# Review of Vapour Cloud Explosion Incidents

**VCE or UVCE :**
**(Unconfined) Vapour Cloud Explosions**
INERIS – TOTAL Journée Technique
Campus Total, Bougival, France
Friday 5 April 2019

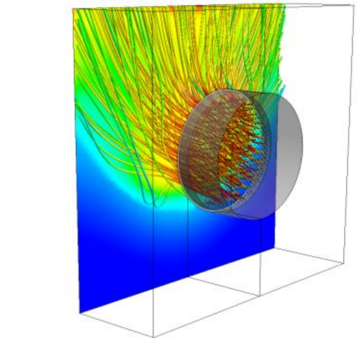
Graham Atkinson, Simon Gant*
and Jason Gill

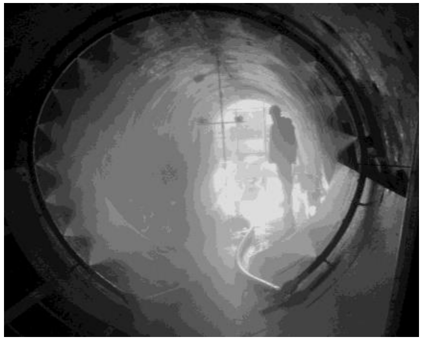
# Outline

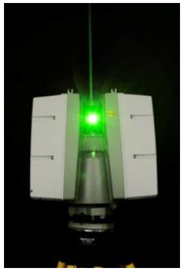
- Background
- Objectives
- Selection of historical VCE incidents
- Common factors
- Dispersion characteristics
- Detonation or deflagration?
- Practical implications for risk management
- Future work?
- Other relevant topics
  - Ongoing research on VCEs in steel-clad structures
  - Review of Q9

# Background to HSE Science & Research

- Multi-disciplinary laboratory:
  - Fire and process safety
  - Computational modelling
  - Exposure control
  - Toxicology etc.
- Approx. 400 staff
- 550 acre test site
- Fire galleries and burn hall
- Impact track
- Anechoic chamber
- Thermal test chamber

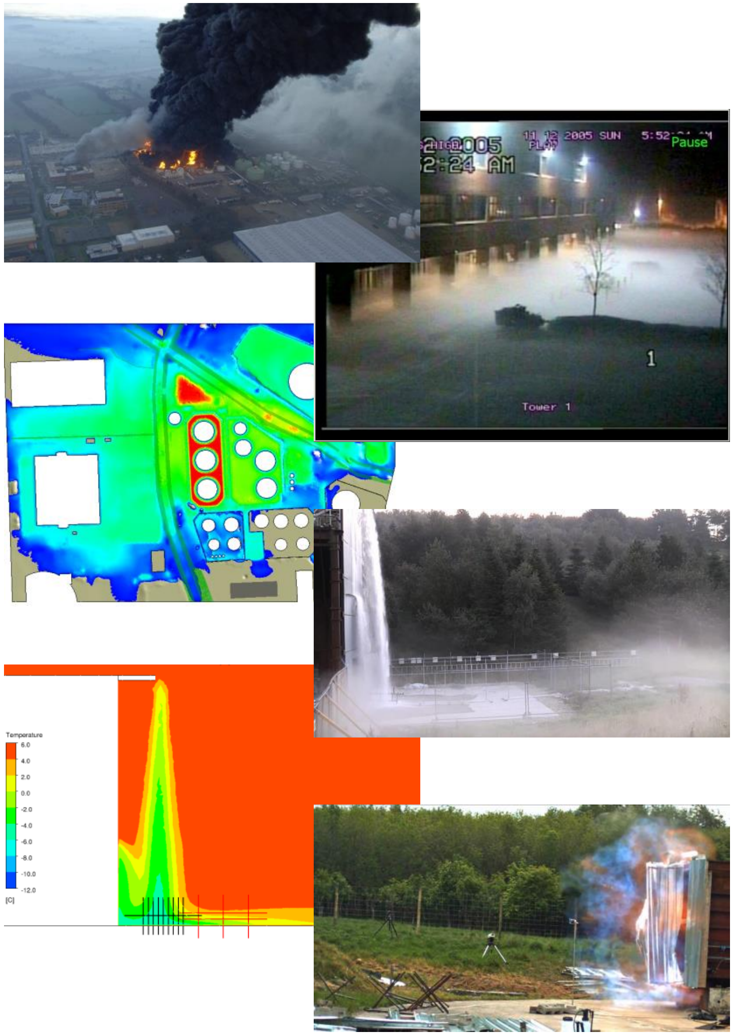






# Background to Research Post-Buncefield

- Buncefield (2005)
  - Incident investigation (2005 – 2007)
    - Liquid flow and vapour production
    - Dispersion of the vapour cloud
    - Possible explosion mechanisms
  - Research (2008 – 2013)
    - Vapour generation from tank overfilling releases
- Review of vapour cloud explosion incidents (2015 – 2017)
- Ongoing research
  - Vapour cloud explosions in steel clad structures (2015 – 2021)



