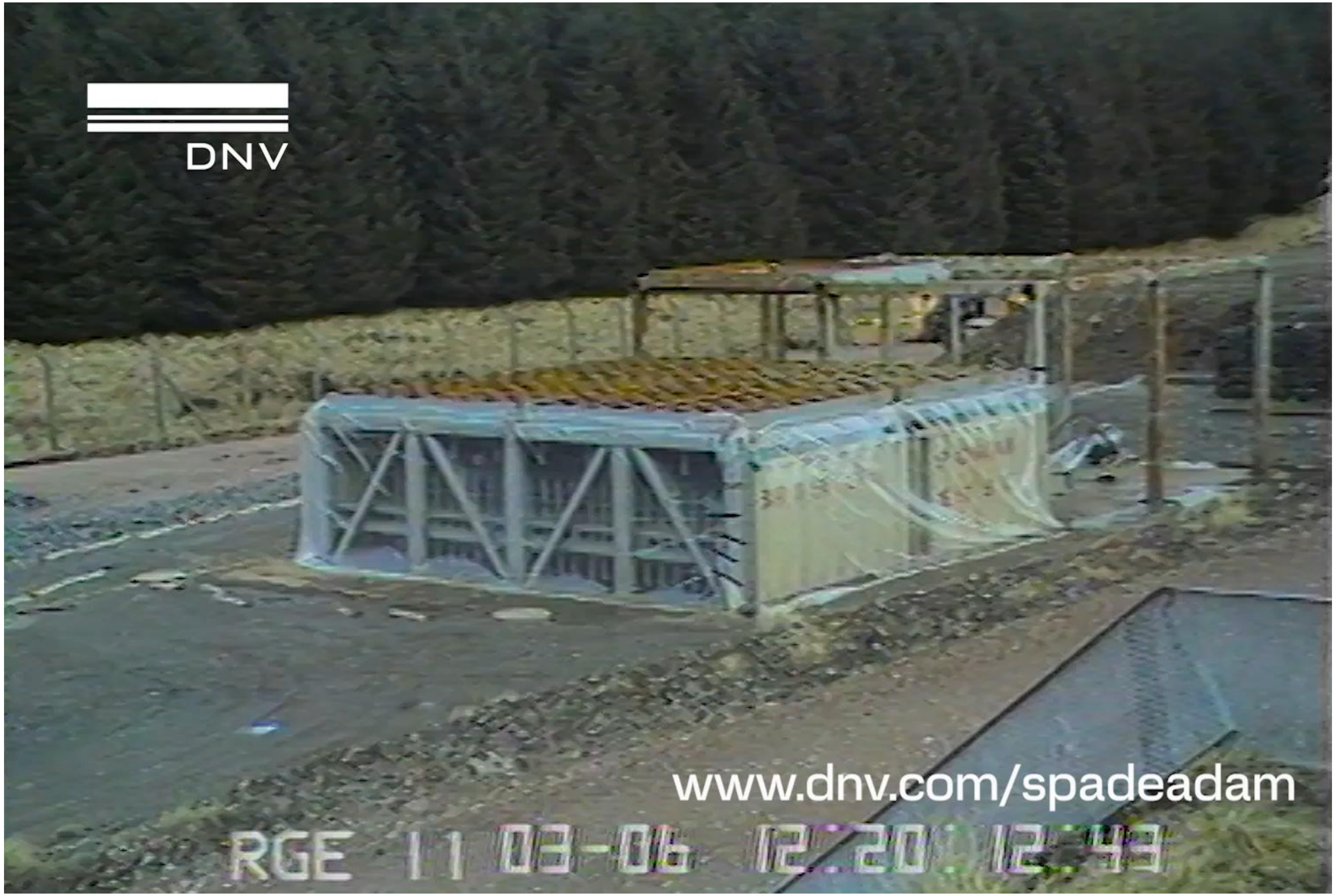
167 fatalities

Industry responded with research, including full scale experiments

# Explosions Research for Offshore

- Christian Michelsen Institute (now Gexcon) were conducting offshore geometry experiments before Piper Alpha
  - Development of FLACS CFD
- DNV Spadeadam began offshore research
- Needed to understand the explosion loads generated in offshore facilities
- Ultimately to allow design against explosion loads


# 1/3rd Linear Scale Test



# Joint Industry Research

Following the Piper Alpha disaster the Steel Construction Institute initiated a Joint Industry Project:

- Blast & Fire Engineering for Topside Structures (BFETS)

**Phase 1**

Collation of knowledge related to explosions and fires to provide interim guidance

**Finding**

Severity of events is scale dependent and models not validated at full scale

**Proposal**

Recommended a 2nd phase to carry out full scale fire and explosion experiments

**Modelling**

Modelling of full scale experiments to be carried out in advance of tests

# Full Scale Experiments

**BFETS Phase 2 – Full Scale Experiments**

Explosion test rig up to 28m x 12m x 8m high

Initial model predictions had nearly two orders of magnitude variation

Followed by two additional projects

1. Mitigation of explosions – reducing confinement, activation of water deluge (UK HSE funded)
2. Realistic high pressure releases - JIP with lab scale tests (Shell) medium scale tests (Gexcon) and full scale (Spadeadam)

