The Buncefield Explosion Mechanism

Phase 1

Summary

Objectives

- Provide a definitive record of the characteristics of the Buncefield explosion.
- Provide guidance (where possible).
- Define additional research based on the findings of Phase 1.

The work was conducted under the guidance of a Technical Group comprising the following experts:

Dr Ian Barnes	Defence Ordnance Safety Group, UK Ministry of Defence
Professor Geoff Chamberlain	Waverton Consultancy Ltd and Loughborough University
Dr Laurence Cusco	Health and Safety Laboratory
Professor Dougal Drysdale	University of Edinburgh
Dr Paul Uijt de Haag	National Institute for Public Health and the Environment (RIVM)
Dr Jens Holen	StatoilHydro
Dr Pol Hoorelbeke	Total Petrochemicals
Mr Mike Johnson	Germanischer Lloyd
Mr Patrick McDonald	Health and Safety Executive (Chairman)
Mr David Painter	Health and Safety Executive
Dr Jonathan Puttock	Shell Global Solutions
Mr Niall Ramsden	Energy Institute
Mr Clark Shepard	ExxonMobil
Mr Robert Simpson	Health and Safety Executive
Professor Vincent Tam	bp

The project was directed by a Steering Group comprising:

Professor Dougal Drysdale	University of Edinburgh
Mr Chris Hunt	UK Petroleum Industries Association (UKPIA)
Mr Kees van Luijk	National Institute for Public Health and the Environment (RIVM)
Mr Patrick McDonald	Health and Safety Executive (Chairman)
Dr Christophe Proust	Institut National de l'Environnement Industriel et des Risques INERIS
Mr John Murray	Health and Safety Executive
Mr Robert Simpson	Health and Safety Executive
Professor Vincent Tam	bp

Technical work was undertaken by:

bp
Defence Ordnance Safety Group, UK Ministry of Defence
Fluid Gravity Engineering Ltd
Germanischer Lloyd
Health and Safety Laboratory
Kingston University
Shell Global Solutions
Weidlinger Associates

Work package reports were peer reviewed by Dr David Bull and INERIS (France).

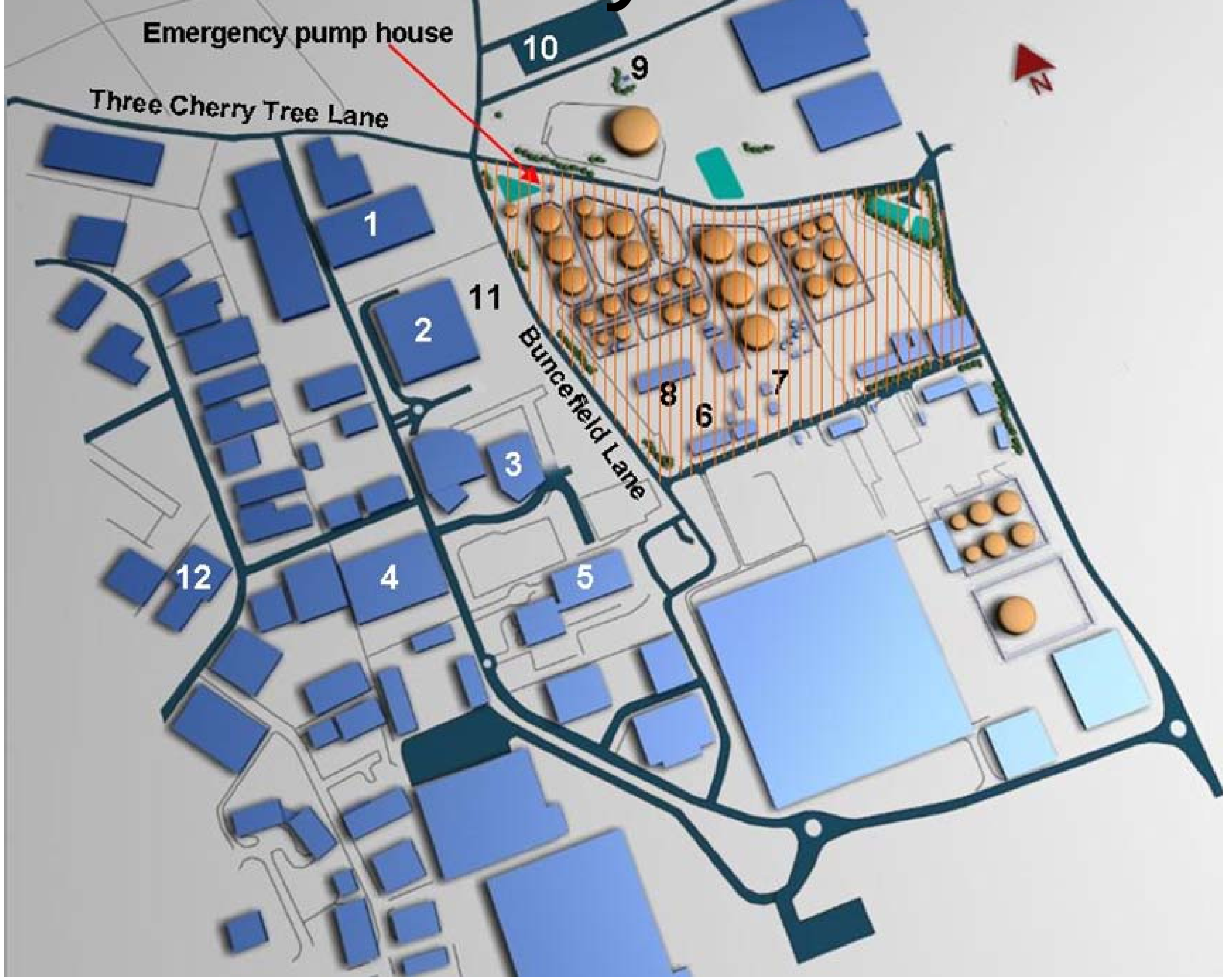
The project was managed by:

Dr Bassam Burgan	The Steel Construction Institute (SCI) and the Fire and Blast Information Group (FABIG)

The incident

- Sunday 11 Dec 2005. Explosion at 6.01 am.
- Overfill of gasoline tank for 23 minutes. Up to 300 tons spilled into bund.
- Winter grade gasoline at 15^{o}C. 10%C4, 17%C5, 16%C6, 57%C10 w/w
- Air at 0^{o}C. No wind.
- Flammable cloud approx 400m across.
- Main explosion 2.4 on Richter scale. Several explosions occurred.
- 23 fuel storage tanks on fire.
- 43 injured, none seriously. No fatalities.
- Fire burned for several days.

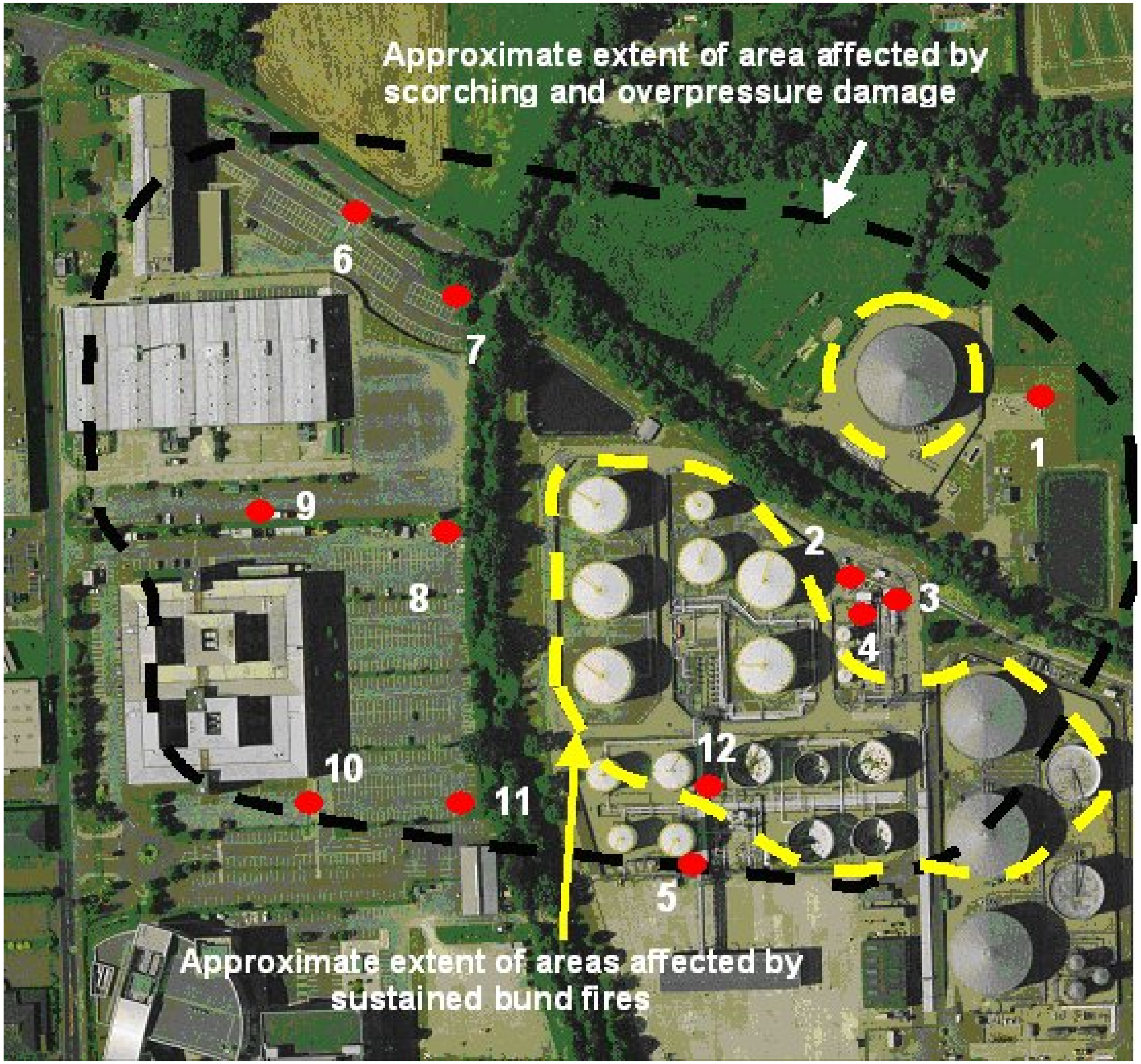
Site Layout



1. Fuji Building
2. Northgate Building
3. RO Building
4. Avica Building
5. Alcon Building
6. Control room
7. Mess room
8. Tanker loading bay
9. The Cottages
10. Fircones
11. Northgate Building car park
12. Furnell Building

