Severe, unconfined petrol vapour explosions

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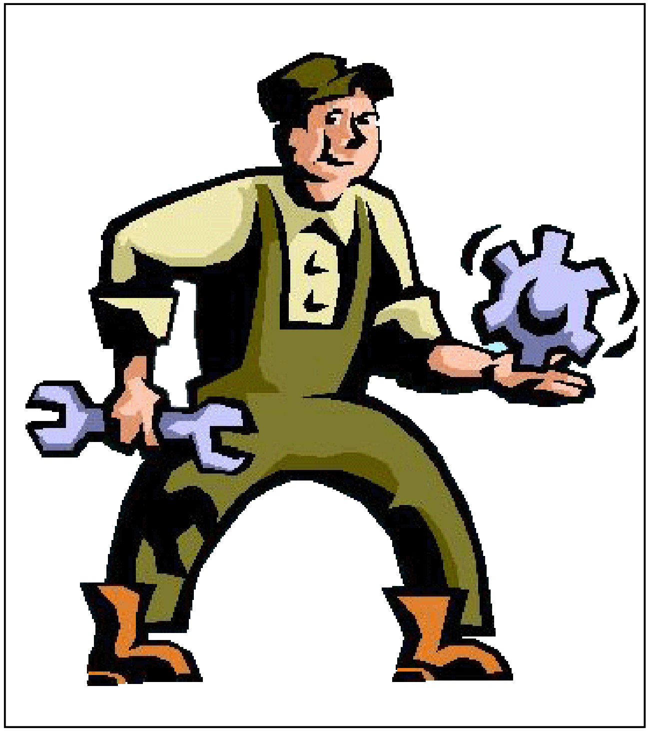
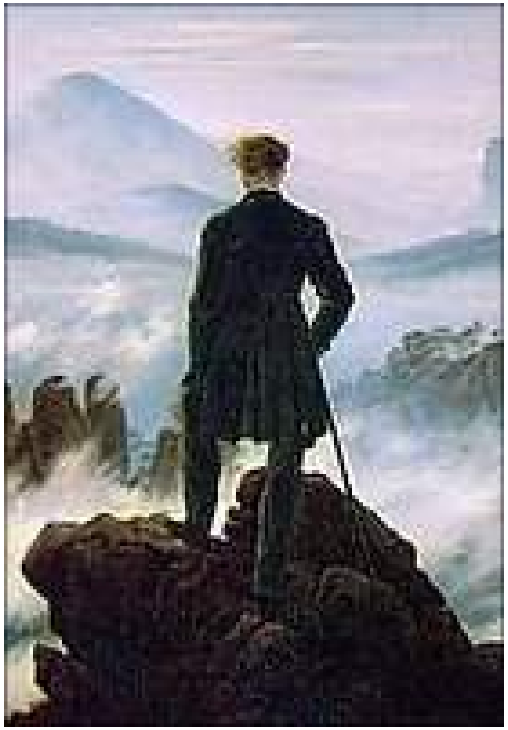
Buncefield - Lessons for whom?





Plant managers

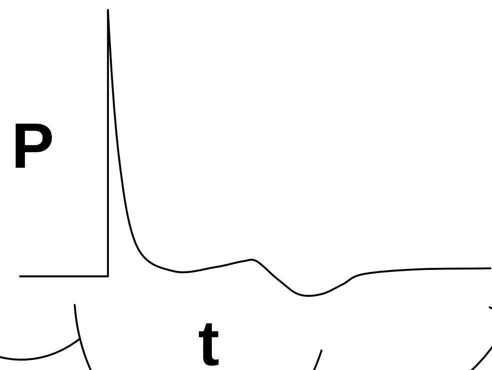
Safety managers

Risk assessors

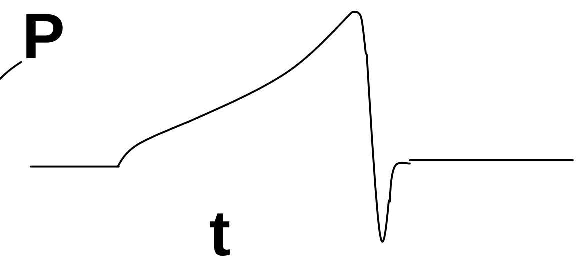
Explosion scientists

Deflagration or detonation?