Reports available on FABIG website (free to members)

# Effect of Water Spray

- 1/5th scale version of 45m rig failed to give high flame speeds if the rig was set up in the rain
- Suggested that water droplets were affecting flame acceleration.
- Returned to large scale 45m rig and added a water spray curtain (~1986)
  - Flame speed before the curtain >500ms$^{-1}$
  - Flame speed after the curtain ~40ms$^{-1}$
- Direct relevance to offshore facilities already fitted with water deluge systems

# General Area Deluge

- Need to understand how water deluge mitigates explosions
- Experiments carried out in an explosion chamber – vent area and obstacles can be altered
- With large vent and significant internal pipework congestion – high flame and flow speeds
- Demonstrated that water deluge systems mitigate explosions due to droplet break-up in high-speed flows

# Buncefield – December 2005

- Storage tank overfilling
- Major vapour cloud explosion
- Fires on many storage tanks that burned for days
- Widespread pressure offsite

# Jaipur – October 2009

1000 Tonnes of gasoline spilled

Major vapour cloud explosion

Cloud area 3 times that of Buncefield


Buncefield Site 2005
Fire Water Pumphouse
Tanker Loading Bay
Site Boundary
Tank 912

# Forensic Evidence – Directional Indicators

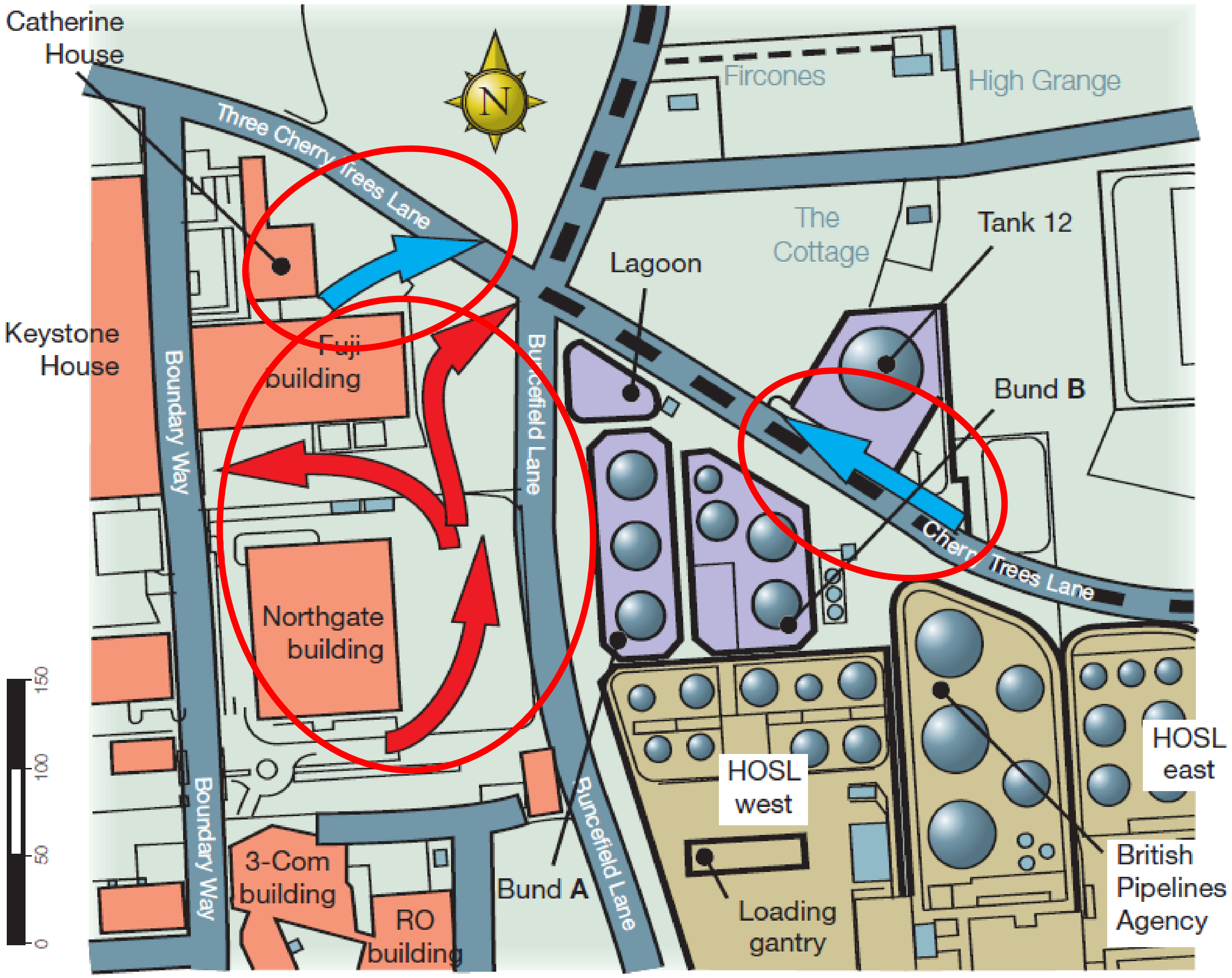
- Observed throughout cloud in both Buncefield (top) and Jaipur (bottom)
  - Bent or leaning lampposts
  - Trees scorched on one side
  - Branches on trees snapped and bent over in one direction
  - Scoured paintwork on one side of posts