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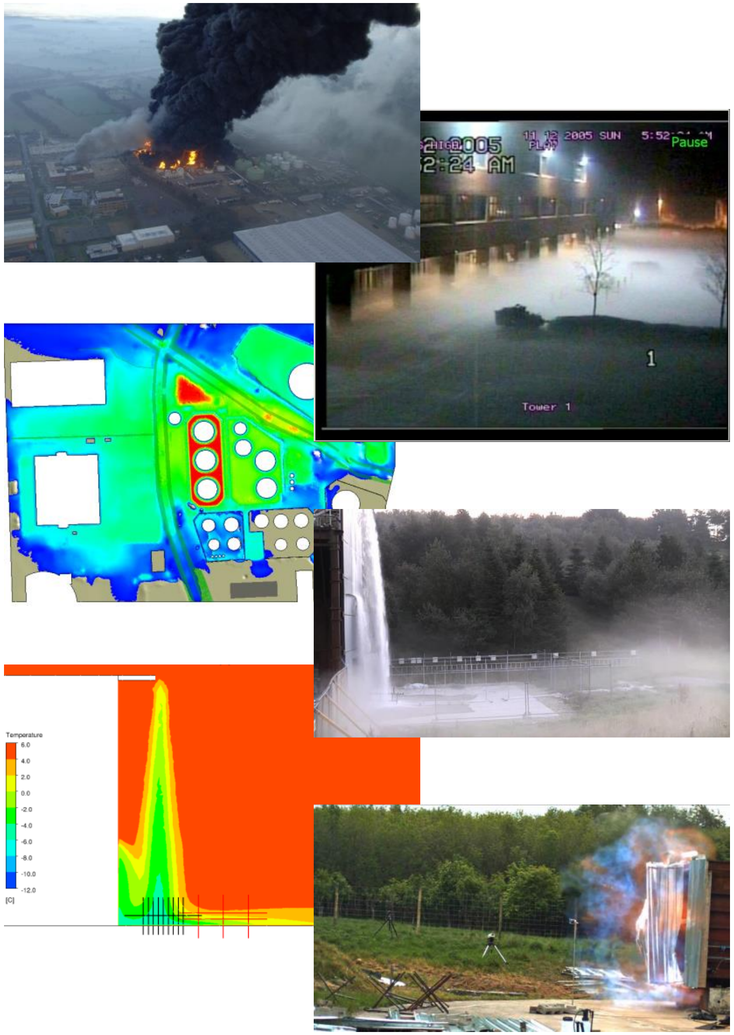


# Objectives

- **Aim:** to review historical severe unconfined VCE incidents
  - Characterise the events and identify common factors
  - Improve our understanding of vapour cloud development and explosion
- **Motivation:**
  - Public concerns about potential for VCEs at LNG export terminals in USA
  - Recent VCEs at Buncefield, Jaipur, San Juan and Amuay produced unexplained high over-pressures in unconfined, uncongested areas
- Jointly funded by US PHMSA and HSE

Buncefield (2005)

Jaipur (2009)

Puerto Rico (2009)

Amuay (2012)

# Selection of VCE Incidents

- LNG export terminals handle:
  - LNG (predominately methane) ⟵ Cannot produce severe unconfined VCEs
  - Refrigerants: ethane, butane, propane, ethylene (typically 100,000 US Gal)
  - Condensates: pentane, hexane (typically 500,000 US Gal)
- Only one recorded VCE incident at an LNG export terminal (Skikda, Algeria, 2004)
- Incidents reviewed from other LPG, LNG, gasoline and petrochemicals sites to assess potential VCE risk from refrigerants/condensates at LNG export terminals
- Similar combustion properties for C2-C6 hydrocarbons:

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

# Selection of VCE Incidents

| | |
|---|---|
| **Brenham, TX, 1992** | LPG Storage |
| **Newark, NJ, 1983** | Gasoline storage |
| **Big Spring, TX, 2008** | Refinery (LPG) |
| **San Juan, Puerto Rico , 2009** | Gasoline storage |
| **Skikda, Algeria, 2004** | LNG facility |
| **Buncefield, UK, 2005** | Gasoline storage |
| **Amuay, Venezuela, 2012** | Refinery LPG storage |
| **Jaipur , India, 2009** | Gasoline storage |
| **Austin , TX, 1973** | LPG pipeline |
| **North Blenheim, NY, 1990** | LPG pipeline |
| **Donnellson, IA, 1978** | LPG pipeline |
| **Ruff Creek, PA, 1977** | LPG pipeline |
| **Port Hudson, MO, 1970** | LPG pipeline |
| **St Herblain, France, 1991** | Gasoline storage |
| **Geismer, LA, 2013** | Petrochemicals |
| **Naples, Italy, 1995** | Gasoline storage |
| **La Mede, France, 1992** | Refinery (LPG) |
| **Baton Rouge, LA, 1989** | Refinery (LPG) |
| **Norco, LA, 1988** | Refinery (LPG) |
| **Pasadena, CA, 1989** | HDPE |
| **Flixborough, UK, 1974** | Petrochemicals |
| **Devers, TX, 1975** | LPG Pipeline |
| **Lively, TX, 1996** | LPG Pipeline |
| **Ufa, USSR, 1989** | LPG Pipeline |

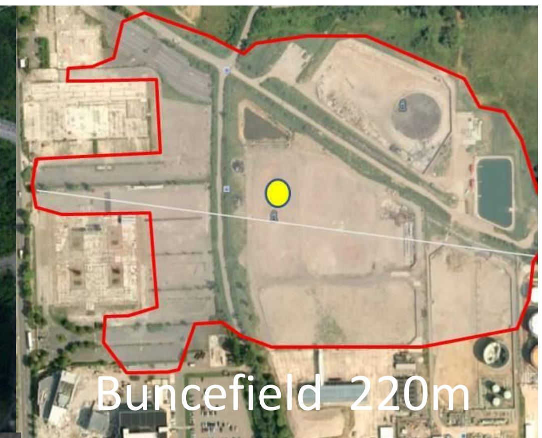
Information sources:

- Significant national incidents investigated by CSB, NTSB, HSE etc.
- Marsh insurance 100 largest losses

# VCE Incidents Reviewed

- Unexpected findings:
  - Majority of incidents showed vapor clouds that spread in all directions around the source
  - Only a few incidents showed a burned area extending solely in the downwind direction

# VCE Incidents: Common Factors

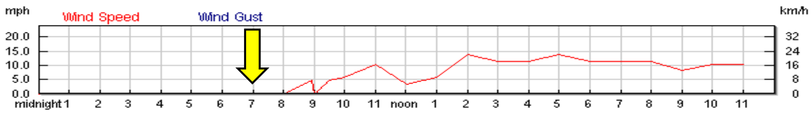

Approximate cloud radii shown

Burn patterns do not look like this

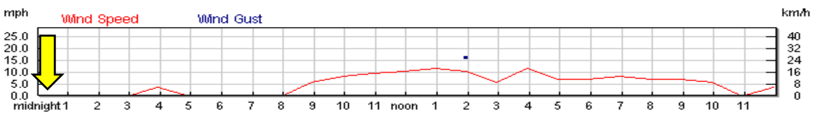

Dispersion in a 2 m/s wind (Pasquill Stability Class F)