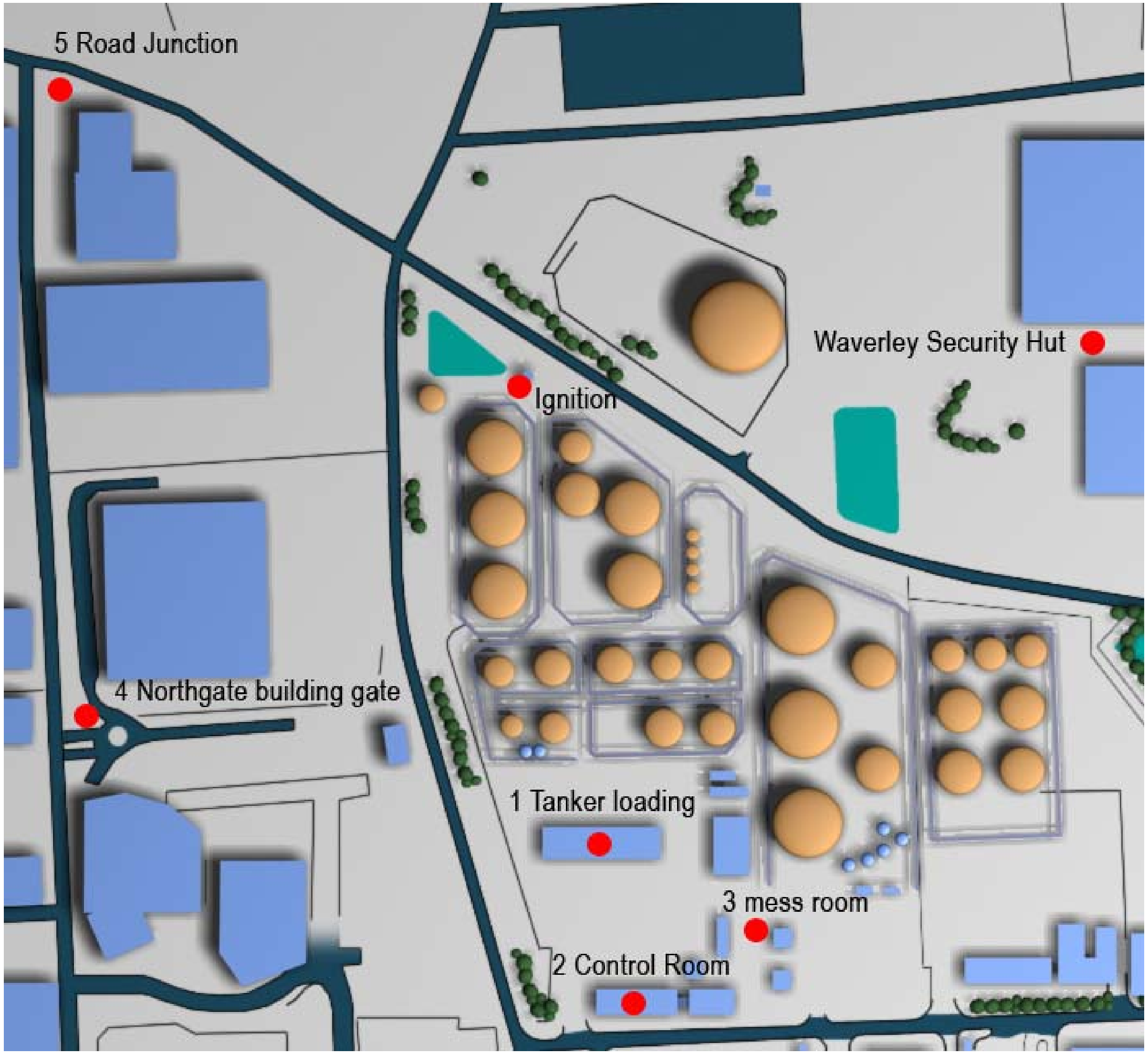
Shaded area is Hertfordshire Oil Storage Ltd (HOSL) and British Pipeline Agency (South)

Extent of the flammable cloud




11 12 2005 SUN
PLAY
Pause
5:53:43 AM
1
Tower 1

Witness Locations



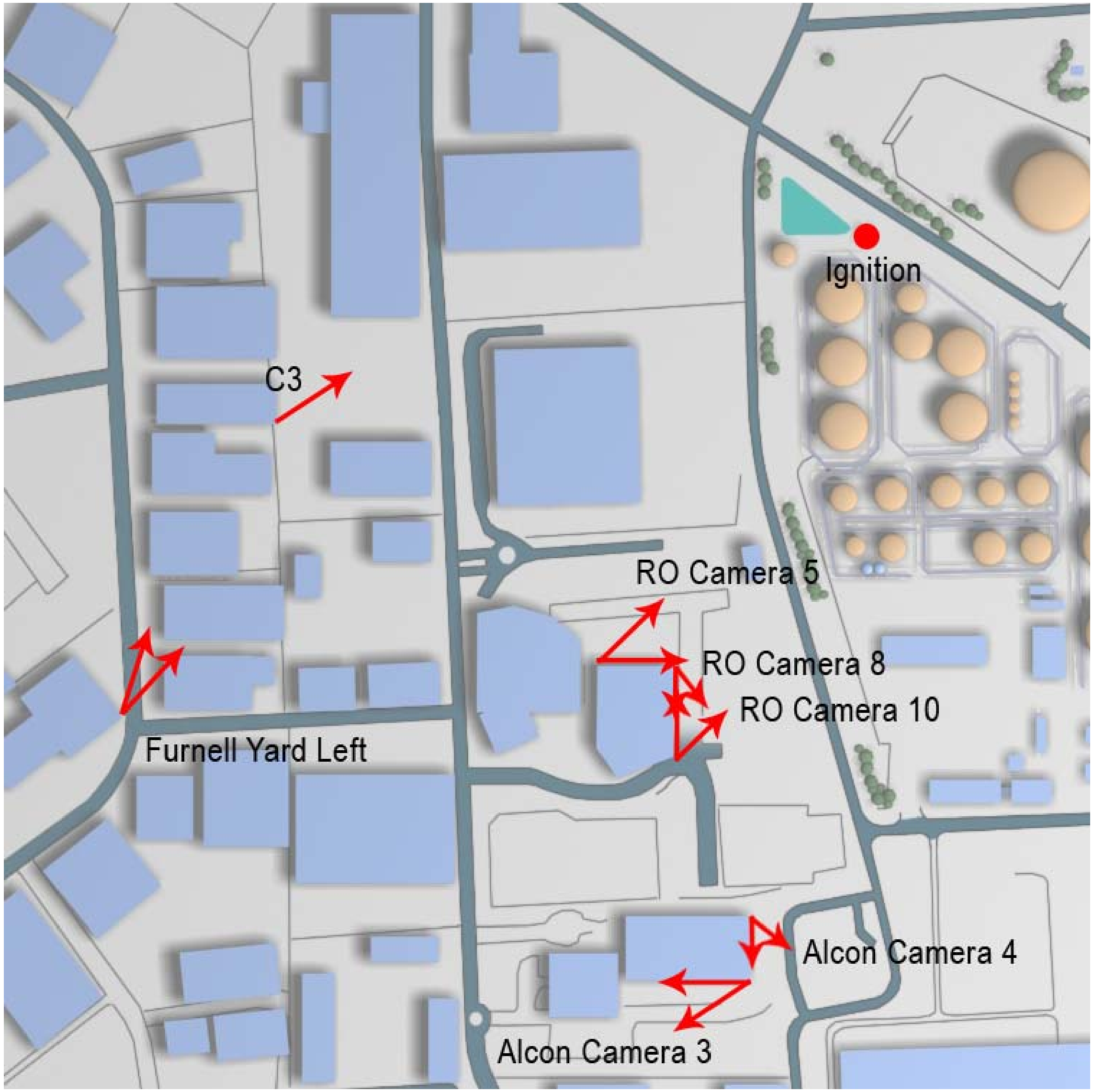
Witness Observations

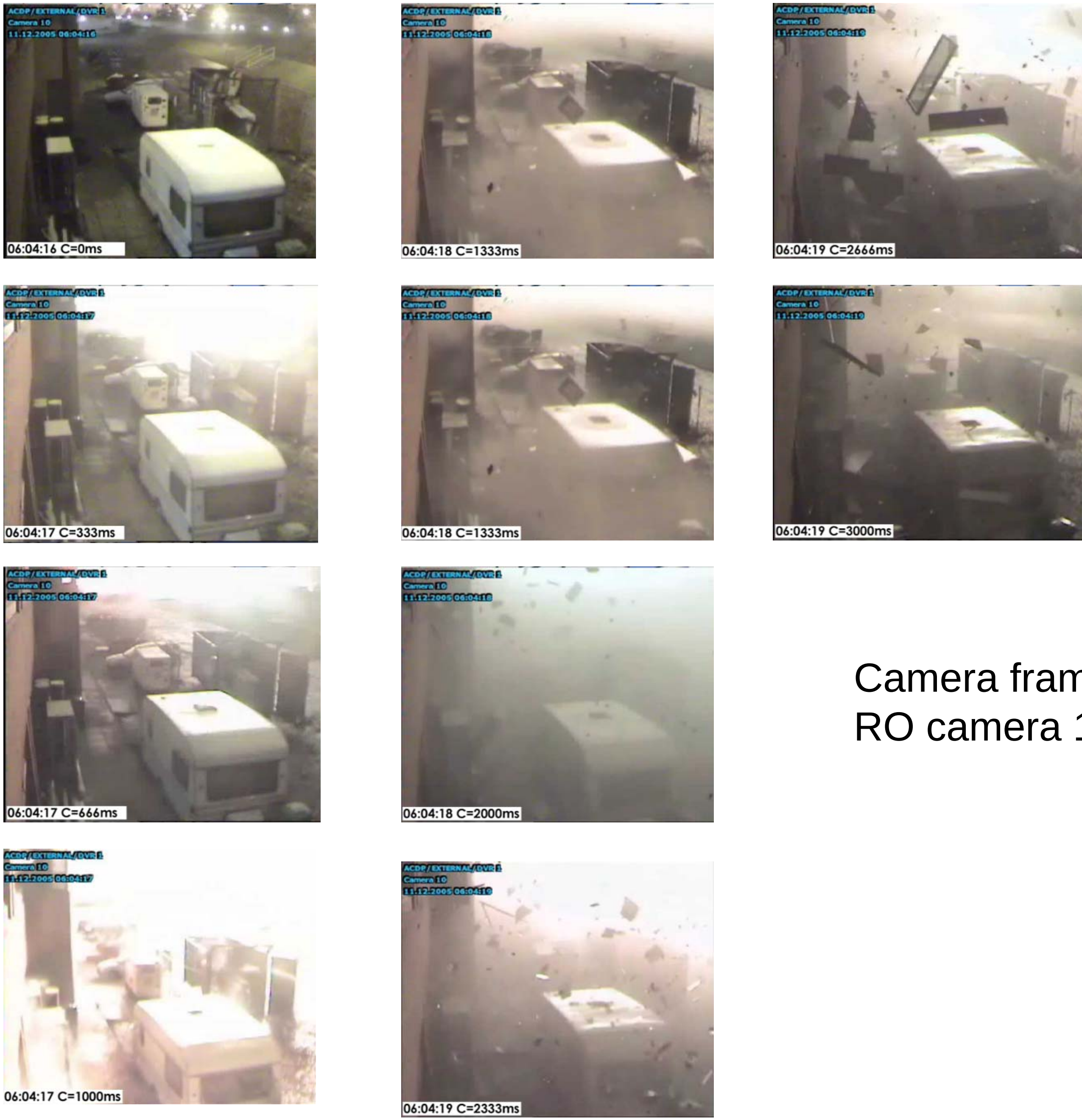
- The explosion lasted for a period of time
- Initial stages heard (*rushing/roaring noises*) or seen (*spreading out of the ignited vapour cloud*) before they were felt
- Next stage – "*a very loud bang*"
- A "flash" was reported in the sequence of events
- Witnesses blown to the ground, damage to rooms
- No temporary or permanent hearing damage