# Initial Investigation

- Early Buncefield report gave initial assessment of the directional indicators

- Suggested <u>three</u> explosion events!! (Indicated by the red and blue arrows)

Assumed direction of explosion



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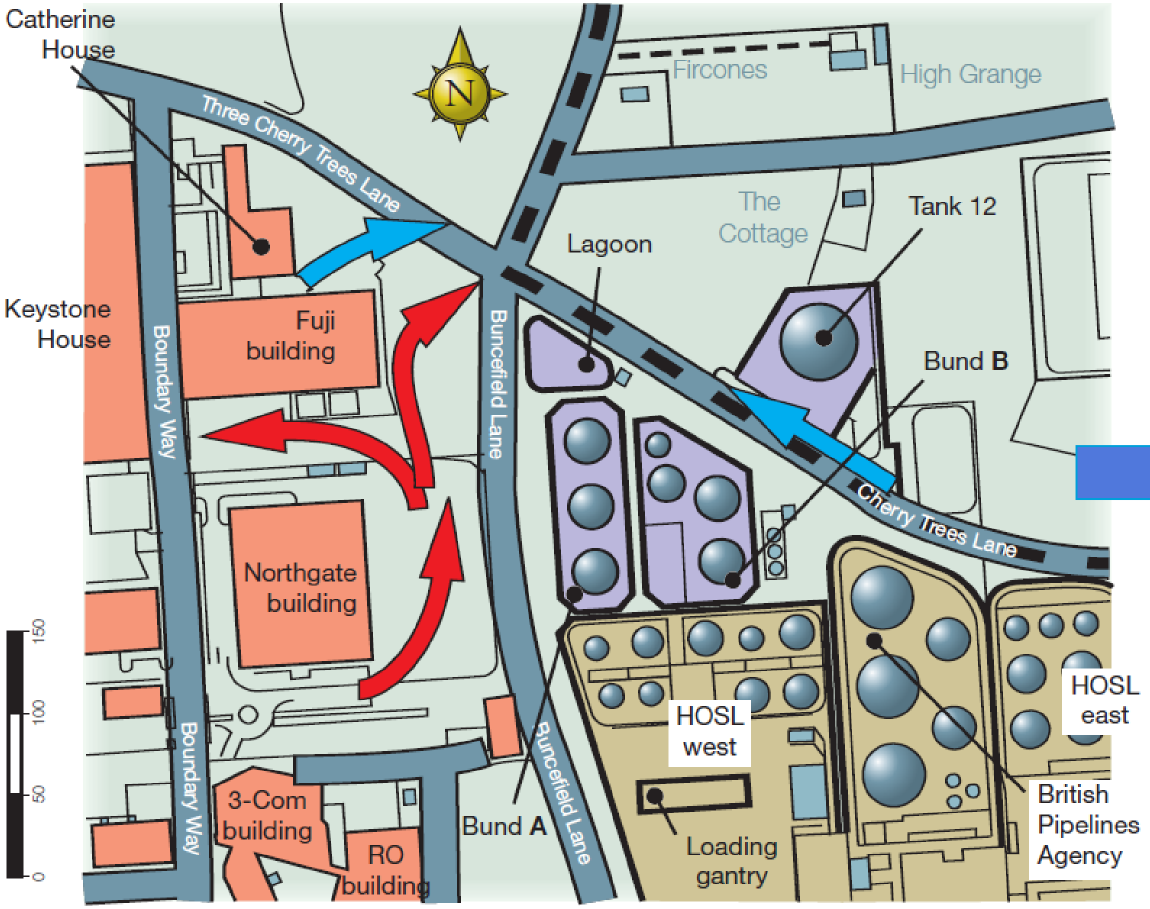
# Directional Indicators