Detonation
(Flame speed >> V_{sound})

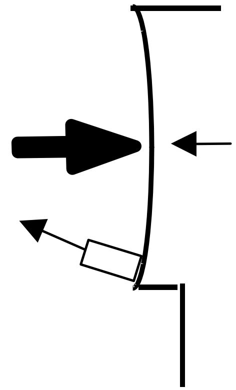


Deflagration
(Flame speed < V_{sound})



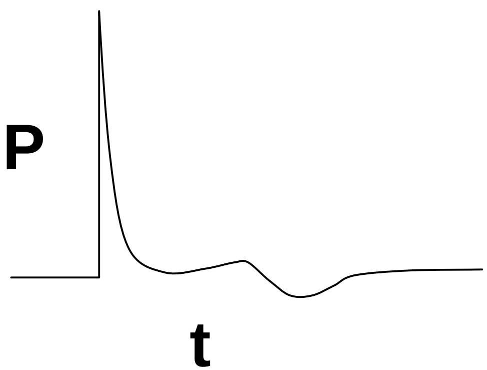
Pressure

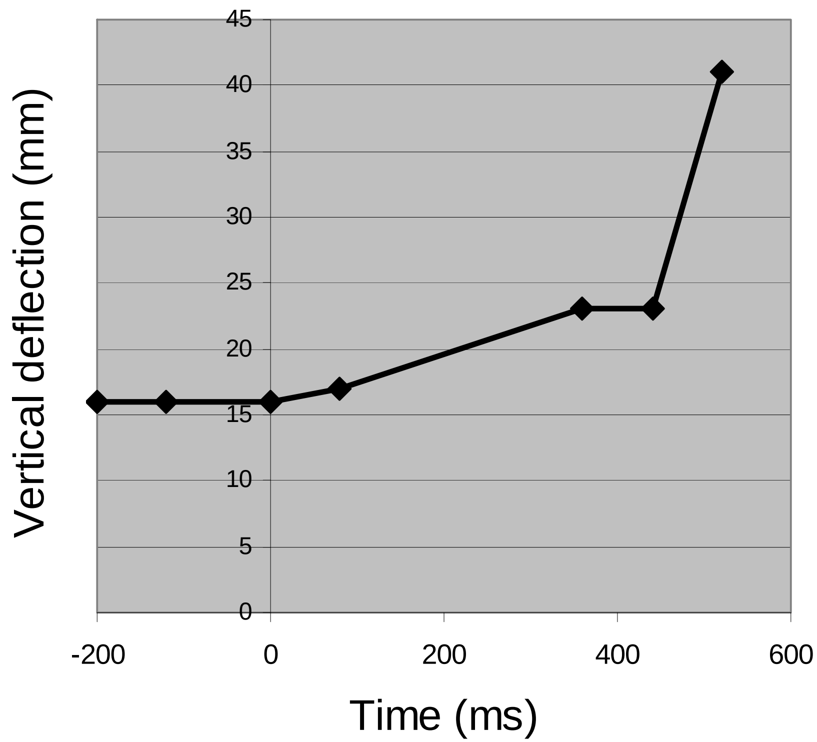
Deflagration or detonation?



Detonation

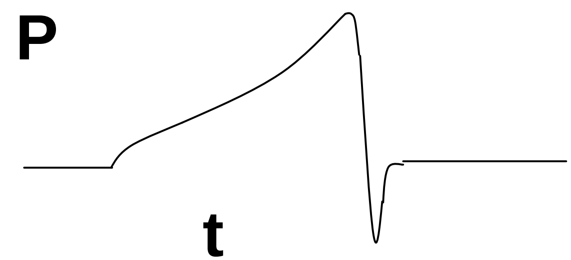
(Flame speed >> V_{sou}





Deflagration

(Flame speed < V_{sound})



Deflagration or detonation?

Detonation

Blast front advances at up to 2000 m/s

Deflagration

Pressure waves radiate out at sound speed

~ 331m/s

Blast wave speed

Deflagration or detonation?