Table 1 Overpressure estimates based on witness locations

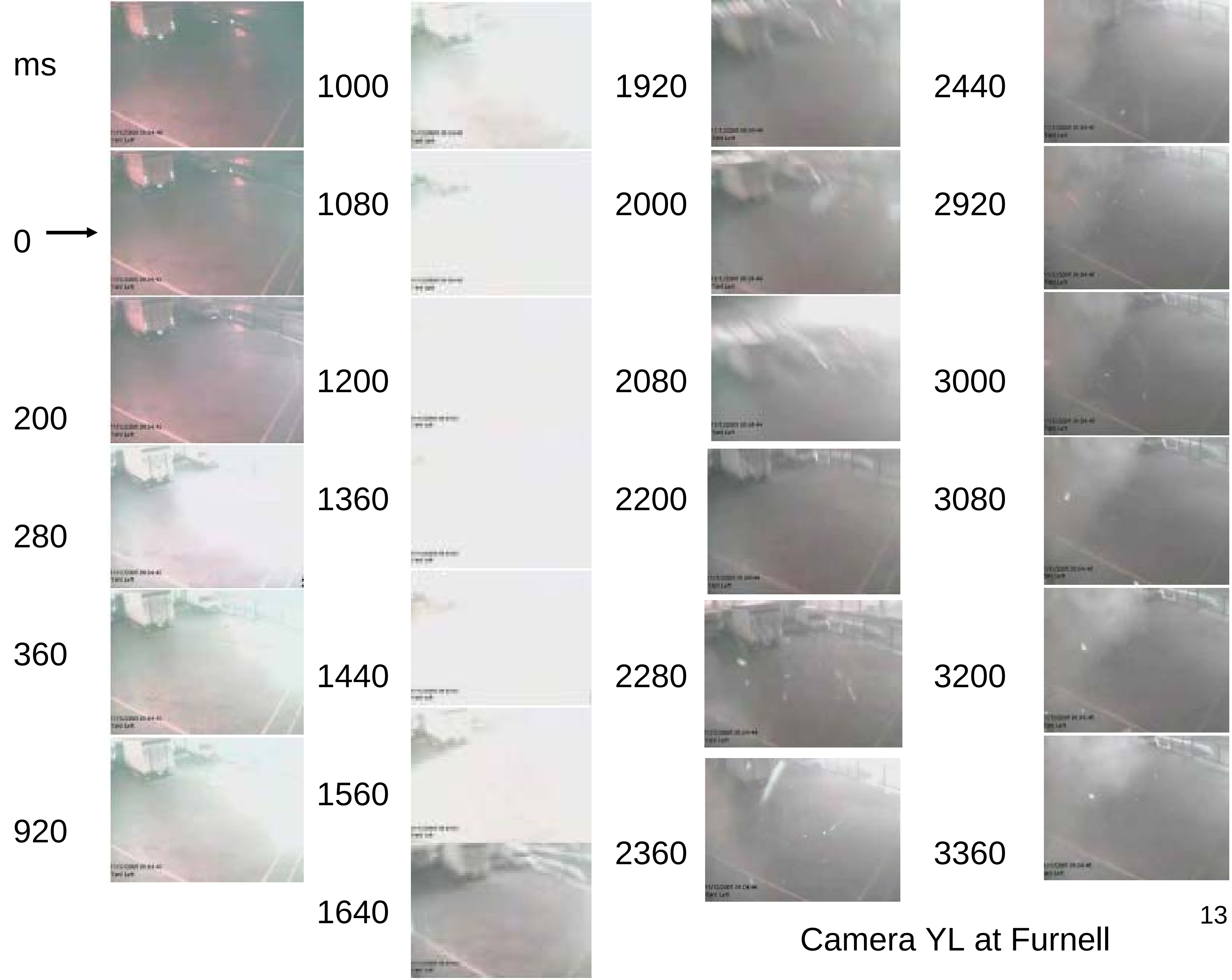
Witness location	***Observations***	***Estimated overpressure***[1]
Tanker loading	Tankers were shaken. Witnesses were blown from their feet to the ground	~ 10 kPa
Control Room	Witness was blown across the room	~ 10 kPa
Mess room	Ceiling of room damaged and objects blown around the room	~ 5 kPa
Northgate building gatehouse	Door and windows were blown in	~ 7 kPa
Junction of Boundary Way and Three Cherry Trees Lane	Witnesses were blown from their feet to the ground	~ 10 kPa
Waverley security hut	Witnesses were blown from their feet to the ground	~ 10 kPa
1 Note: there is uncertainty associated with these estimates. However, as none of the witnesses suffered any hearing damage, it can be concluded that the overpressure at the witness locations is < hearing damage threshold (The threshold for eardrum rupture is 35kPa, with a 50% chance of rupture at 100kPa.).		

CCTV Cameras





Camera frames taken from RO camera 10

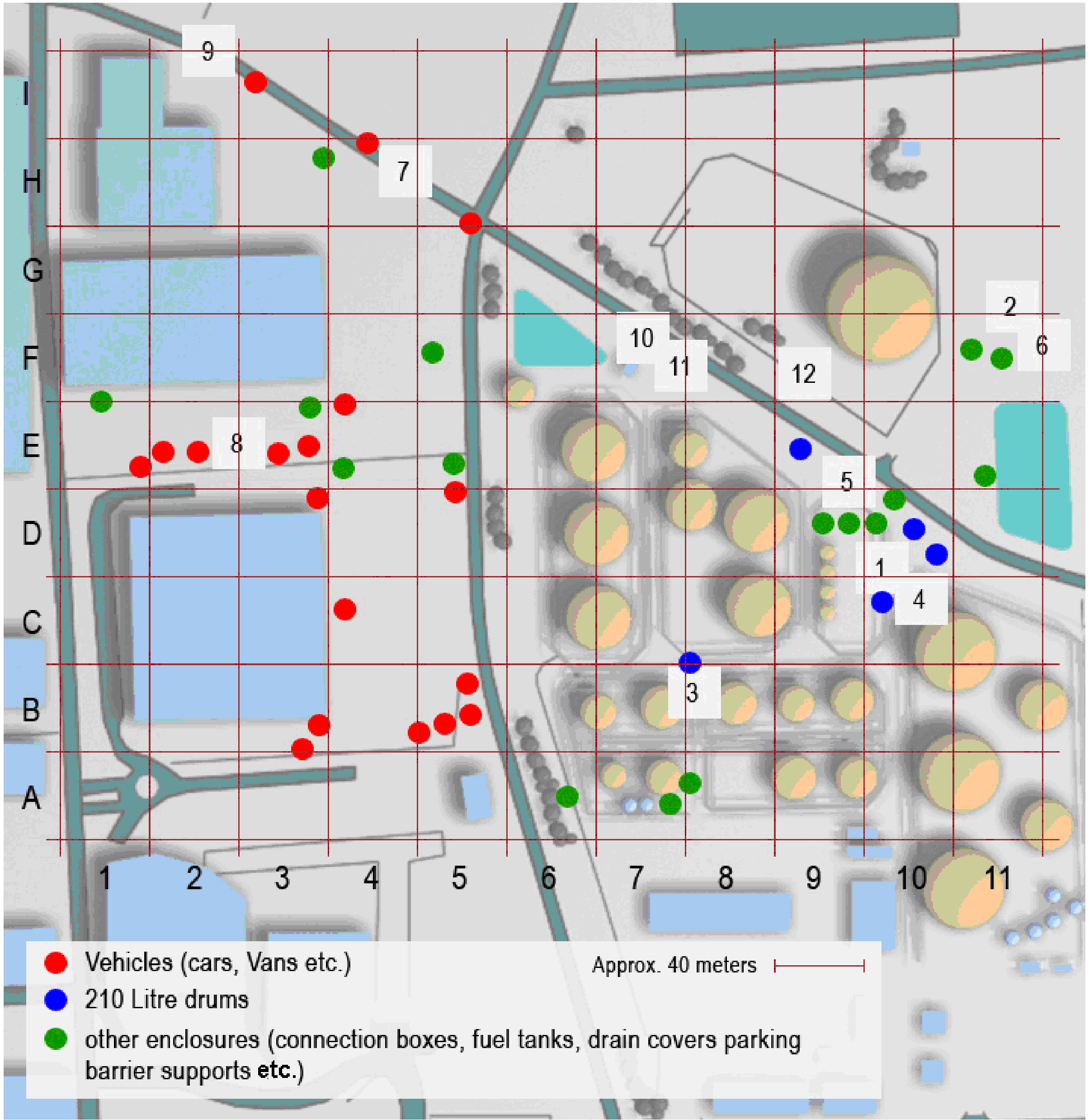


Camera YL at Furnell

CCTV Cameras

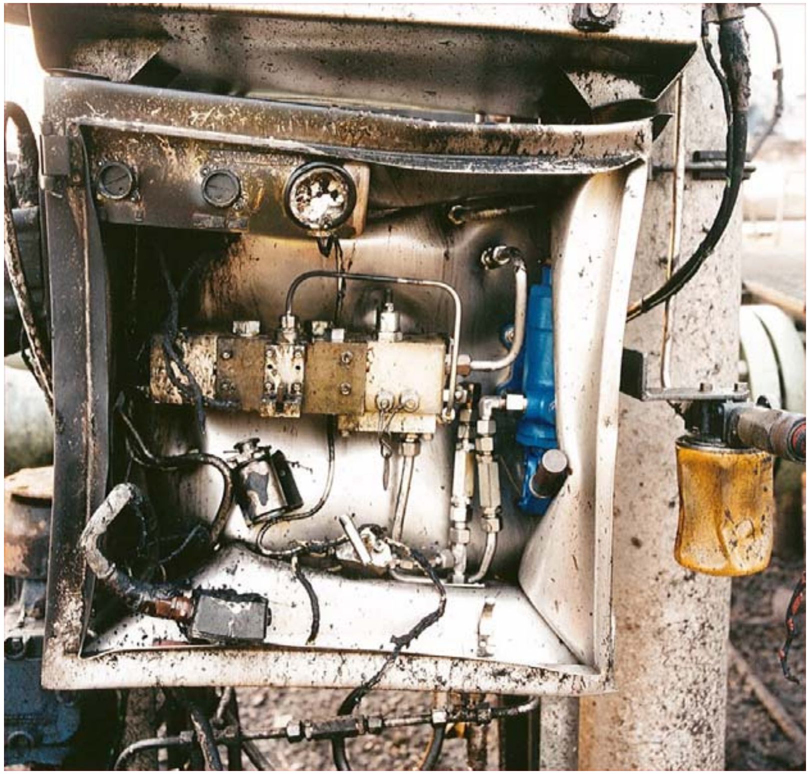
- Helped locate the ignition point
- Information on
  - illumination from the explosion;
  - arrival of shock waves;
  - appearance of condensation of water vapour (evidencing the arrival of rarefaction); and
  - the end of the rarefaction phase.
- Long period (>600 ms) between start of +ve phase and start of –ve phase

Damage to Objects



Lightweight Metal Boxes

- Evidence of overpressure > 200 kPa with duration of ~ 50 ms. [from tests using hydrostatic pressure, gas explosions, and HE.]



Steel Drums

- Evidence of overpressure ~ 200 kPa
- [from hydrostatic tests and gas explosions.]



Cars

- Evidence of overpressure > 200 kPa with duration of ~ 50 ms.