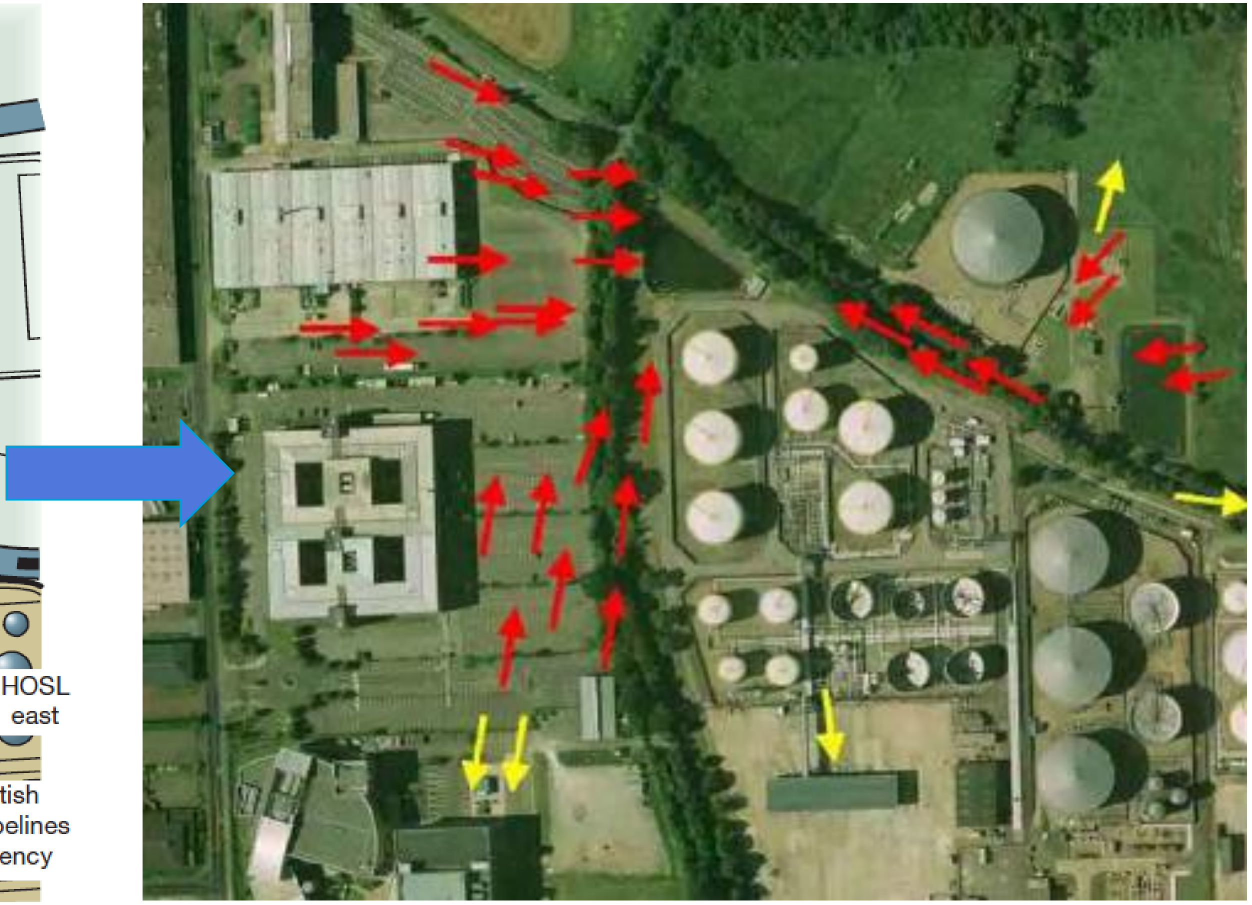
- Experimental work showed significant reverse flow