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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

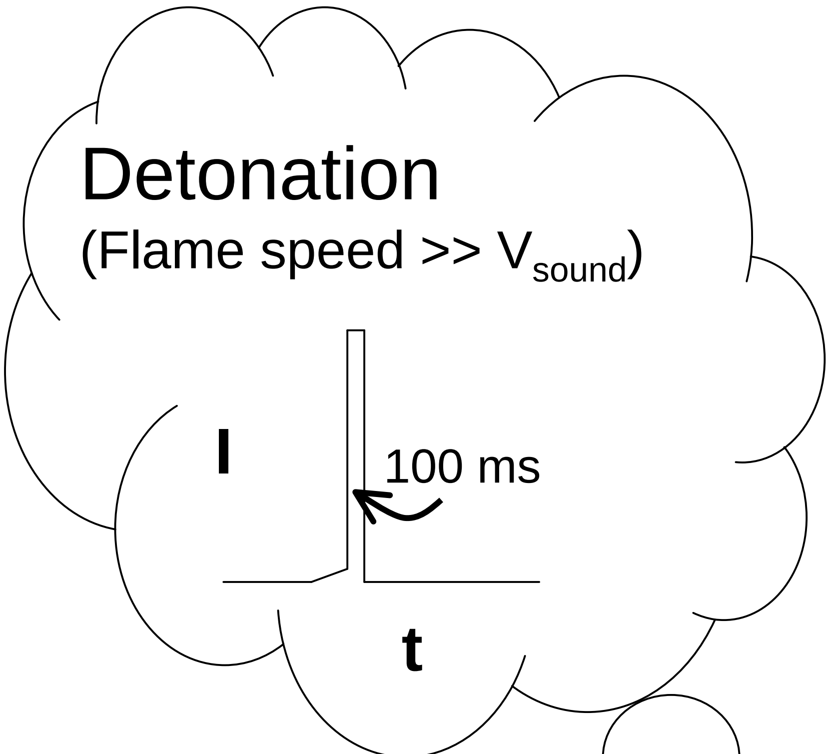
Blast front advances at 2000 m/s

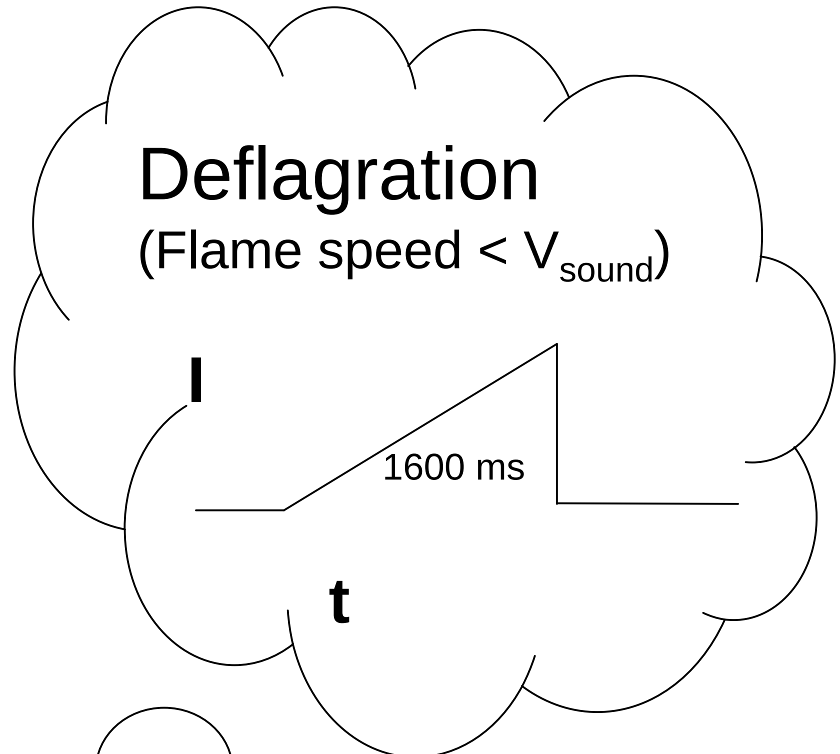
Deflagration

Pressure waves radiate out at sound speed

~ 331m/s

Deflagration or detonation?