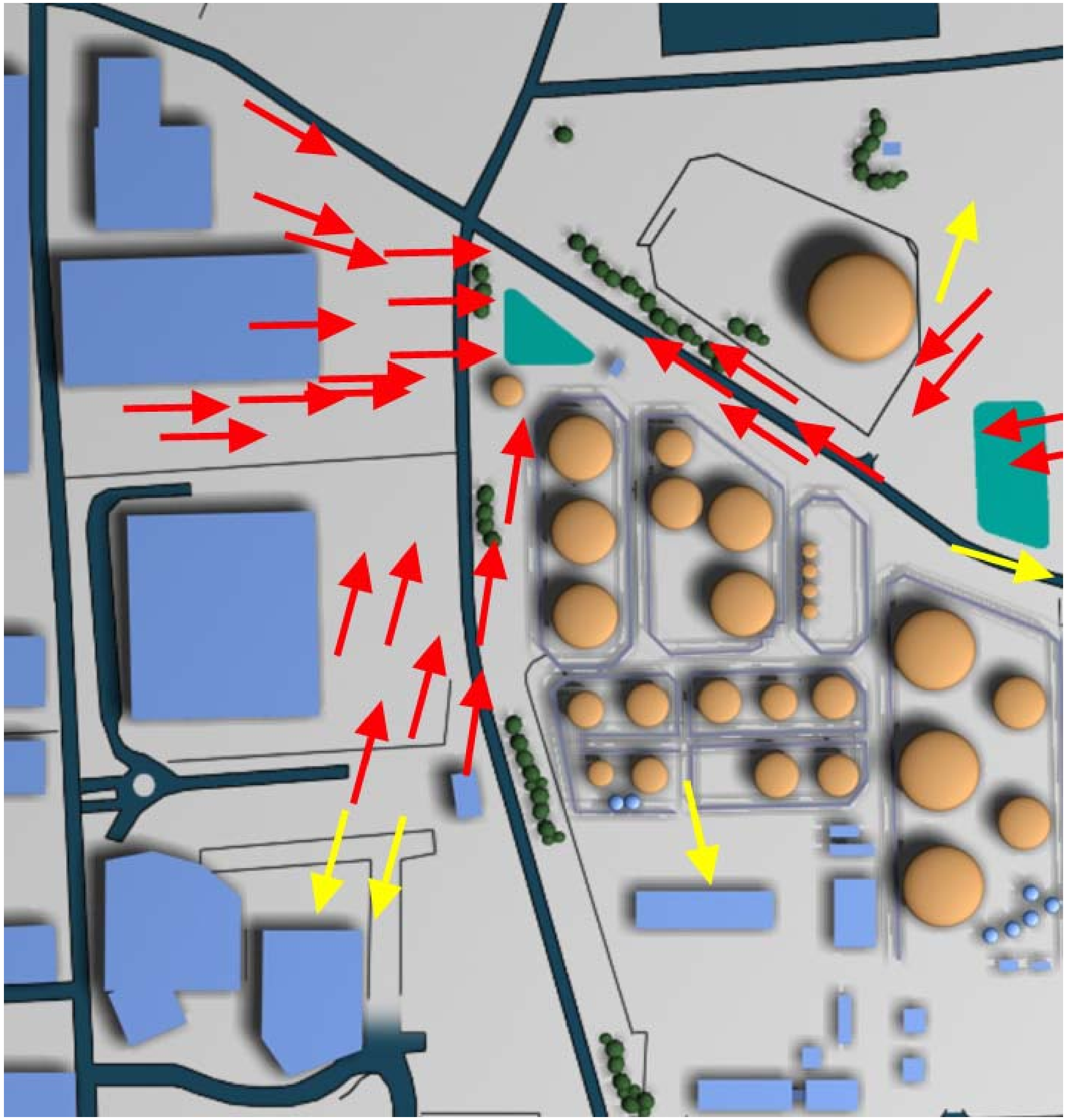
Cars

- Rapid drop in overpressure from the edge of the cloud.

Objects in Emergency Pump House

- Evidence of low overpressure

Directional Evidence – net drag



Building Damage – Near Field

7500 kg TNT



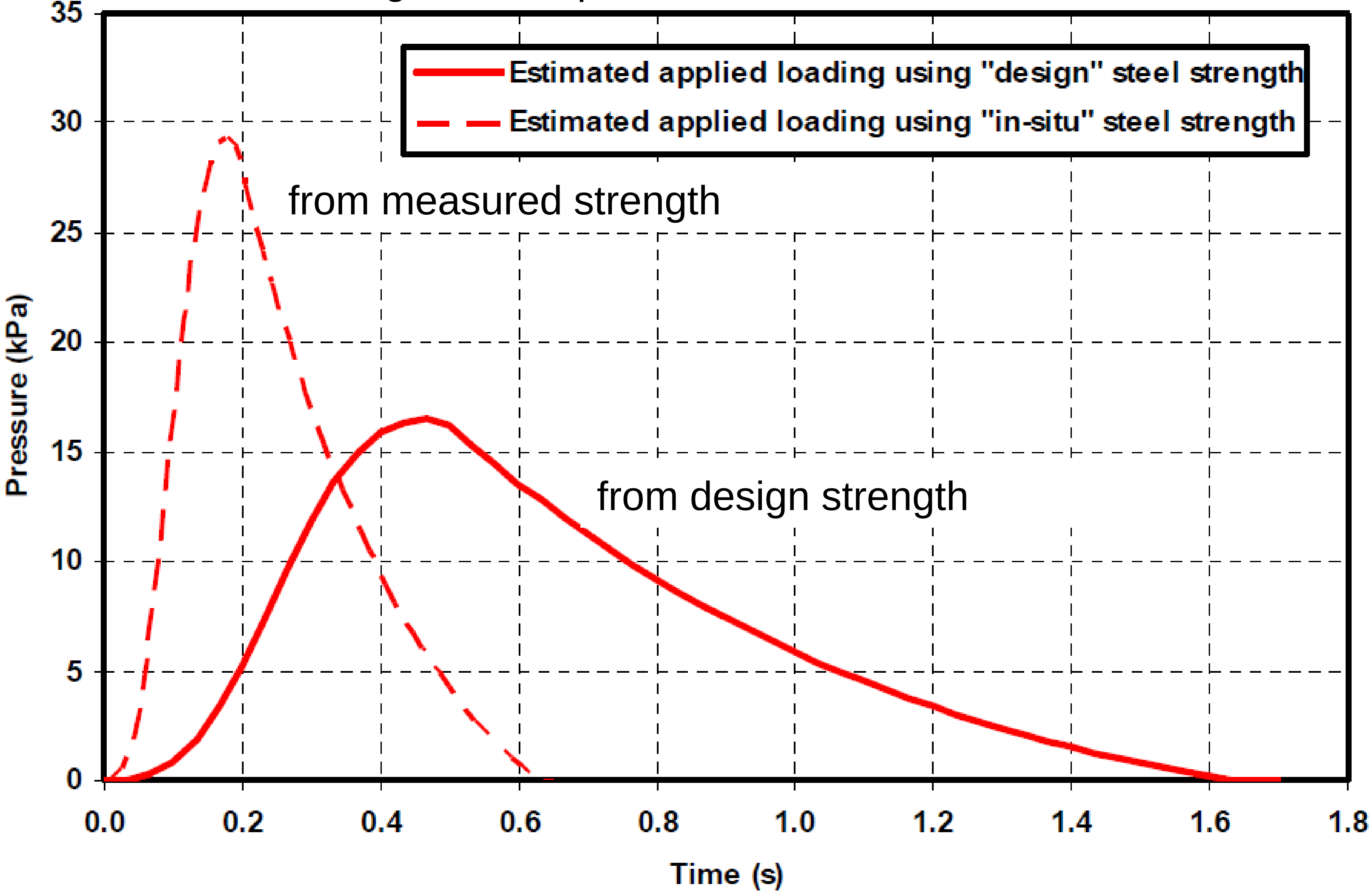
Building Damage – Far Field

105,000 – 250,000 kg TNT

Northgate – Cladding Damage – by Weidlinger Associates

Northgate – Cladding Damage

160,000 iso-damage analyses. Load profile consistent with damage to both panels is:



Overpressure Distribution

> 200 kPa

Previous Incidents

Accident	***Date***	***Type of fuel and release***
Flixborough	1974	Cyclohexane – Process leak
Port Hudson	1970	Propane – Pipeline failure
Ufa	1989	LPG - Pipeline failure
Naples	1985	Petrol - Tank overfill
Saint Herblain	1991	Petrol - Process leak
Newark (NJ)	1983	Petrol - Tank overfill
Beek	1975	Propylene- Process leak
Texas City	2005	C5-C7 Process leak

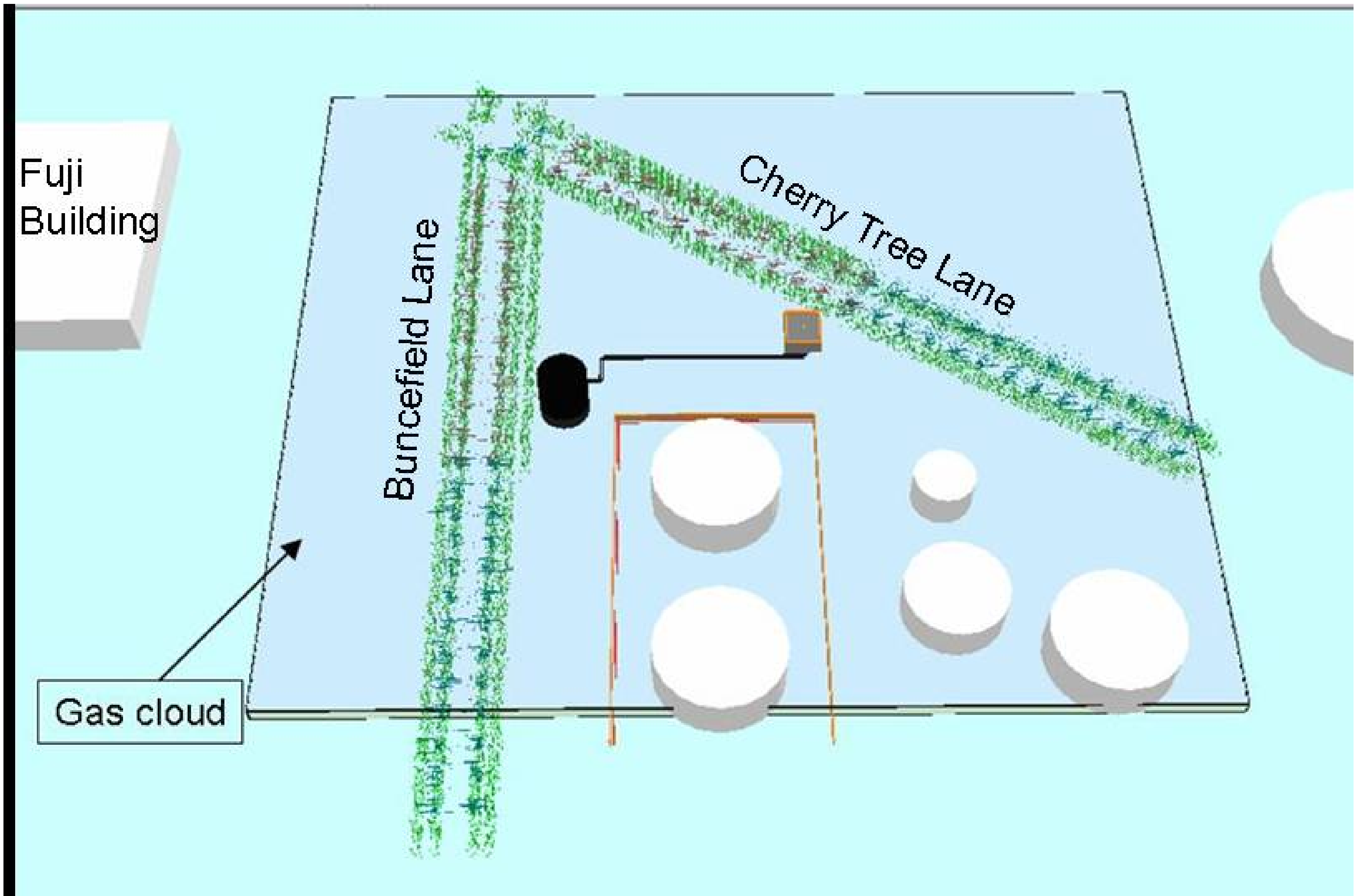
very different uncertain similar

Deflagration Scenario – by Shell Global Solutions

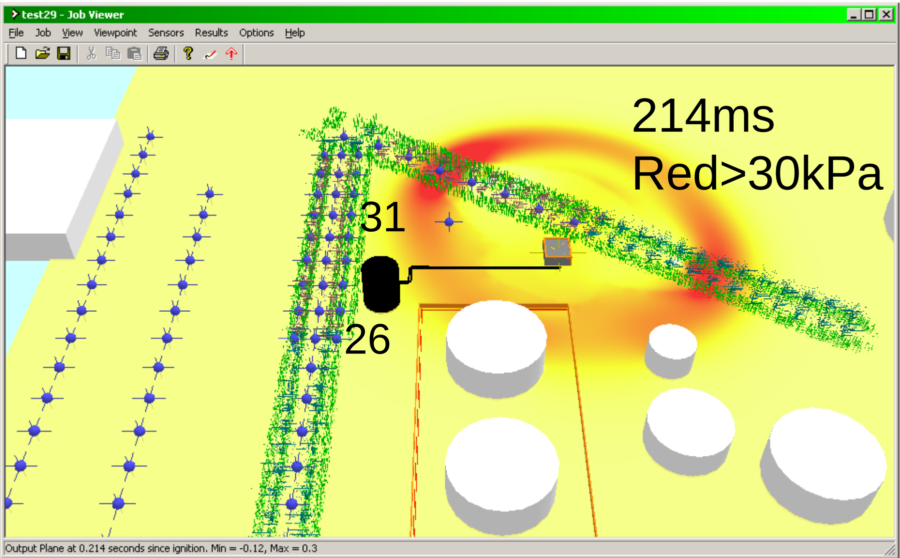
- Modelled using EXSIM
- Large domain simulation with geometric simplifications (uniform stoichiometric propane cloud 3m high, 0.9m cartesian cells, many small obstacles replaced by larger obstacles with same blockage and drag.)
- Small domain simulation (detailed model of the area surrounding the emergency pump house)