- 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

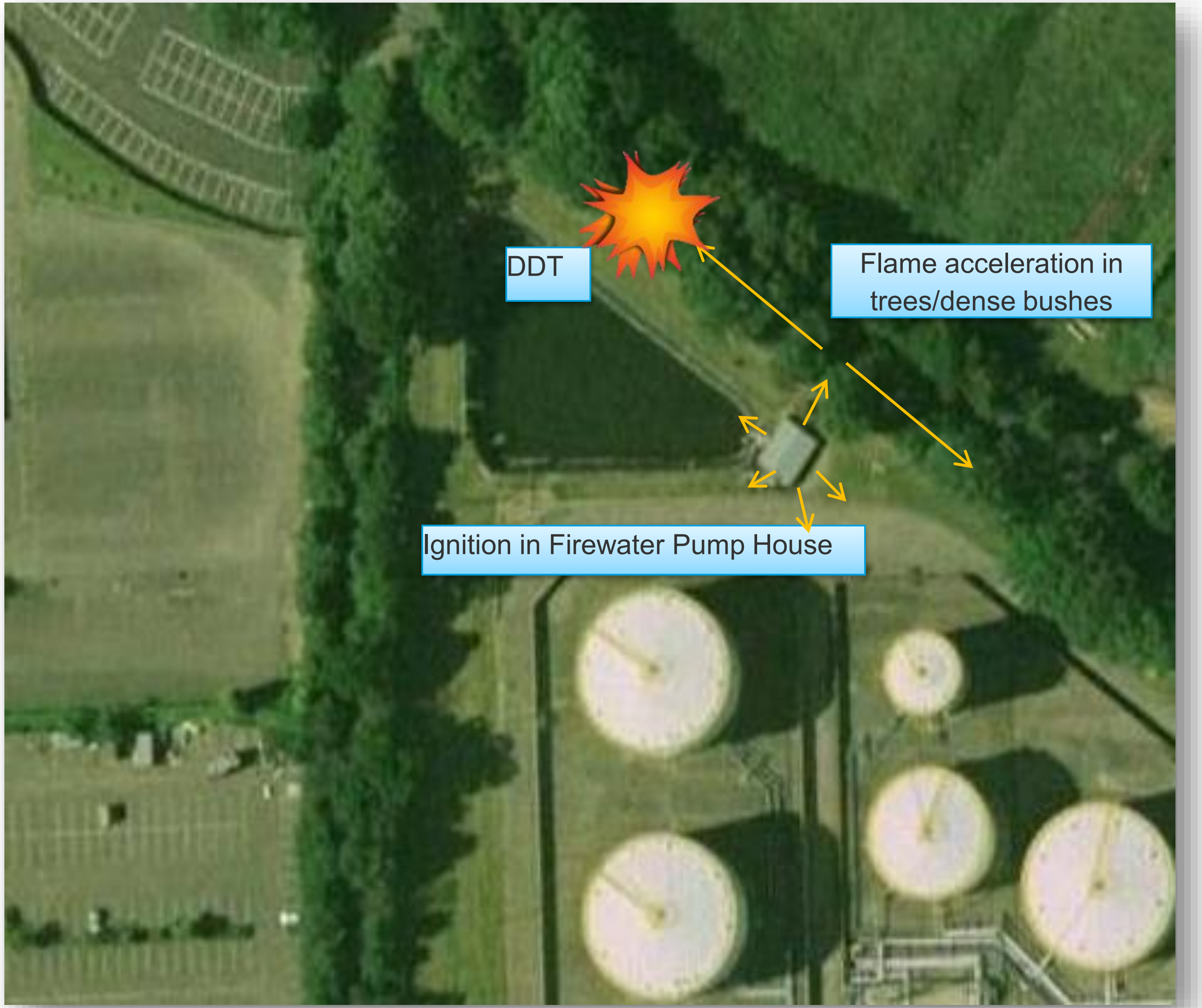
# Damage to Cars – Short Duration Shock Loadings

Outside the Cloud




Inside the Cloud

# Explanation Consistent with the Evidence




Research reports available on FABIG website

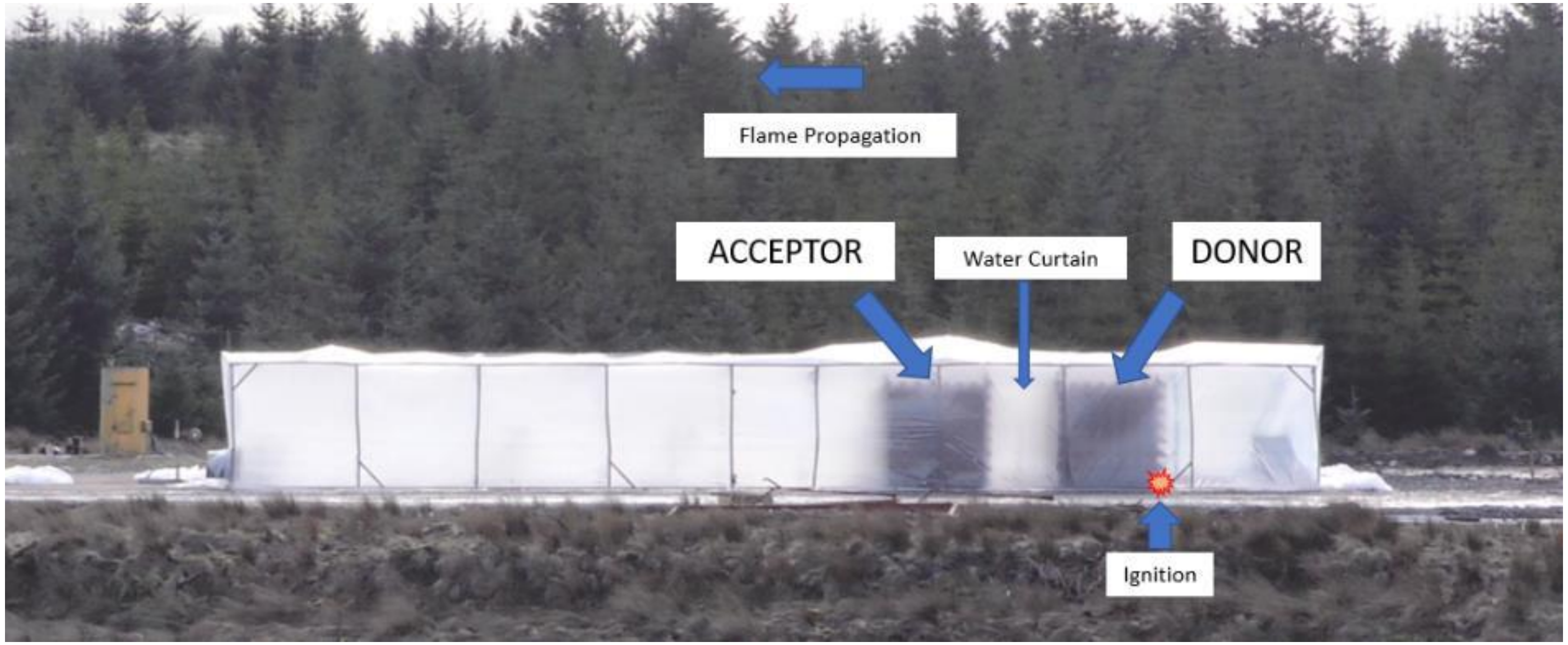
Since this research, Shell have conducted a review of previous VCE incidents