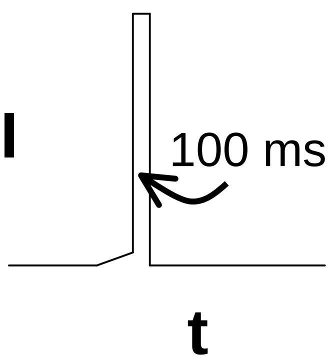
Illumination

Deflagration or detonation?

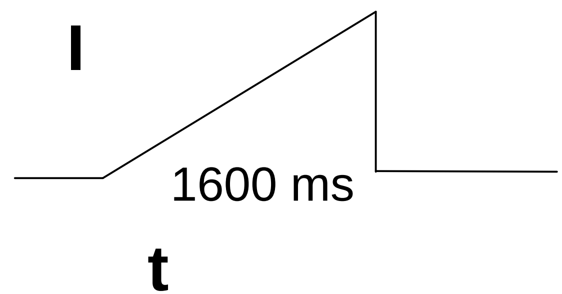
Detonation test

Buncefield

Detonation



Deflagration



Deflagration or detonation?

Detonation
(Flame speed >> V_{sound})

Flash ! Bang!

Deflagration
(Flame speed < V_{sound})

I saw it coming…

I felt it coming…

Witnesses

Deflagration or detonation?

"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})

Flash ! Bang!

Deflagration ✓

(Flame speed < V_{sound})

I saw it coming…

I felt it coming…

Deflagration or detonation?

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})

Flash ! Bang!

Deflagration ✓
(Flame speed < V_{sound})

I saw it coming…

I felt it coming…

All buildings have large holes in **exactly** one face

Front wall holed – Sides and roof intact

Walls reinforced concrete –

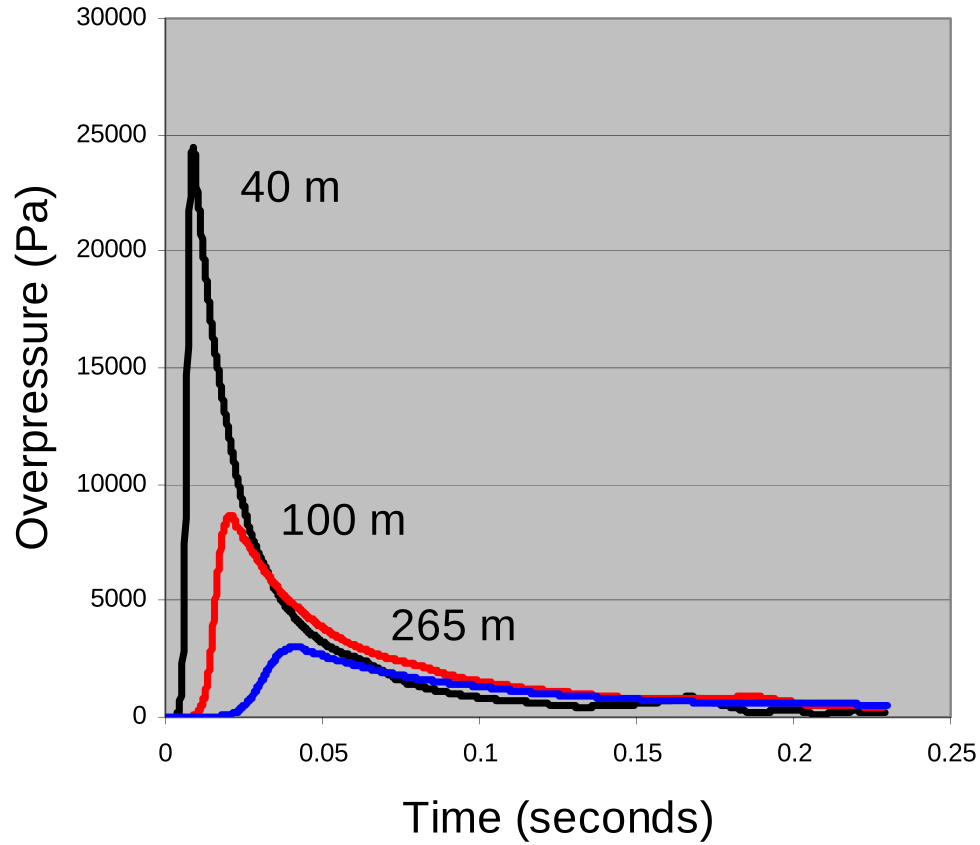
Front half of roof pushed down

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.