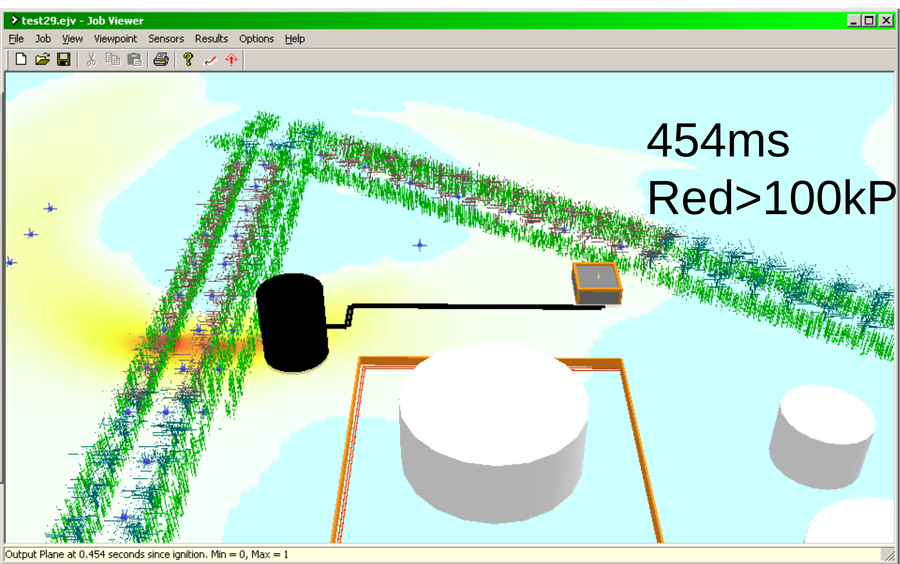
  (0.43m cells, increased congestion – believed to be more realistic.)
- Trees and shrubs modelled as rigid pipe elements (plus randomised blockage ratios.)