# VCE Incidents: Common Factors

Wind speeds measured at nearest met stations

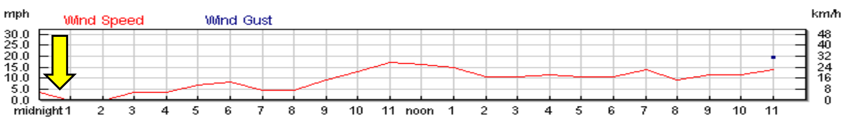



Brenham, Texas (7:00am)




San Jan, Puerto Rico (00:23 am)


Big Spring , Texas




Newark, New Jersey (0:10 am)

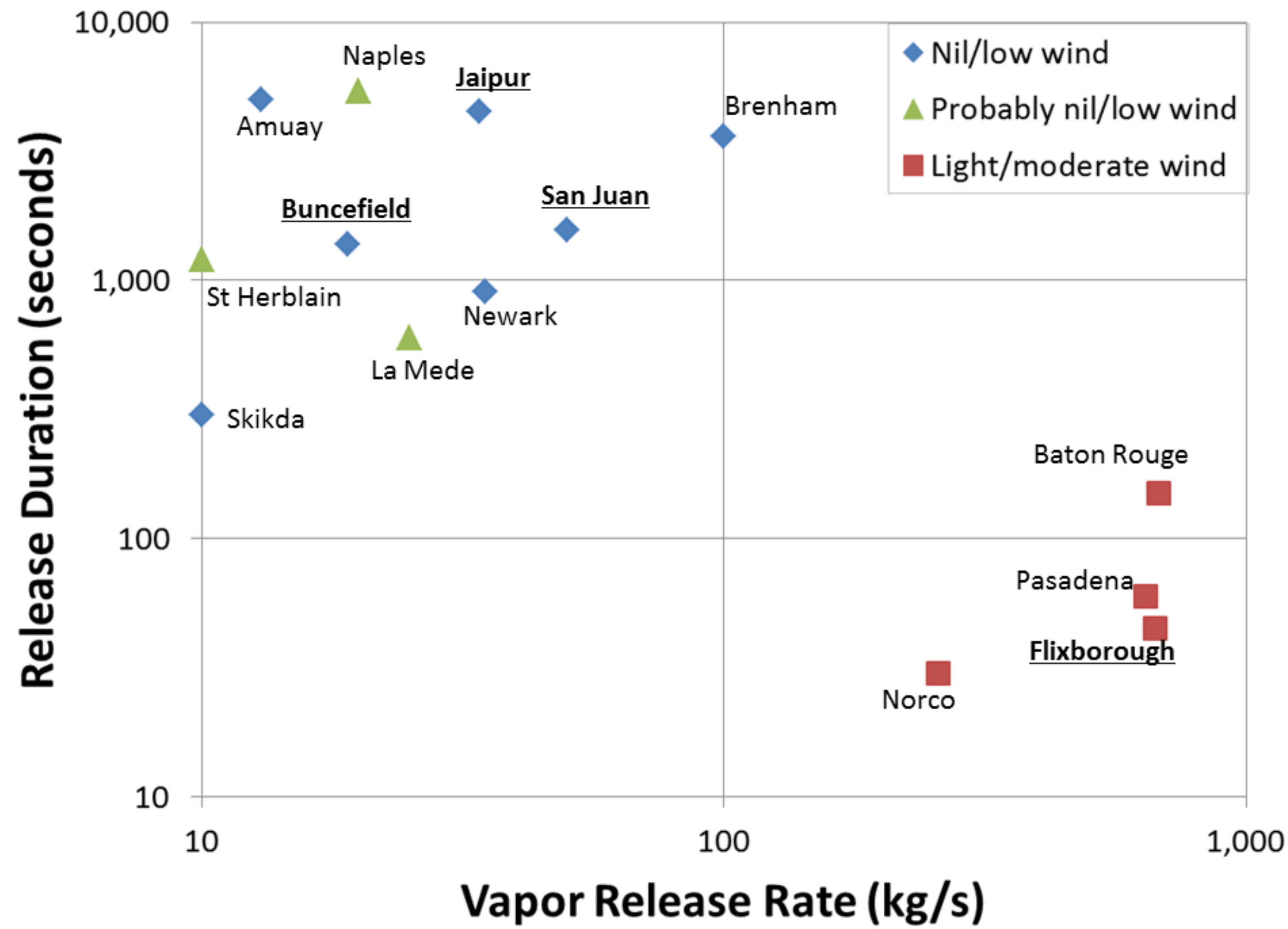
Vapor cloud structure


Dense vapor cloud spreads in all directions around the source in nil/low wind speeds

# VCE Incidents: Common Factors

| Incidents that occurred in nil/low–wind conditions | | Vapor release rate (kg/s) | Duration prior to ignition (s) |
|---|---|---|---|
| Brenham, TX, 1992 | LPG Storage | 100 | 3600 |
| Newark, NJ, 1983 | Gasoline storage | 35 | >900 |
| Big Spring, TX, 2008 | Refinery | not known | not known |
| San Juan, Puerto Rico, 2009 | Gasoline storage | 50 | 1560 |
| Skikda, Algeria, 2004 | LNG facility | ~10 | <300s |
| Buncefield, UK, 2005 | Gasoline storage | 19 | 1380 |
| Amuay, Venezuela, 2012 | Refinery LPG storage | 13 | >5000 |
| Jaipur , India, 2009 | Gasoline storage | 34 | 4500 |
| **Incidents that probably occurred in nil/low-wind conditions** | | | |
| St Herblain, France, 1991 | Gasoline storage | ~10 | 1200 |
| Geismer, LA, 2013 | Petrochemicals | not known | not known |
| Naples, Italy, 1995 | Gasoline storage | 20 | 5400 |
| La Mede, France, 1992 | Refinery | 25 | 600 |
| **Incidents that occurred in light/moderate winds** | | | |
| Baton Rouge, LA, 1989 | Refinery | 681 | 150 |
| Norco, LA, 1988 | Refinery | 257 | 30 |
| Pasadena, CA, 1989 | HDPE | 643 | 60 |
| Flixborough, UK, 1974 | Petrochemicals | 670 | 45 |