If the front wall is strong the front part of the roof fails; the rear part is left intact.

Detonation of vapour cloud

1 m deep, 200 m radius



Marginal increases in strength prevent failure

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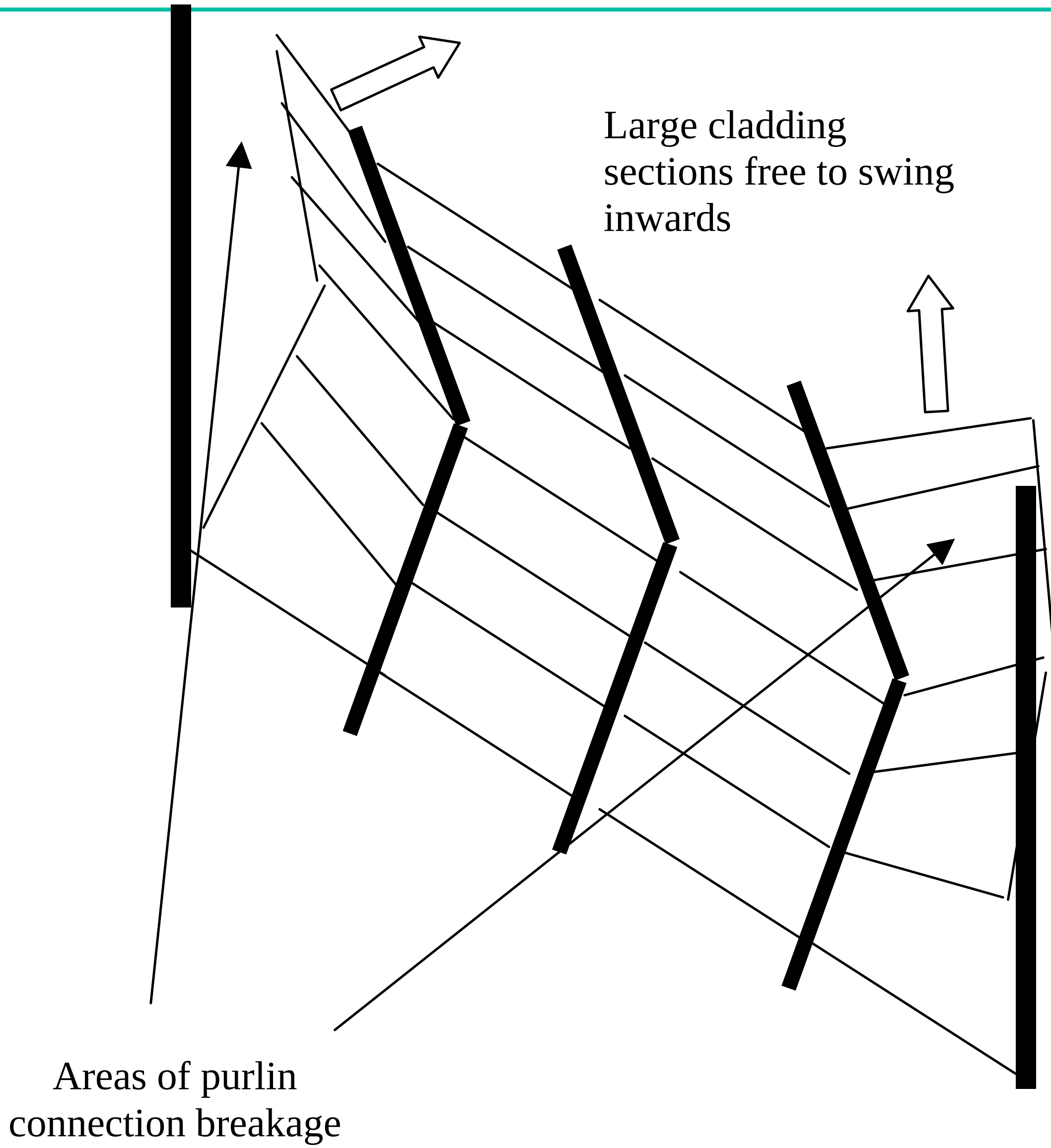
The blast is always ***just*** strong enough to vent the warehouse – no more and no less