Found indications, or clear evidence of, the same forensic indicators in many*

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

# Projects MEASURE and DOWSES

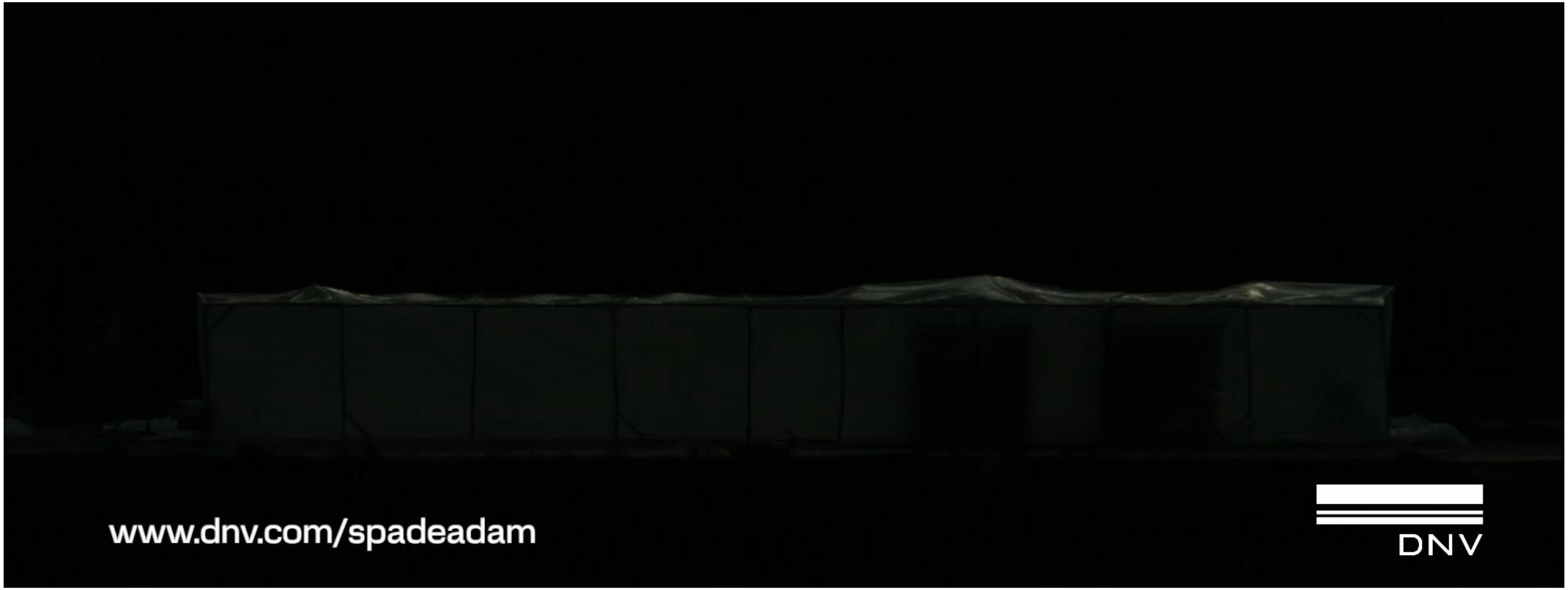
- MEASURE investigated the effect of gaps between congested regions, ignition in DONOR propagating into ACCEPTOR
- Follow-on DOWSES examined the effect of water curtains introduced into the gap between the regions