# VCE Incidents: Common Factors



# VCE Incidents: Common Factors

- Dense gas clouds become laminar in far field
  - Slow mixing and dilution, nearly uniform concentrations across wide area




Jack Rabbit 1
Trial 2
Wind speed = 0.6 m/s

© DHS Chemical Security Analysis Center (CSAC)

# Dispersion Characteristics

Liquid nitrogen release in very low wind speed

# Dispersion Characteristics

- Blast damage also indicates that gas concentrations were nearly uniform (within flammable range) across a wide area
- Fairly uniform damage throughout cloud
- Similar damage across different incidents

Buncefield

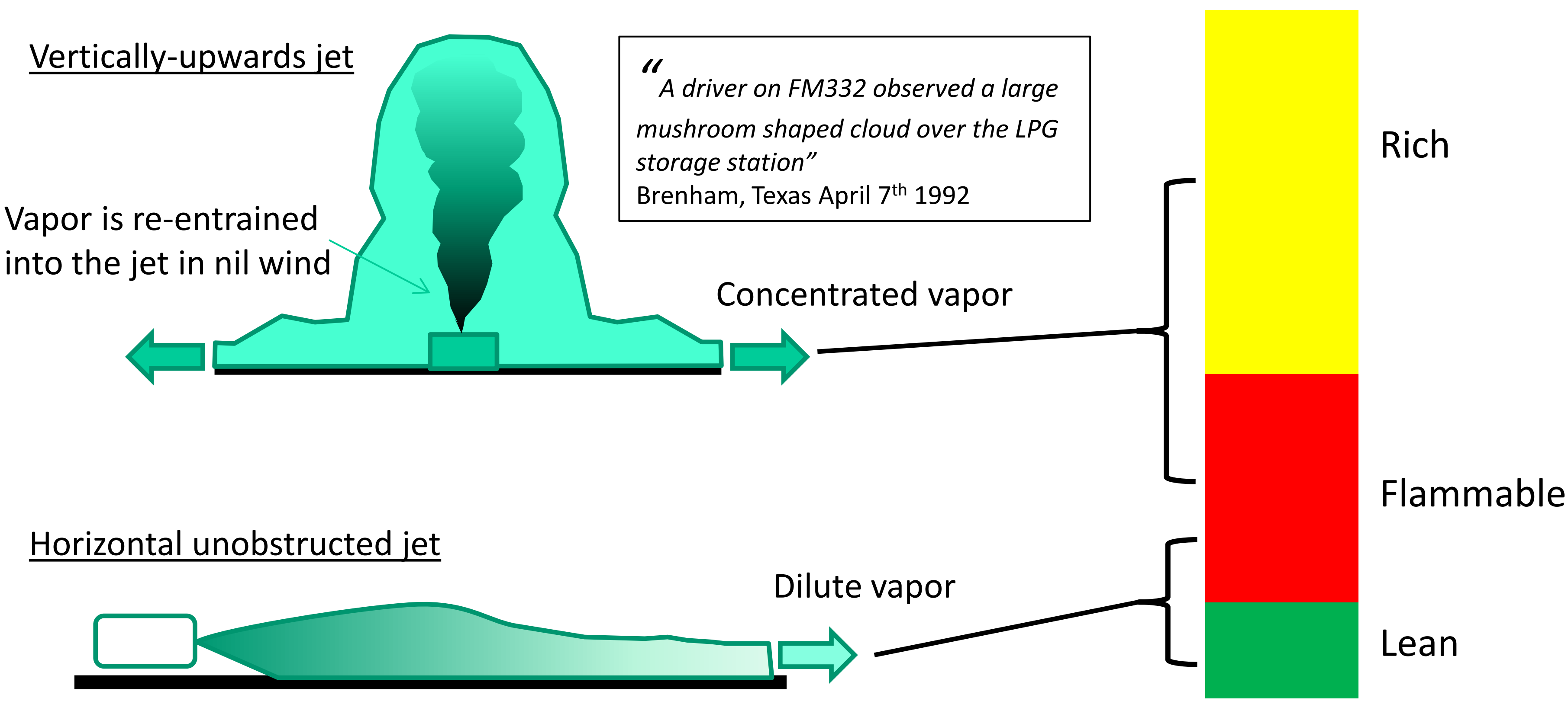
Jaipur

Amuay

Test Explosion (1 bar)

# Source conditions

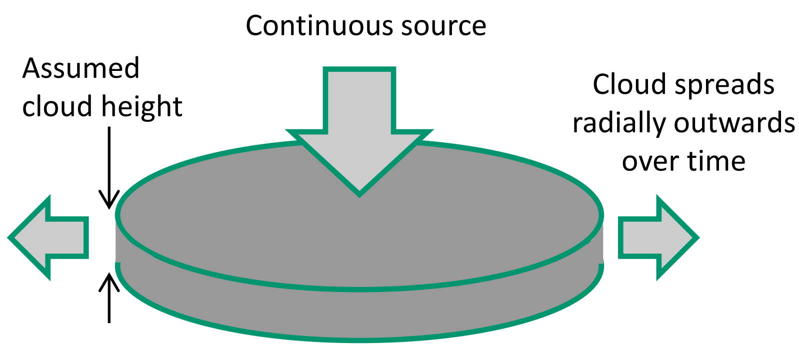
- Range of source conditions possible
- Limitation: models usually ignore re-entrainment of vapor



# Dispersion Modelling Options

1. Simple vapor cloud assessment method
2. Integral dispersion models, e.g. PHAST ← Not valid in zero/low wind speed
3. Shallow-layer models
4. Lagrangian particle/puff models
5. Computational Fluid Dynamics (CFD) ← Costly, user-variability Validation needed