Mechanism of venting



Example calculation
Mammoth – 30% venting – 3 kPa incident

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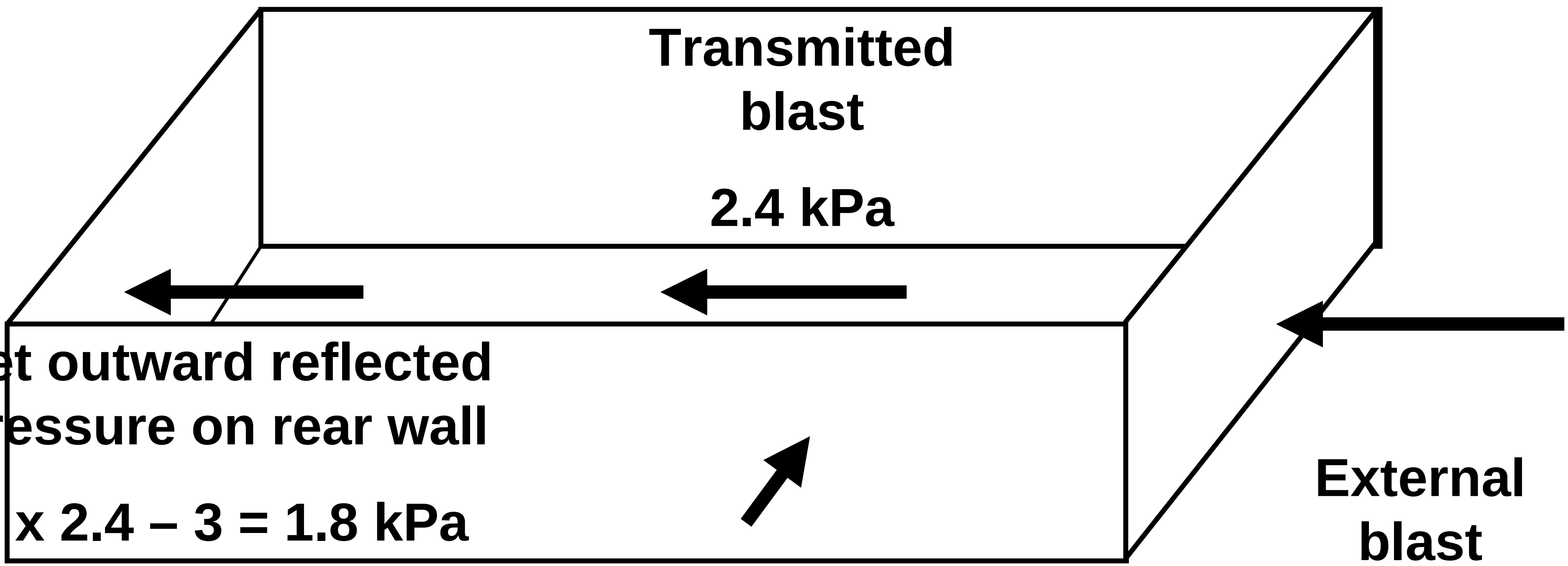