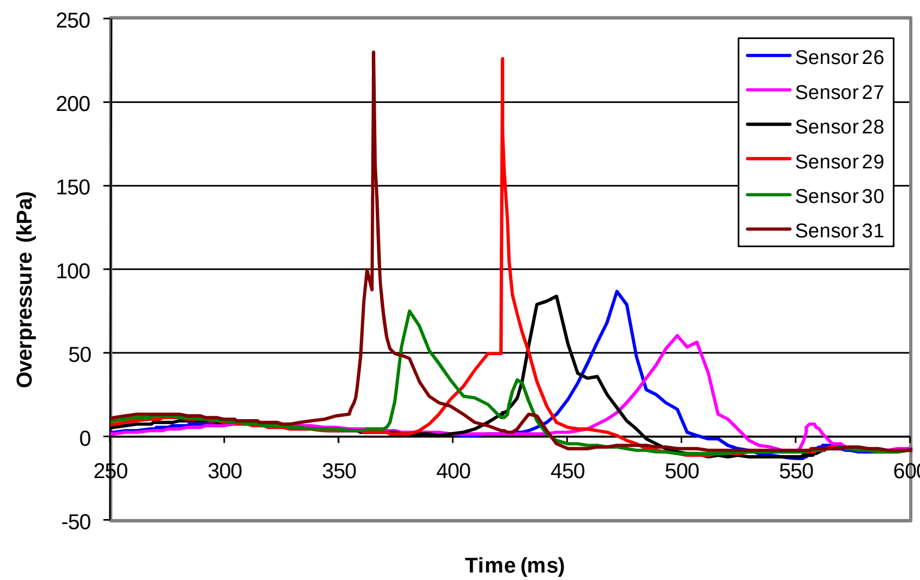
Large Domain Simulation



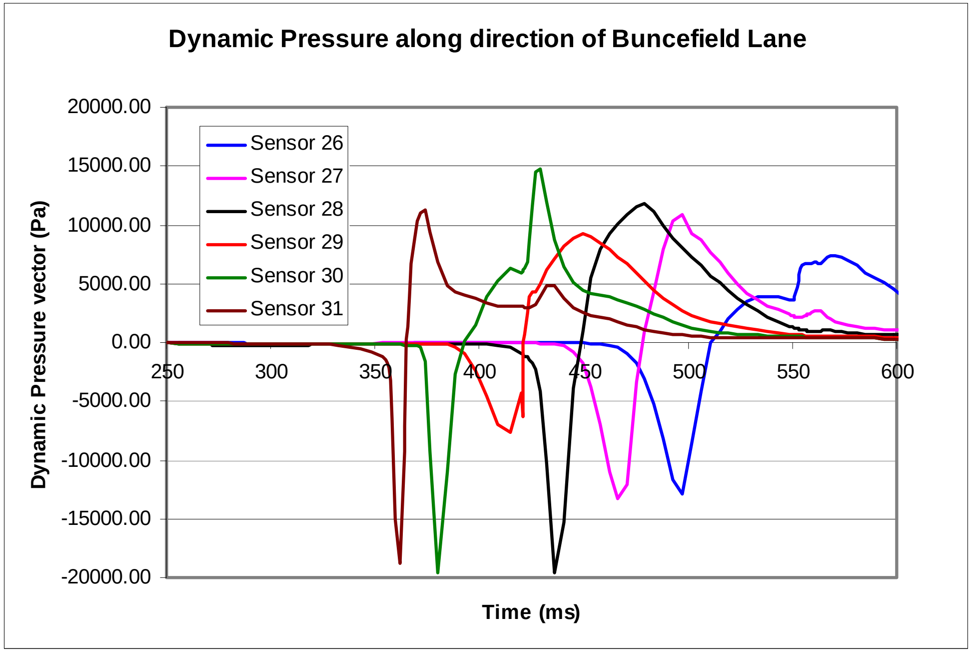
Large Domain Simulation

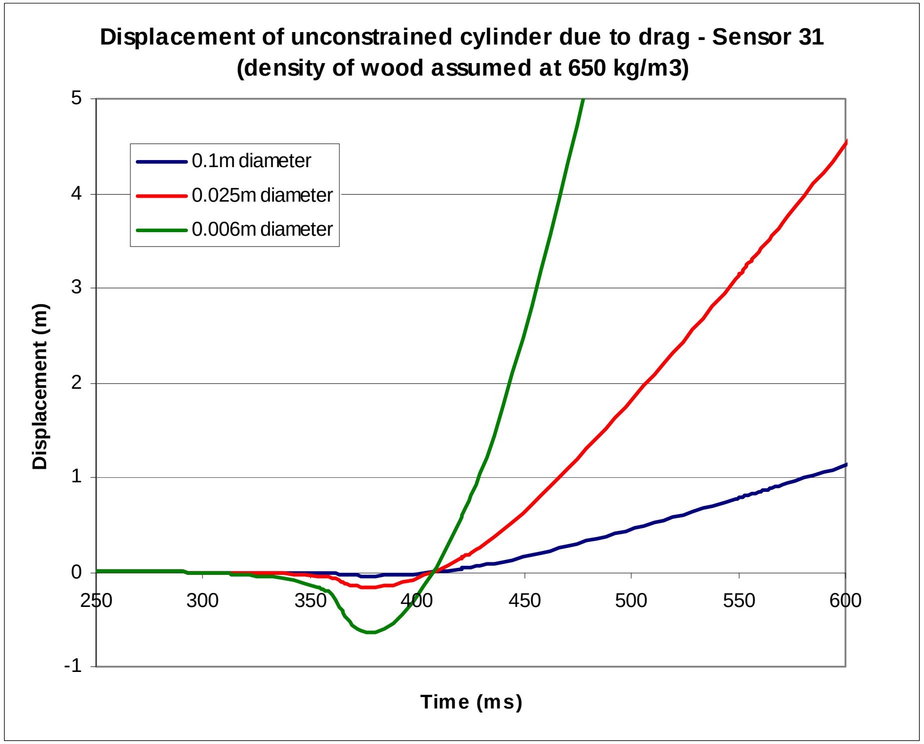




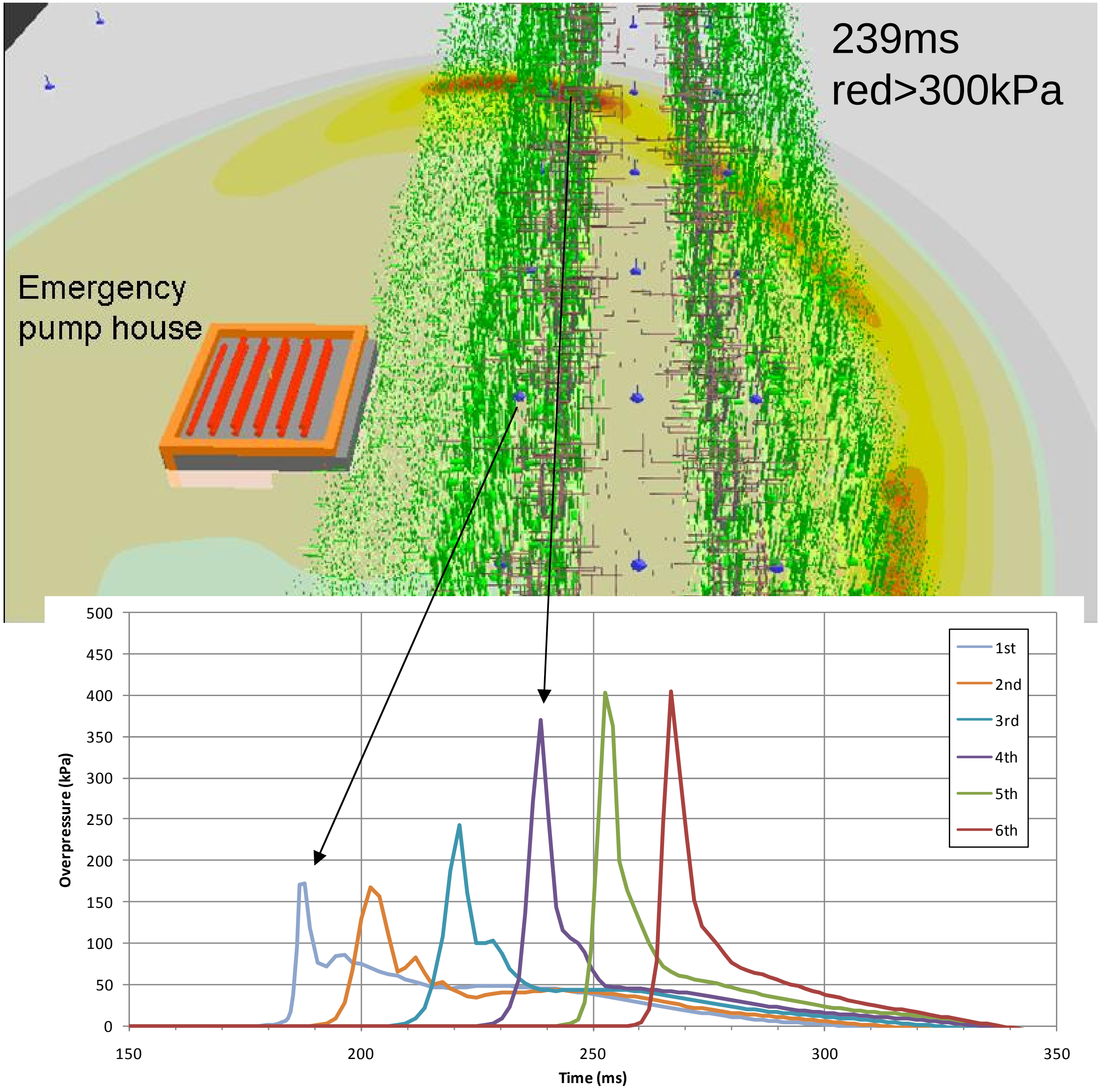


Large Domain Simulation

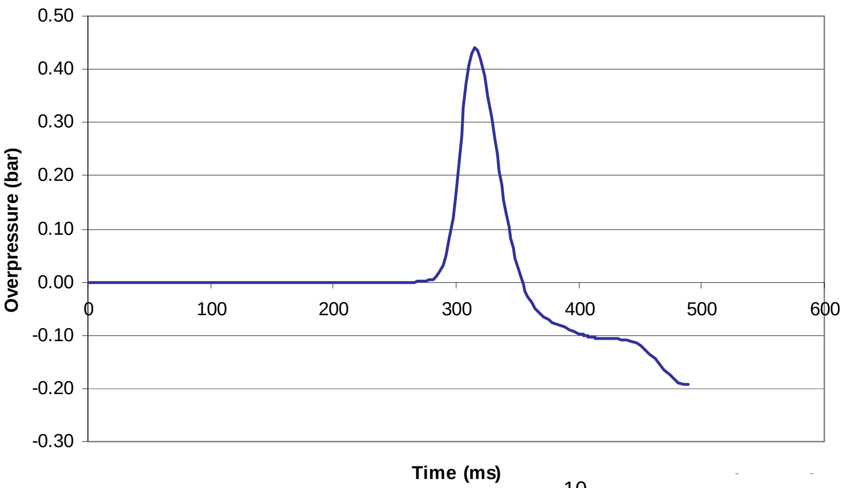


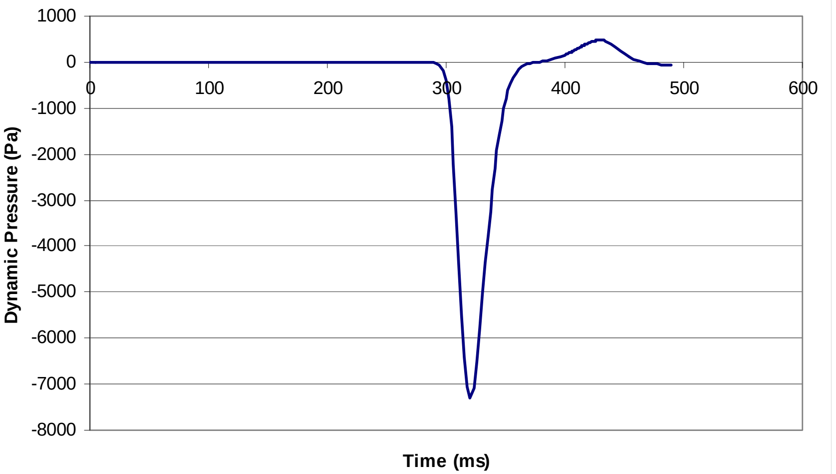


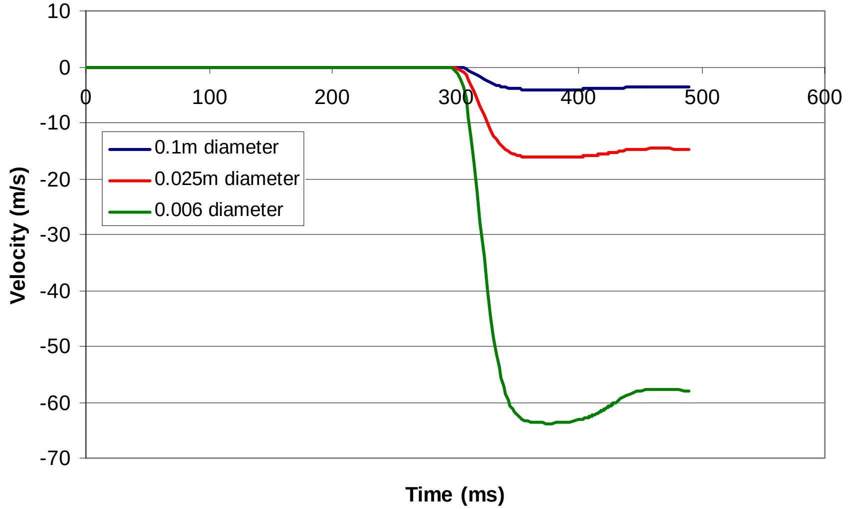
Small Domain Simulation



Small Domain Simulation – dynamic pressure and displacement in middle of car park, well outside the congestion







Deflagration Scenario - Summary

- Deflagration scenario does not explain:
  - Overpressure damage in car park and HOSL site.
  - Directional indicators outside the congested areas.
- Deflagration scenario does explain the rapid flame acceleration in the trees and undergrowth.
- At junction between Buncefield Lane and Three Cherry Trees Lane:
  - Overpressure ~ 400 kPa
  - Flame speed ~ 700 m/s
- Transition to detonation possible.
- But, remember model uncertainty!

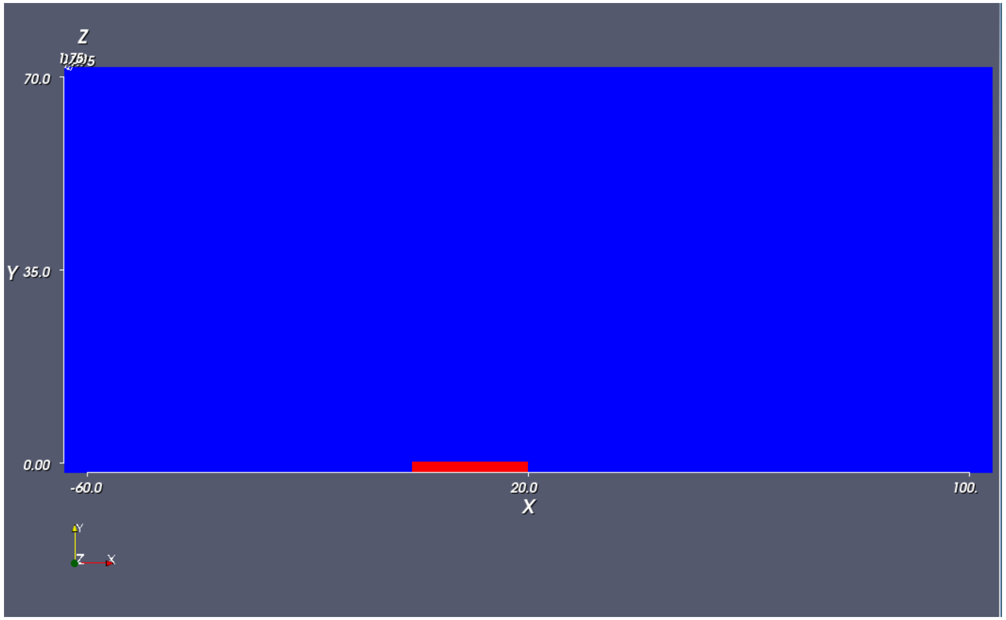
Detonation Scenario – by Germanischer Lloyd

- Ignition in the emergency pump house.
- Confined explosion venting into the external cloud.
- Flame propagates into the tree line to the north of the emergency pump house along Cherry Tree Lane.
- Flame accelerates in the tree line.
- Transition to detonation near the junction of Buncefield Lane and Three Cherry Trees Lane.