Simple vapor cloud assessment method, e.g. FABIG Technical Note 12



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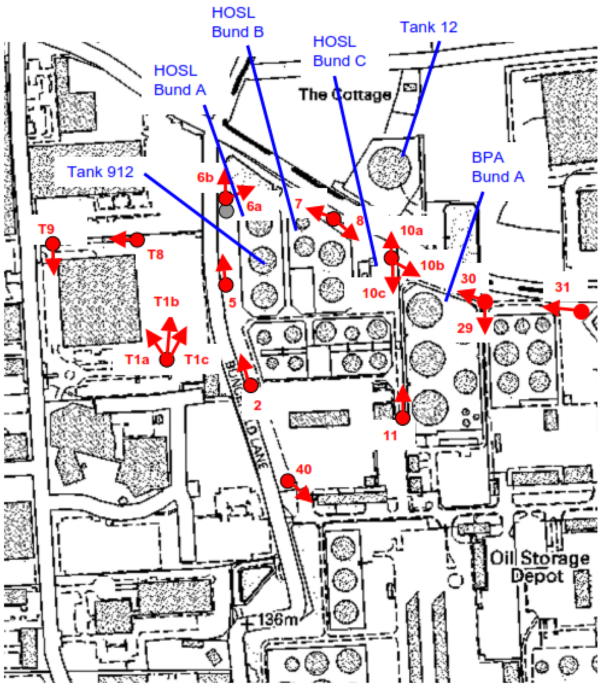
# Deflagration or Detonation?

| Evidence | Detonation | Deflagration |
|---|---|---|
| Blast wave timing | ? | ? |
| Deflection of camera mount | ? | ? |
| Illumination | ? | ? |
| Witnesses | ? | ? |
| Building response | ? | ? |
| Damage to cars, drums and steelwork | ? | ? |

# Blast wave timing

Measured blast wave speed based on first recorded light and pressure disturbance

| | |
|---|---|
| Furnell Cameras | 321 – 346 m/s |
| Alcon Cameras | 317 – 356 m/s |




**Detonation**

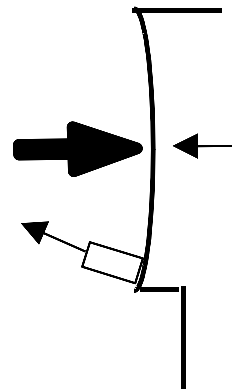
Blast front advances at 2000 m/s

**Deflagration** ✓

Pressure waves radiate out at sound speed ~ 300m/s

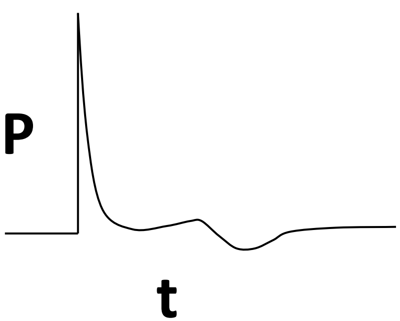
# Deflection of CCTV Camera Mount

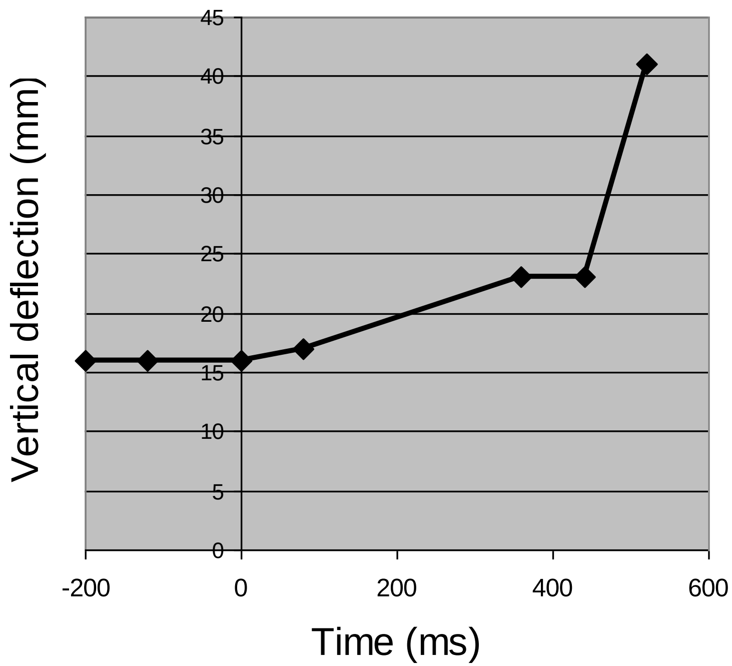
Camera on corner of building



Detonation

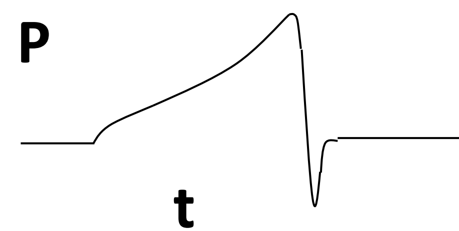
(Flame speed >> $V_{sound}$)




Deflagration ✓

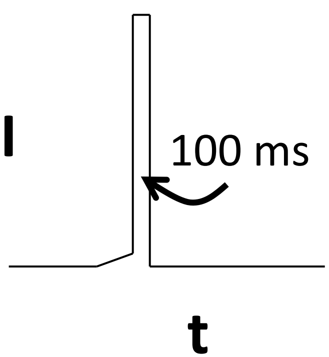
(Flame speed < $V_{sound}$)

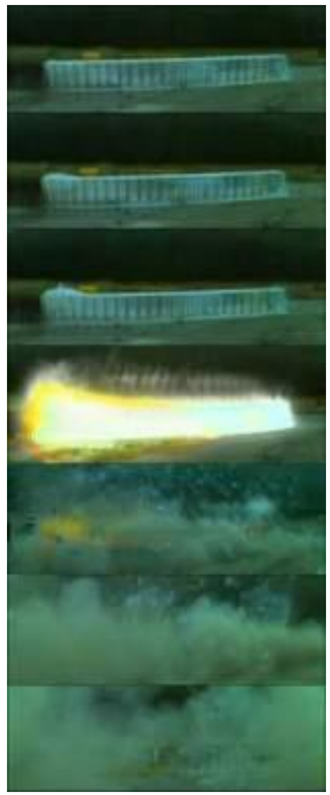


# Illumination

**Detonation test**

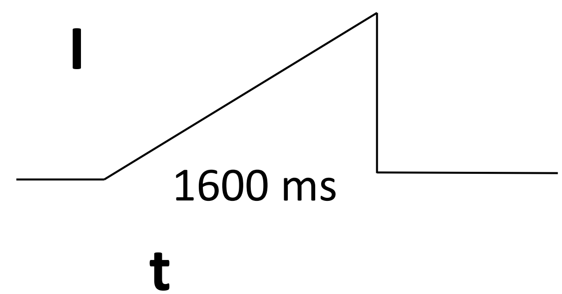
Detonation



**Buncefield**

Deflagration ✓



# Witnesses

Detonation

(Flame speed >> $V_{sound}$)

**Flash ! Bang!**

Deflagration

(Flame speed < $V_{sound}$)

I saw it coming…

I felt it coming…

# Witnesses

"I clasped my hands over my ears and kept an eye on the mirror, seeing the flame coming towards me. I continued to look, to see whether the flames went past me, being concerned due to the fact my window was still down……..