# MEASURE – DDT

20 bar shock wave compresses mixture to autoignition temperature

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

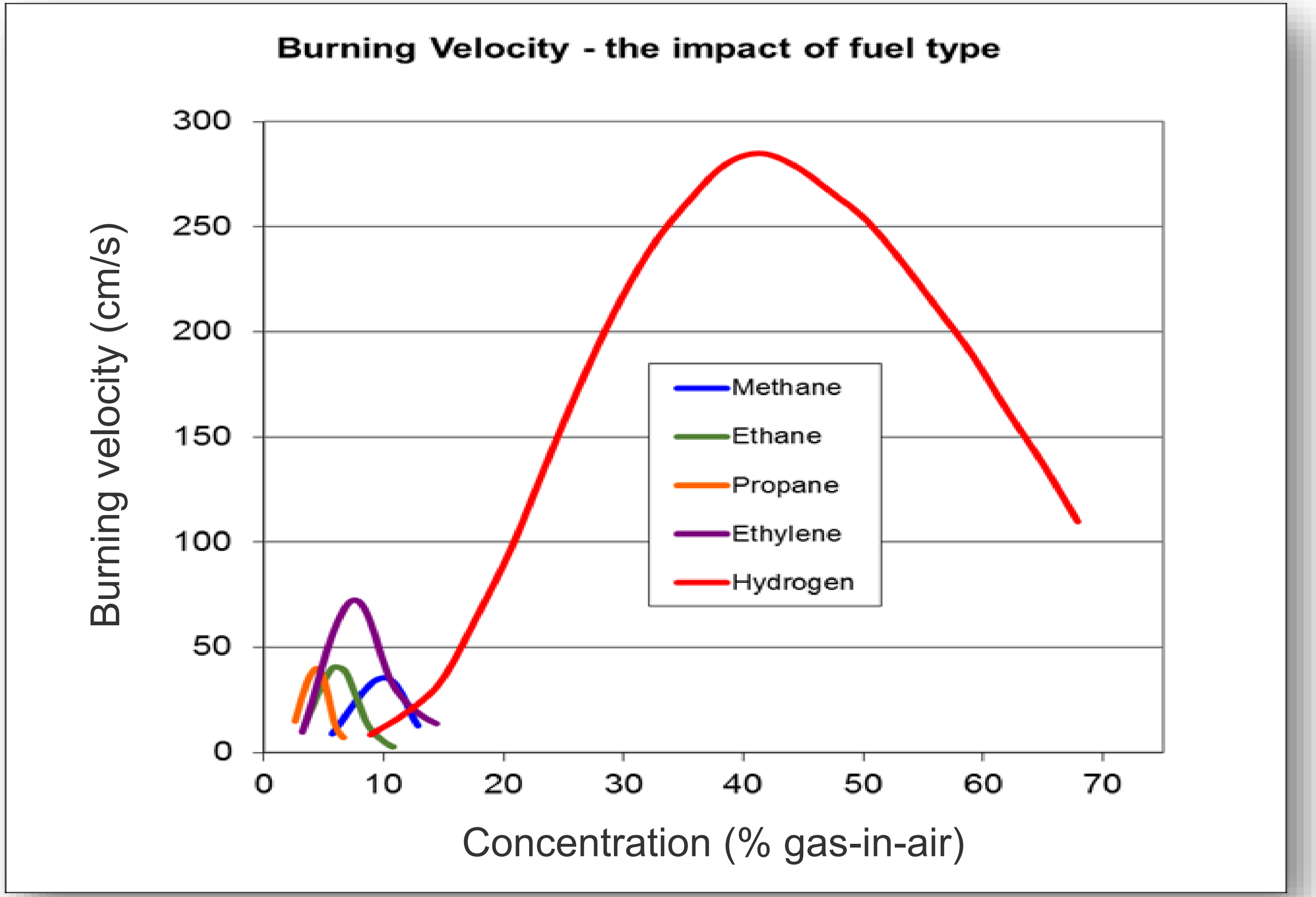


# Energy Transition - Hydrogen

# Managing Explosion Risk

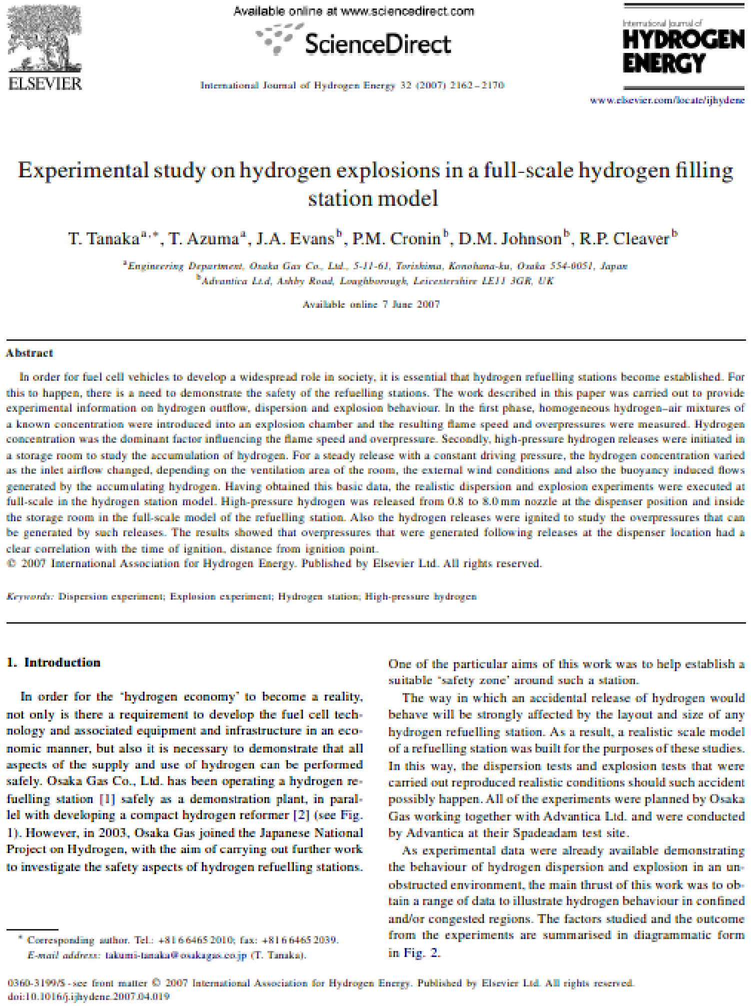
Hydrogen has a much greater reactivity compared to most hydrocarbons