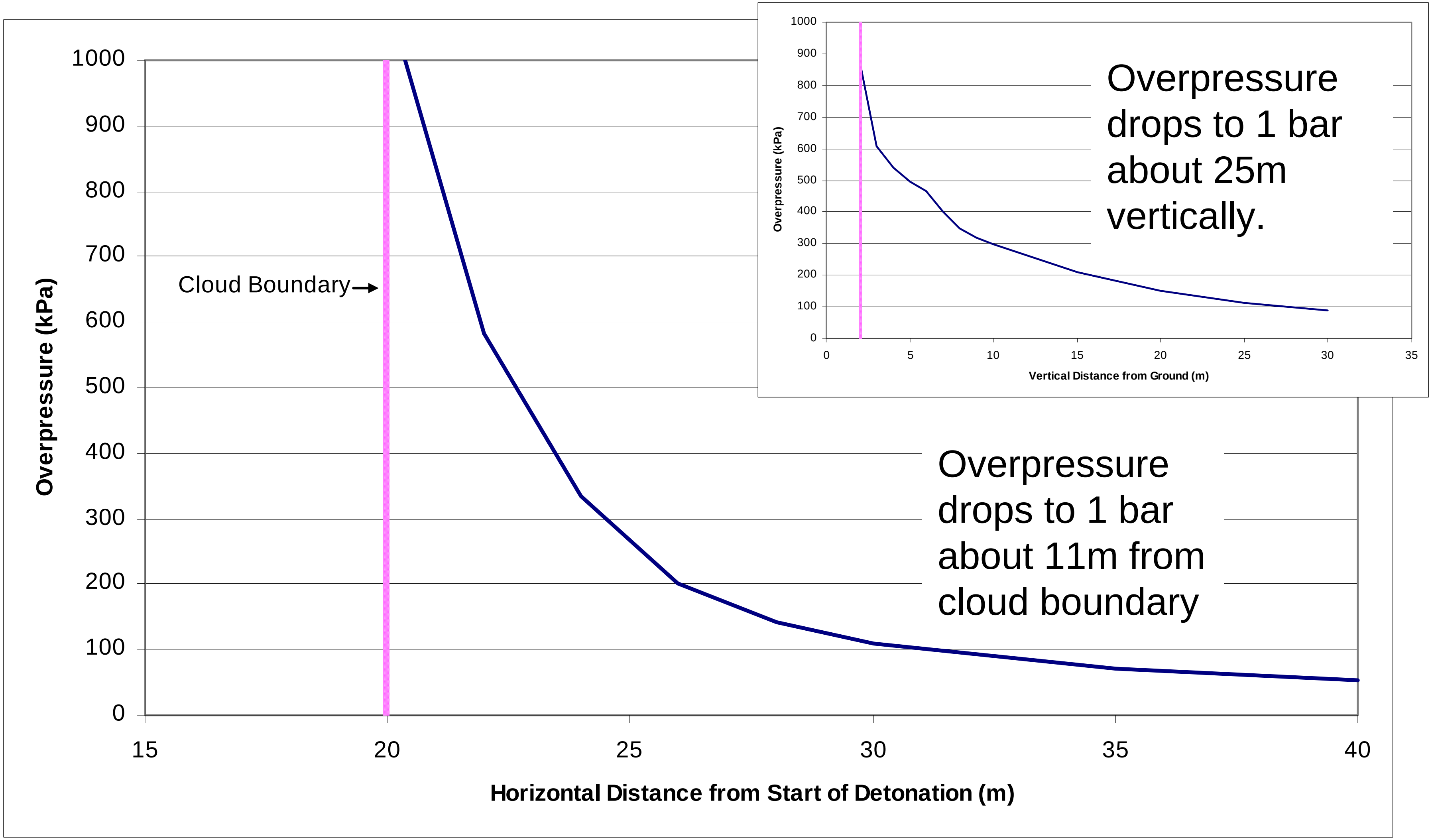
Small Scale Detonation Simulation

– by Kingston University

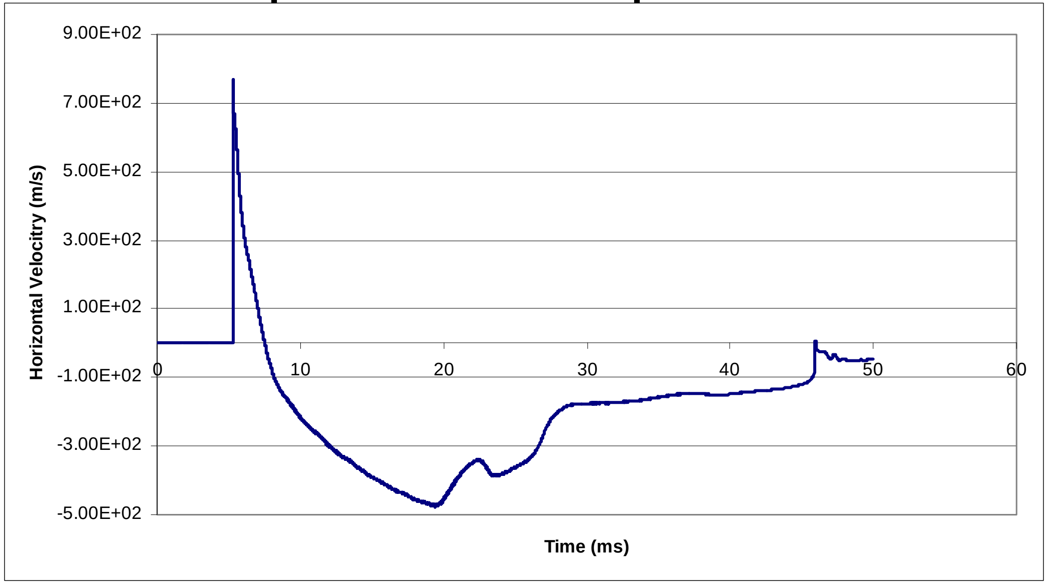
- Idealised rectangular gas cloud
- 10 x 7, 10 x 2, 20 x 2 and 20 x 1.5 m
- 2 D simulation
- Stoichiometric propane/air mixture

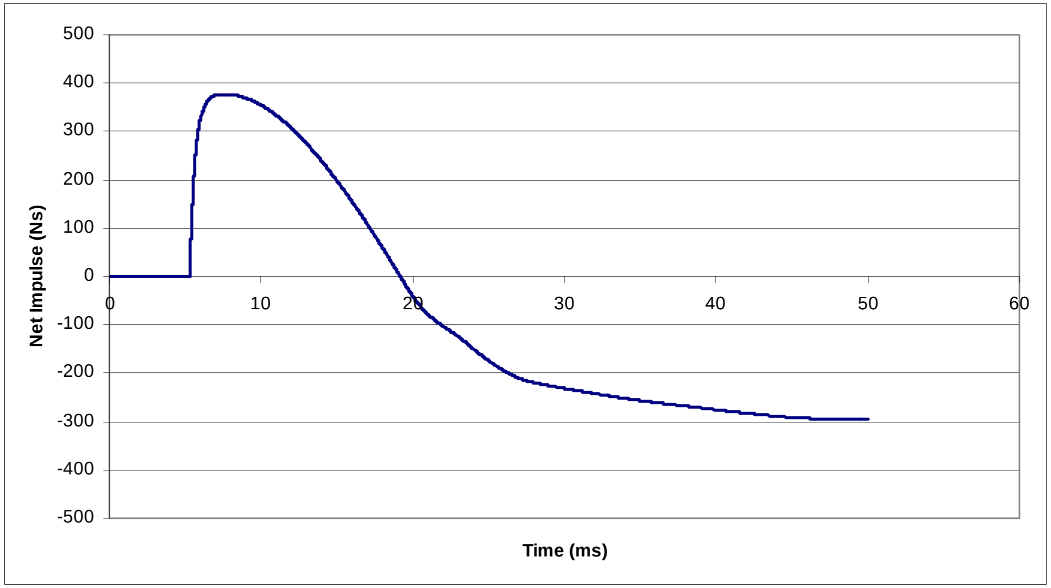


Small Scale Simulation - horizontal and vertical pressure decays



Small Scale Simulation – gas velocities and impulse at mid point in cloud

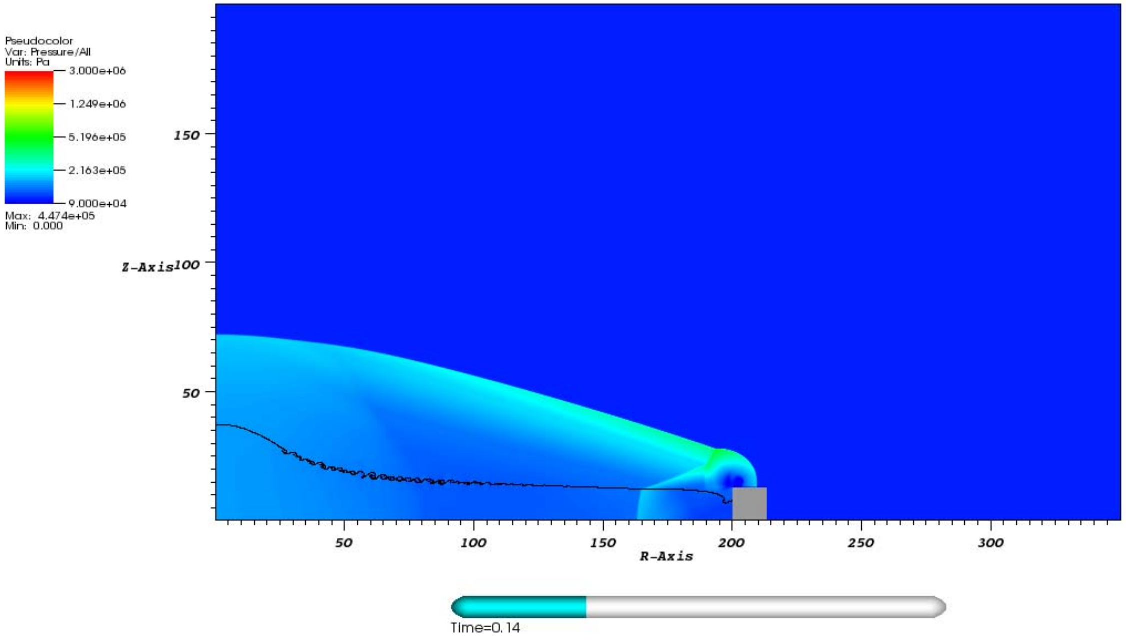




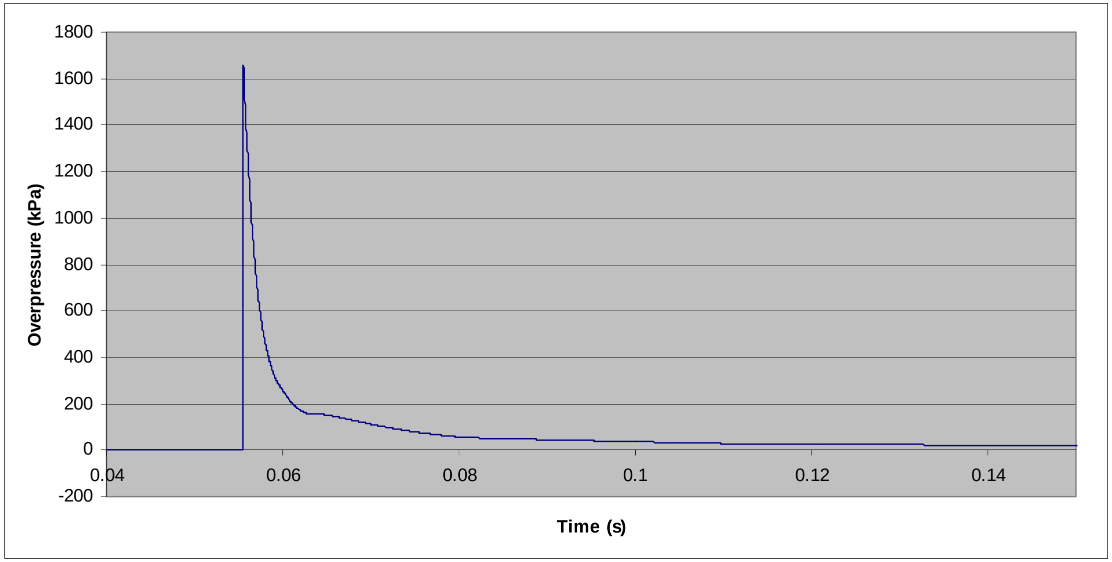
Large Scale Detonation Simulation

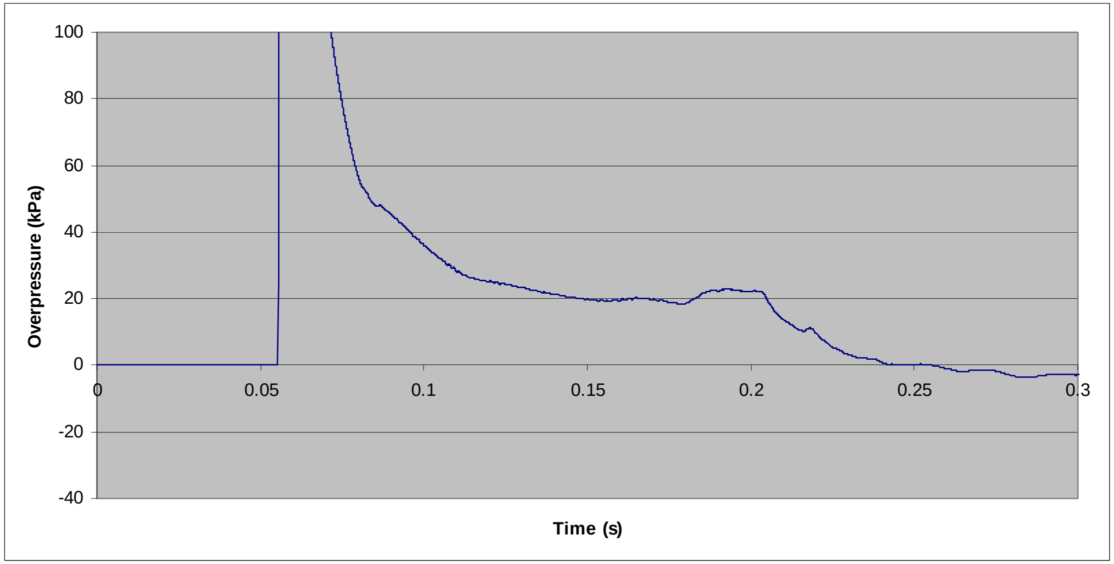
– by Fluid Gravity Engineering Ltd

- Axisymmetric pancake shaped cloud
- 400m diameter, 2 m high
- Obstructed and unobstructed