I could see the flame engulfing cars in the lane. It lasted for two seconds."

Detonation
(Flame speed >> $V_{sound}$)

Deflagration ✓
(Flame speed < $V_{sound}$)

# Witnesses

All witnesses report sustained noise and/or pressure effects:

"It was like being buffeted by a strong wind…."

"There was a very loud crackling sound……"

"The sound was like a jet engine……"

"The was a huge pressure sound….."

Detonation
(Flame speed >> $V_{sound}$)

Deflagration ✓
(Flame speed < $V_{sound}$)

# Building response

All buildings have ***exactly*** one large hole





Front wall holed – Sides and roof intact

Walls reinforced concrete –

Front half of roof pushed down

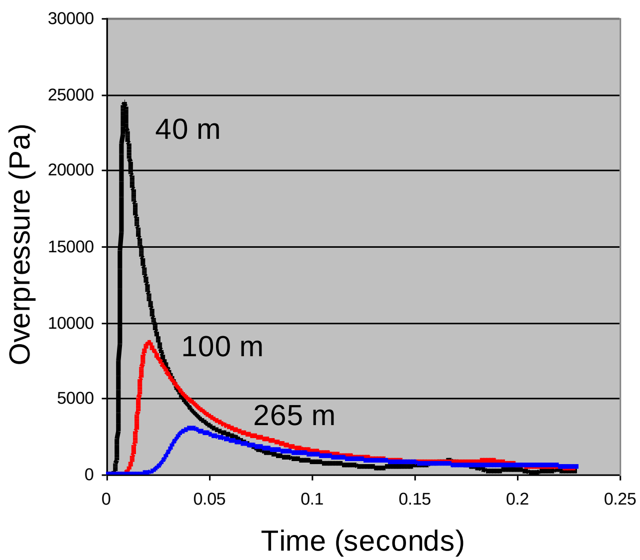
# Building response

Tianjin: solid phase explosion 21 tonne TNT equivalent, sudden pressure rise

# Building response

## Detonation

Despite the widely varying blast curves at different distances, the net effect is always to fail the front wall and leave the roof and sides intact? Strange coincidence…




Detonation of vapour cloud 1 m deep, 200 m radius

## Deflagration ✓

1. The pressure rises slowly
2. The most vulnerable part of the building bursts
3. Internal pressurisation rapidly relieves net inwards forces on all other faces.
4. Even if the blast pressure then rises much further, there will only be one large hole.

# Damage to cars, drums and steelwork

Detonation test
Obviously directional damage

Typical incident
No clear directional damage

# Damage to cars, drums and steelwork

Detonation test

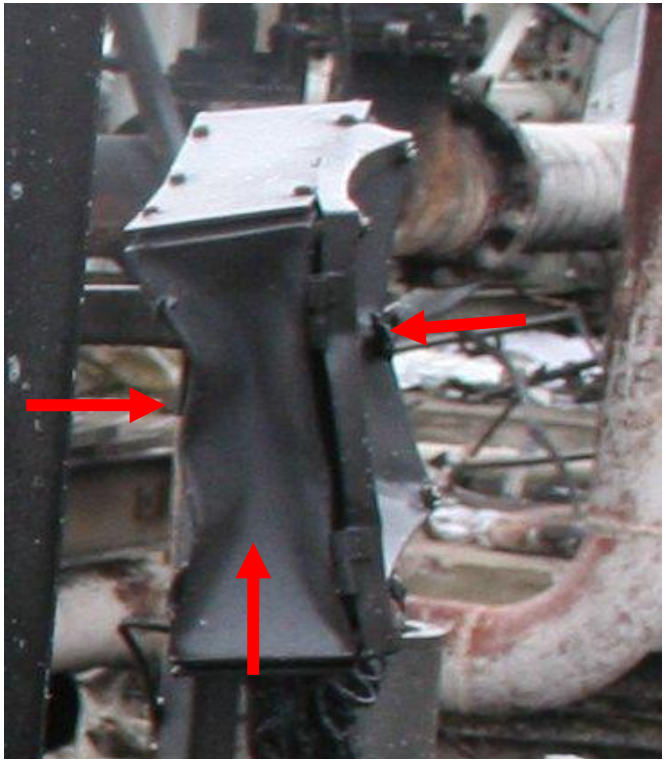

Static crushing at 2 bar

Incident

# Damage to cars, drums and steelwork

Detonation test
Obviously directional damage

Typical incident
No clear directional damage



# Damage to cars, drums and steelwork

## Detonation test

Sills pushed in and tyres lost



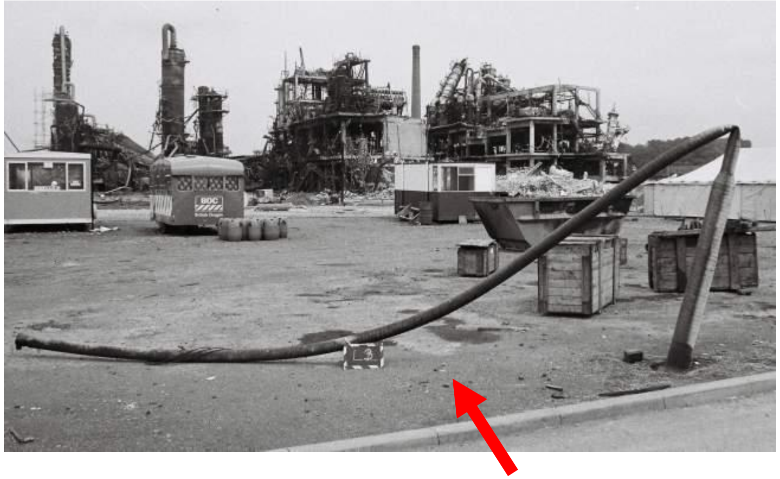
## Buncefield

## Explosion chamber 1 bar

# Damage to cars, drums and steelwork

Flixborough

Detonation: continuous curvature of steelwork



# Damage to cars, drums and steelwork

Buncefield

No signs of continuously curved steelwork

# Deflagration or Detonation?

| Evidence | Episodic Deflagration | Detonation |
|---|---|---|
| Blast wave timing | ✓ | |
| Deflection of camera mount | ✓ | |
| Illumination | ✓ | |
| Witnesses | ✓ | |
| Building response | ✓ | |
| Damage to cars, drums and steelwork | ✓ | |