The greater the burning velocity, the more severe the explosion



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

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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.

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# Fuel Concentration and 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

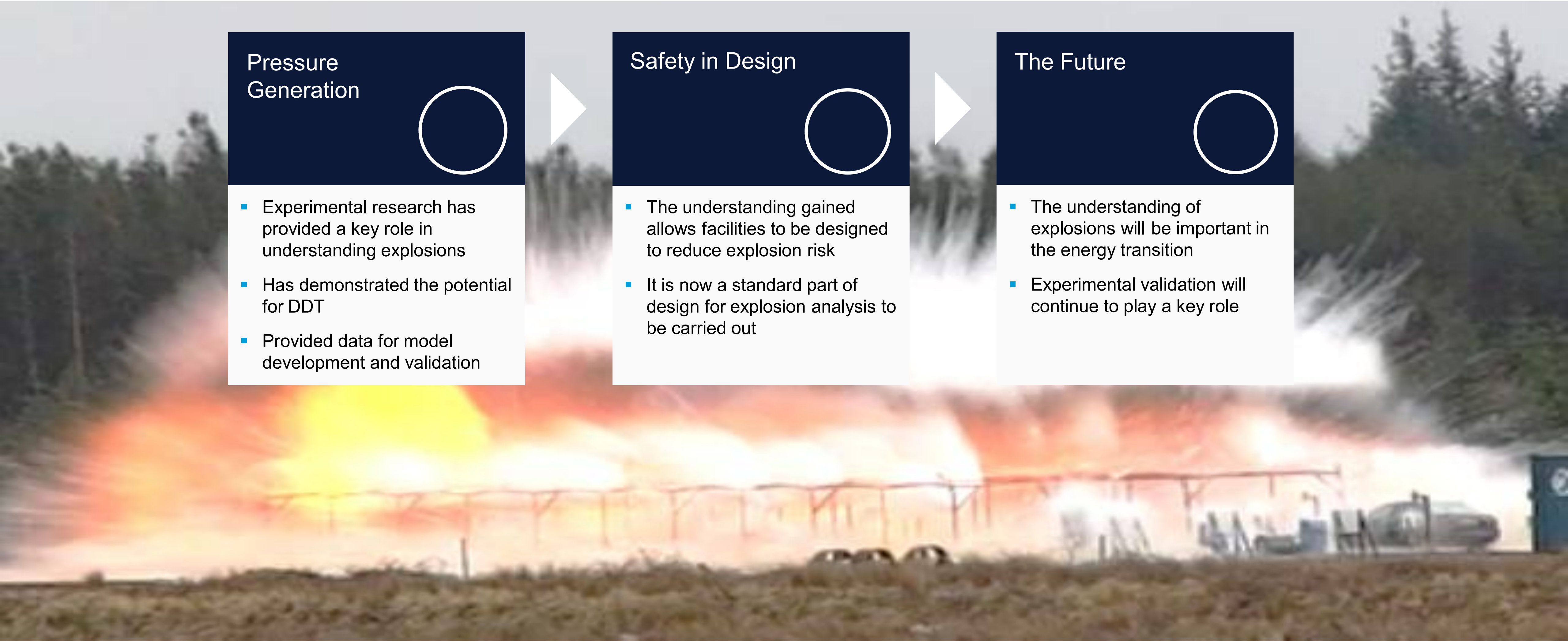

$8\%\ H_2$


$26\%\ H_2$

# Hydrogen and DDT

- More recently, results have from the CostFX JIP have been presented (FABIG and ICHS25)
- Investigated potential for DDT in various geometries and mostly with high pressure hydrogen releases

# Summary



## Pressure Generation

- Experimental research has provided a key role in understanding explosions
- Has demonstrated the potential for DDT
- Provided data for model development and validation

## Safety in Design

- The understanding gained allows facilities to be designed to reduce explosion risk
- It is now a standard part of design for explosion analysis to be carried out

## The Future

- The understanding of explosions will be important in the energy transition
- Experimental validation will continue to play a key role

# Thank You

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