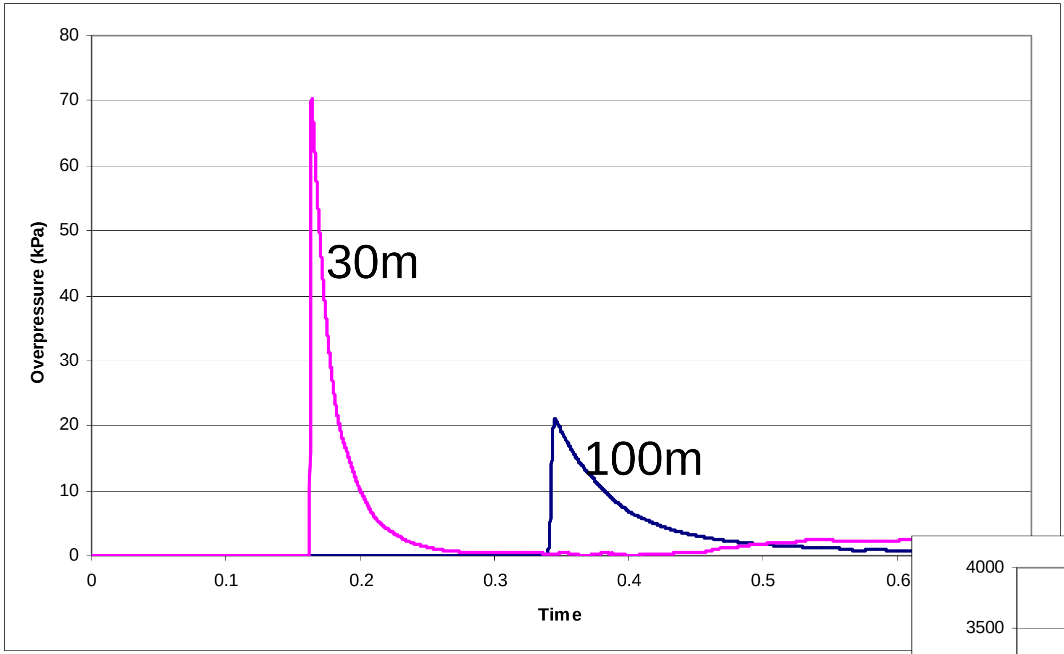


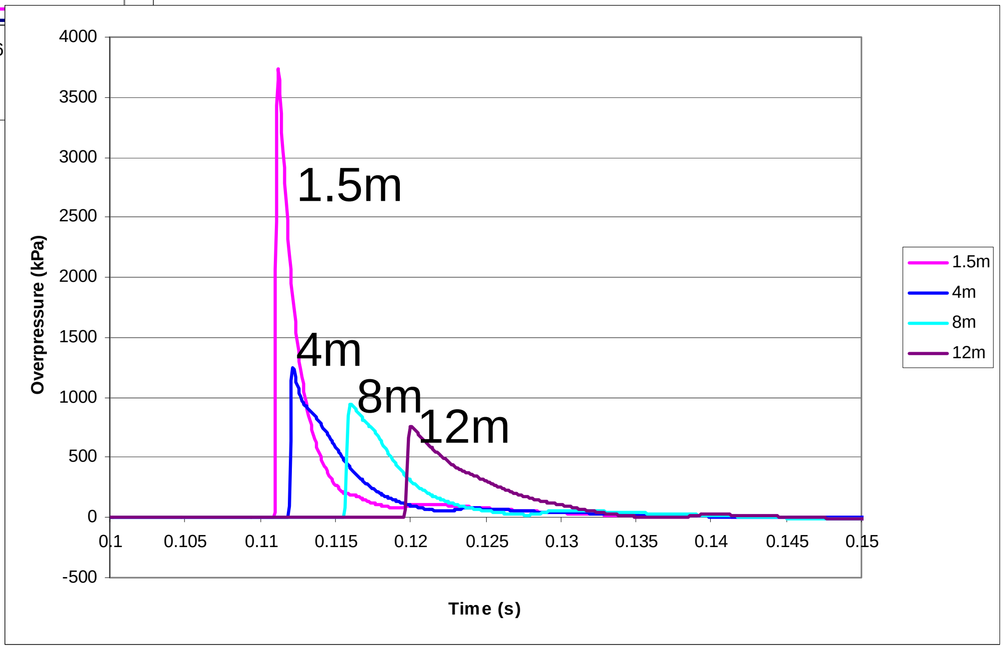
Overpressure Simulation Inside the Cloud (100m from ign. Point)



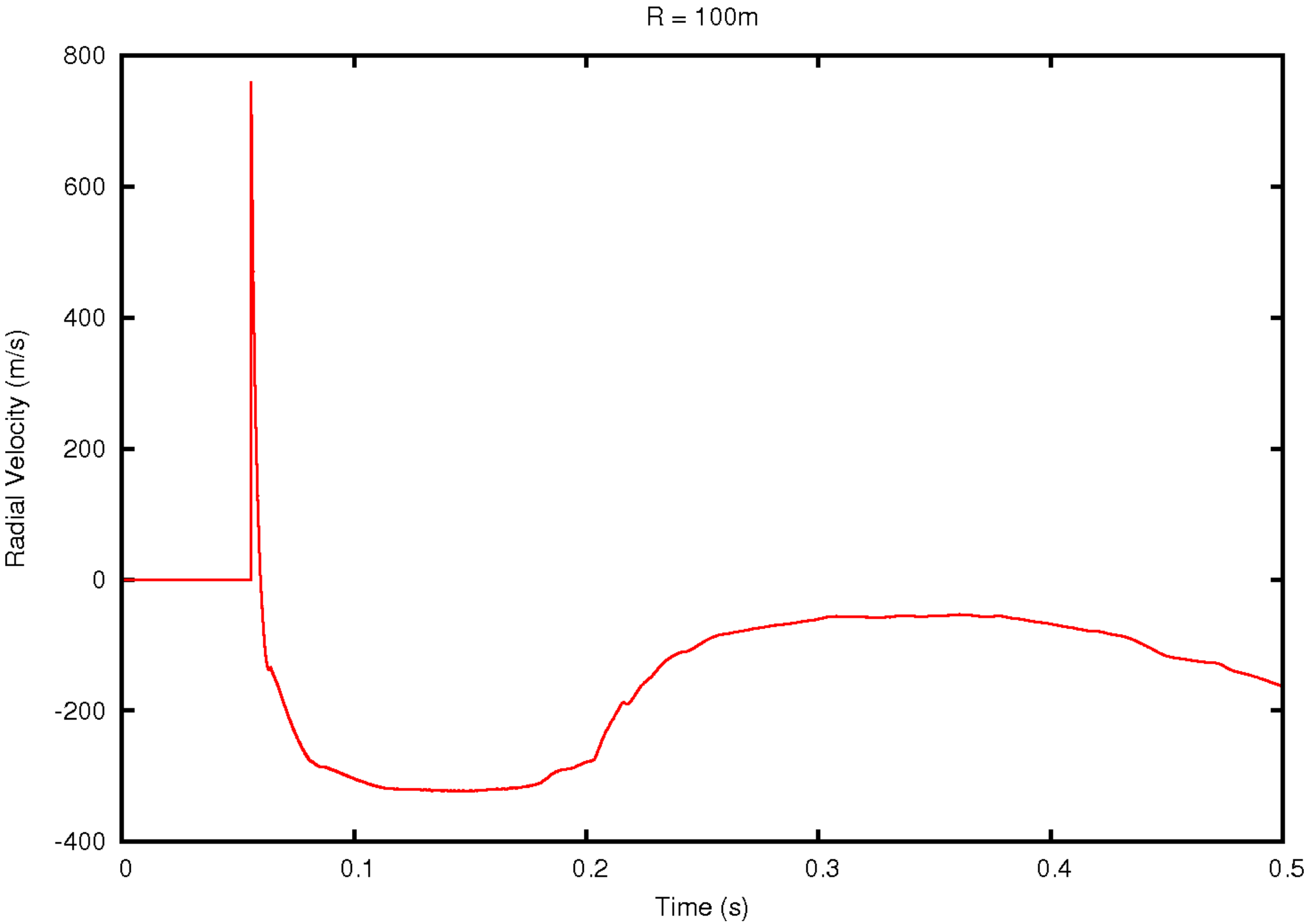


Overpressure Simulation Outside the Cloud – horizontally and vertically (on object)





Gas Velocities (100m from ignition)



Detonation Scenario - Summary

- **Detonation is consistent with:**
  - Eye witness reports.
  - The timings of overpressure and rarefaction arrival, from CCTV cameras.
  - The damage distribution to cars and other objects across the site.
  - The directional indicators within and outside the cloud.
  - The rapid rate of overpressure decay from the edge of the cloud.
  - The lack of hearing damage to witnesses.
  - The complete annihilation of the south side of the Fuji building.
  - The mid-field and far field damage.
  - Deflagration experiments and modelling suggest that DDT is credible.
  - Aspects of previous incidents (Port Hudson and Ufa).

- **Detonation is <u>not</u> consistent with damage to the Northgate building (requires non-shocked, and low pressure).**

Alternative Mechanisms & Characteristics – by the Health and Safety Laboratory

- Mist explosion
- Multiple detonations
- Strong ignition
- Multiple ignitions
- Stratified explosion
- Flame acceleration due to dust particles
- Unsteady deflagration accelerated by forward radiation from the flame front
- Unsteady deflagration without radiative effects
- Cellular flames
- Chemistry effects
- Pancake shaped cloud
- Inhomogeneous fuel concentration
- Internal tank explosion
- Localised high overpressure
- Precursor event

Evidence	Deflagration	Detonation
Timing based on witness evidence	Neither scenario is inconsistent with the evidence	
Arrival of first shock wave at CCTV	Neither scenario is inconsistent with the evidence	
Time between start of +ve and start of -ve phases (CCTV)	Simulations suggest shorter time	Simulations support a period of 100's ms
Luminosity records from CCTV	Neither scenario is inconsistent with the evidence	
Directional indicators	Not consistent with evidence in open areas within the cloud	Consistent with evidence within and outside the cloud
Near/mid-field damage to objects	Not consistent with the damage in open areas within the cloud	Consistent with the damage within the cloud and damage pattern across the cloud edge
Near/mid-field damage to buildings	Consistent with the near to mid-field building damage	Not consistent with damage to Northgate cladding unless detonation fails at a distance from the building
Far-field damage to buildings	Consistency depends on the amount of fuel consumed	Consistent with the far-field damage
Similarity to previous incidents	Similar incidents were not consistent with a deflagration	Similar Incidents were consistent with a detonation

Not consistent | Not inconsistent | Consistent

Conclusions

- Overpressure within the cloud > 200 kPa.
- No distinction between objects in different terrain.
- Rapid decay in overpressure with distance from the edge of the cloud.
- Overpressure of around 5 kPa at distances between 2 and 4 km.
- Net drag impulse
  - Within the cloud: in the opposite direction to the direction of explosion propagation
  - Outside the cloud: in the direction of explosion blast propagation

Conclusions

- Deflagration
  - Inconsistent with net drag impulse within the cloud.
  - Inconsistent with damage to objects in the near-field.
- Detonation
  - Consistent with the evidence.
  - But predicted loading (from detonation models) would have caused greater damage to (Northgate) buildings.
  - This may be explained if the detonation was limited to part of the cloud depth (or some other geometric effect).

Future Work

Phase 2

WP1 Explosion & structural response modelling

- Modelling of pancake shaped clouds
  - Parametric studies to consider the decay in overpressure from the edge of the cloud;
  - Effects of cloud geometry, ignition location, obstacles on the overpressure pattern
- Structural modelling
  - Further analysis of Northgate Building
  - PI diagrams for different construction forms

WP2 - Characteristics of pancake shaped vapour cloud explosions - Tests

- Radius of 25 – 50 m
- Measurements:
  - Overpressures
  - High speed video
- Objects (metal boxes and drums, cars, painted posts and smoked plates) at a range of locations within and outside the cloud

WP3 - Effect of trees on vapour cloud explosions - Tests

- Vary:
  - Length of row of trees: circa 60 m
  - Height of trees: 3m
  - Width of undergrowth: between 1 and 4 m
  - Density of undergrowth
  - Type of trees
  - Fuel type
- Measure:
  - Overpressure
  - Flame speed
  - Fuel composition and concentration
  - Gas velocity

WP4 - Characteristics and modelling of low wind speed dispersion

- Use dispersion modelling and HSL test results to investigate the effect on the development of large vapour clouds of:
  - the cascade
  - the bund design

WP 5 - Design implications

- Modelling low velocity vapour cloud dispersion.
- Modelling of congestion caused by trees and undergrowth.
- The effect of storage tank layout on explosion characteristics.
- The effect of trees on explosion characteristics.
- Structural damage associated with vapour cloud explosions.

Fundamental Research

- Effect of high intensity thermal radiation from an advancing deflagration on particulates immersed in the vapour cloud.
- Data on burning velocities and Markstein numbers of key explosive mixtures at appropriate temperatures and pressures above ambient.
- Data on ignition delay times of key explosive mixtures at appropriate temperatures and pressures and on DDT.
- Nature of premixed turbulent combustion in boundary layers.