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# Practical Implications

- Avoid producing a large flammable cloud
- Incident record show relatively small releases can produce large flammable clouds over minutes / tens of minutes in nil or low wind speeds
- Cloud spread in all directions around release point
- Gas detection and shutoff
- Storage tank overfill protection

RR1113: "if a very large cloud develops in a normal site it is appropriate to assume that the risk of transition to a severe (non-detonative) explosion is high (close to unity). With careful design and operation of sites it may be possible to reduce the risk of such transition but currently we lack the fundamental understanding required to specify what level of control of congestion and confinement is needed."

# Practical Implications

- Risk assessments (or regulation) and emergency planning should consider both windy and nil/low-wind cases
  - Consider different types of release together with the weather conditions in which they could produce large clouds
  - FABIG Technical Note 12 for flat, unobstructed sites

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# Future work?

- We do not understand what will happen to slender steels when they are impacted by detonations…
- We have put drums, cars and boxes in the way of a detonation. We could do the same for  drag sensitive objects
- What would be of most interest?
  - Pipes ½” to 2”, scaffold tubing, angle irons, unistrut
- If they are rarely left with continuous curvature we will be able understand the incident record better
- If they are often left with continuous curvature (i.e. the detonation damage is inconsistent with Buncefield, Jaipur etc.): there must be another mechanism capable of generating high pressures of several bar in open areas

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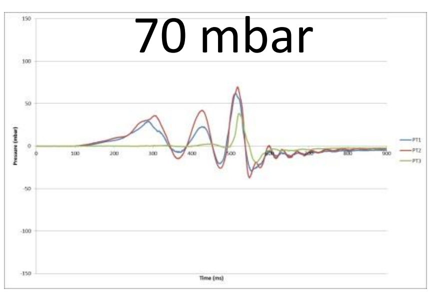
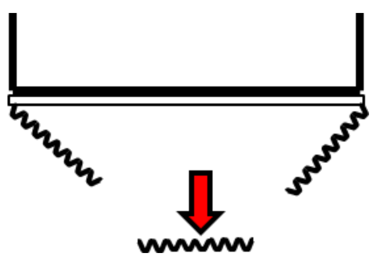
# VCEs in steel-clad structures

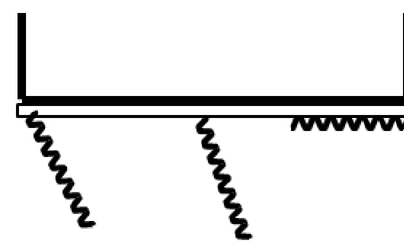
SYMPOSIUM SERIES NO 161 HAZARDS 26

## Vapour cloud explosions in steel clad structures

Jason Gill, Health and Safety Executive, Harpur Hill, Buxton SK17 9JN.
Graham Atkinson, Health and Safety Executive, Harpur Hill, Buxton SK17 9JN.
Edmund Cowpe, Health and Safety Executive, Redgrave Court, Merton Road, Bootle L20 7HS.
David Painter, Health and Safety Executive, Redgrave Court, Merton Road, Bootle L20 7HS.



# VCEs in steel-clad structures

# VCEs in steel-clad structures

Ignition source for Buncefield was probably a star-delta switch enclosure, located inside a pumphouse.

# "Nested bang-box" mechanism for severe vapour cloud explosions

HSE

**Explosions in Electrical Control Boxes as a Potential "Nested Bang-Box" Mechanism for Severe Vapour Cloud Explosions**

Gill J.[1,2,*], Phylaktou H.N.[2,*], Atkinson G.[1], Andrews G.E.[2] Cowpe E.[3]

[1] *Health and Safety Executive's Health and Safety Laboratory, Buxton, Derbyshire, SK17 9JN, UK*
[2] *University of Leeds, Leeds, LS2 9JT, UK*
[3]*Health and Safety Executive, Bootle, Merseyside, L20 7HS, UK*
**Corresponding author emails: jason.gill@hse.gov.uk, h.n.phylaktou@leeds.ac.uk*

Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9), pp. 356-365
Edited by Snegirev A., Liu N.A., Tamanini F., Bradley D., Molkov V., and Chaumeix N.
Published by St. Petersburg Polytechnic University Press
ISBN: xxx-xxx-xx-xxxx-x :: DOI: 10.18720/spbpu/2/k19-130

Collaboration with ongoing work at INERIS on this topic?

# Review of Q9

ISSUE 75
March 2019

## A REVIEW OF THE Q9 EQUIVALENT CLOUD METHOD FOR EXPLOSION MODELLING

FABIG
Fire and Blast Information Group

Foreword by:
M. Bilio, Health and Safety Executive, UK

Written by:
J. Stewart and S. Gant, Health and Safety Executive, UK

Q9 ($m^3$) [7]

$$V_{Q9} = \frac{1}{(SE)_{max}} \sum_{i=1}^{n} (fuel_{vol} \times S \times E)_i$$

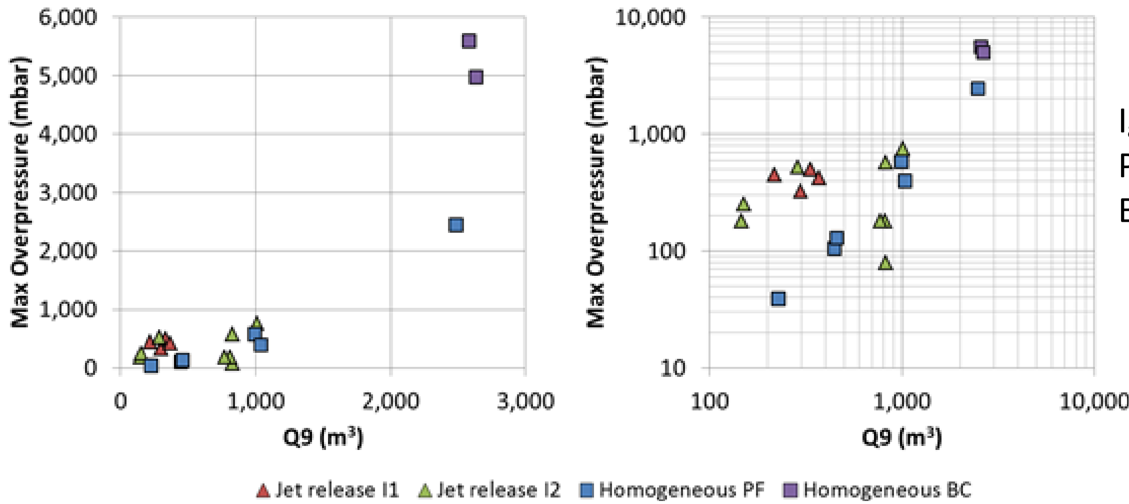
Review of the evidence supporting the Q9 assumptions:

- Explosion model accurately predicts explosion overpressures in uniform gas clouds
- Scaling between realistic (inhomogeneous) clouds and Q9 equivalent volume is such that ignition of the two gas clouds gives a similar explosion overpressure

# Review of Q9: BFETS data

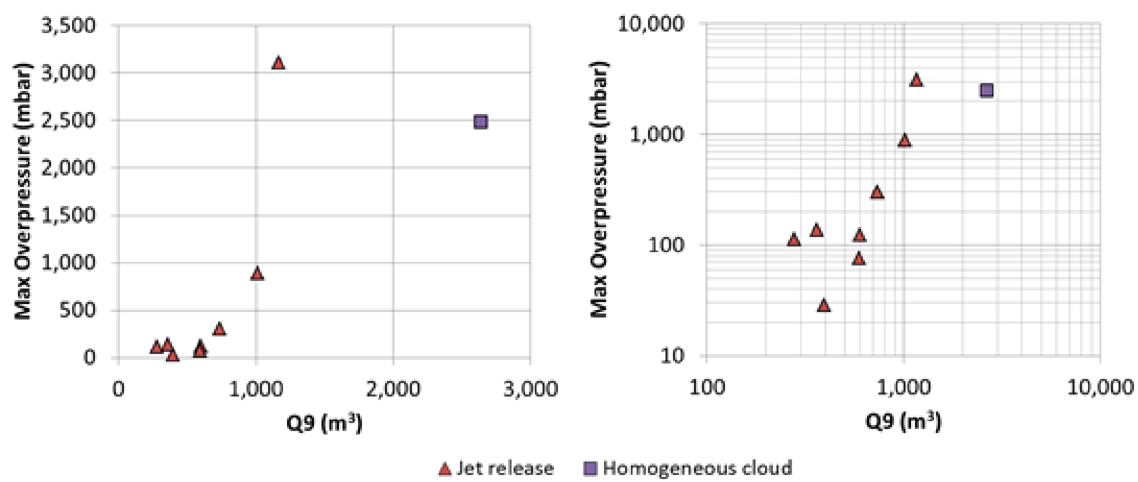
Linear scale | Log scale

Configuration 1




Ignition locations (I1, I2)
Partial Fill (PF)
Base Case (BC)

Configuration 2



# Review of Q9: Literature review

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**SIMPLIFIED FLAMMABLE GAS VOLUME METHODS FOR GAS EXPLOSION MODELLING FROM PRESSURIZED GAS RELEASES: A COMPARISON WITH LARGE SCALE EXPERIMENTAL DATA**

V.H.Y. Tam[1], M. Wang[1], C.N. Savvides[1], E. Tunc[2], S. Ferraris[2], and J.X. Wen[2]
[1]EPTG, BP Exploration, Chertsey Road, Sunbury-on-Thames, TW16 7LN, UK
[2]Faculty of Engineering, Kingston University, Friars Avenue, London, SW15 3DW, UK

**6 CONCLUSION**

Based on the results of this work, we recommend that the non-conservative flammable cloud volume measure ΔFL be adopted as the basis for FLACS at mid to late stage of an engineering project definition. ">LFL" is a conservative measure which may be appropriate during the early stage of design of a process facility where uncertainties in the design is high. This work does not support the use of Q9.

**Assessing the influence of real releases on explosions: motivation and previous work**

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Results of the recent AIRRE project

introducing pre-ignition turbulence in the cloud (Hansen *et al.*, 2013). However, it is not straightforward to determine the appropriate level of turbulence, and better guidelines are required to avoid arbitrary results depending on the settings defined by individual users of the CFD software.

congestion, whereas Q9 tend to be more conservative for high congestion. These trends indicate that the Q9 equivalent method might be not sufficiently conservative for on-shore facilities, or for moderately congested off-shore modules. As such, the real cloud and initial flow field

# Review of Q9: Conclusions

Review of relevant research found that inconsistent results can be produced in probabilistic ERA and there is currently a strong reliance upon expert judgement

Detailed modelling choices concerning:

- Equivalent cloud methods (Q9 versus the alternatives)
- Pre-ignition turbulence
- Choice of optimum cloud locations
- Choice of ignition locations
- Ignition model
- CFD model setup (particularly the choice of mesh resolution)

Different experts can make different choices and get very different results for the same scenario

# Review of Q9: Recommendations

Joint ERA inter-comparison exercise should be undertaken to help:

a.) Identify the current scale of the issues

b.) Share experience

c.) Develop good practice guidelines

The exercise should ideally involve: consultants, software developers, regulators and other experts within the industry

Aim of the good practice guidelines: to provide more prescriptive conditions and/or limits on model input parameters within the ERA to help provide greater transparency in the ERA process and to harmonize results

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# Thank you

# Questions?