The exit wound

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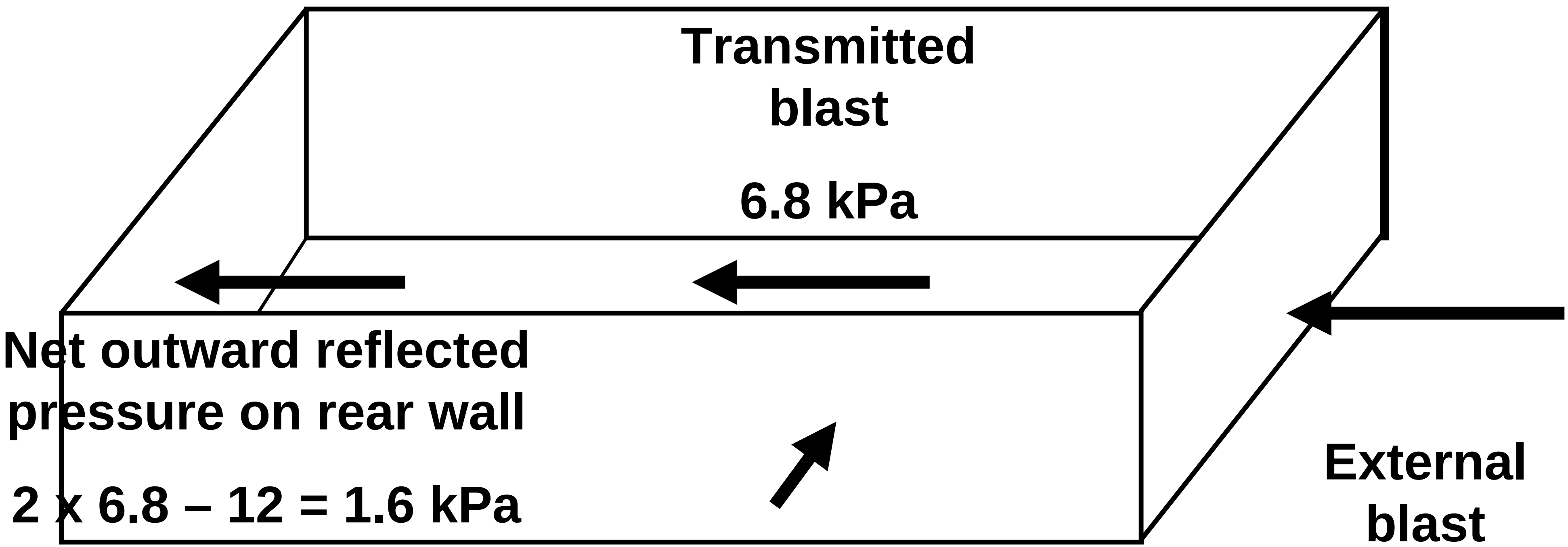
Example calculation
Mammoth – 30% venting – 12 kPa incident



A first estimate of impulse

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Displacement (D) of an *unrestrained* sheet by a blast wave of impulse I

$$D = I / c_{sound} . P$$

If D = 4m, I = 1700 Pa.s

Significant structural resistance will increase the impulse required

The effective displacement is not known – because of freely flapping sheets of cladding

A first estimate of blast duration

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Impulse ~ 1700 Pa.s

Maximum Pressure <6 kPa

(since the transmitted blast has protected the roof and sides at about 30% open area)

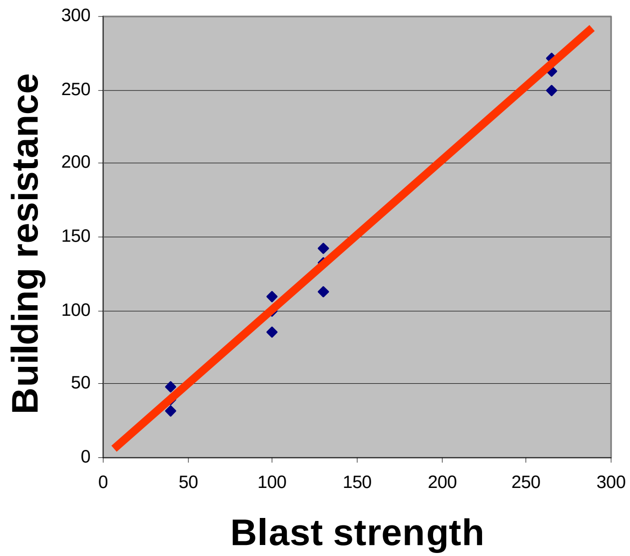
Duration (assuming linear rise to max)

2 x 1700 / 6000 ~ 600ms

This agrees with estimates by witnesses and from CCTV cameras

Deflagration or detonation?

Detonation



Building strength appears to be a function of applied blast pressure !!

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.

What happened at Buncefield?

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Summary of evidence

	Detonation	Deflagration
Pressure profile		✓
Blast wave timing		✓
Illumination		✓
Witnesses		✓
Building response		✓
Objects in the cloud	X	

An apparent paradox

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Flame speed < Sound speed

Flame speed > Sound speed

A related paradox

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High overpressures (2-5 bar) but no substantial difference between upstream and downstream faces

Resolution of paradox

Observation 1:

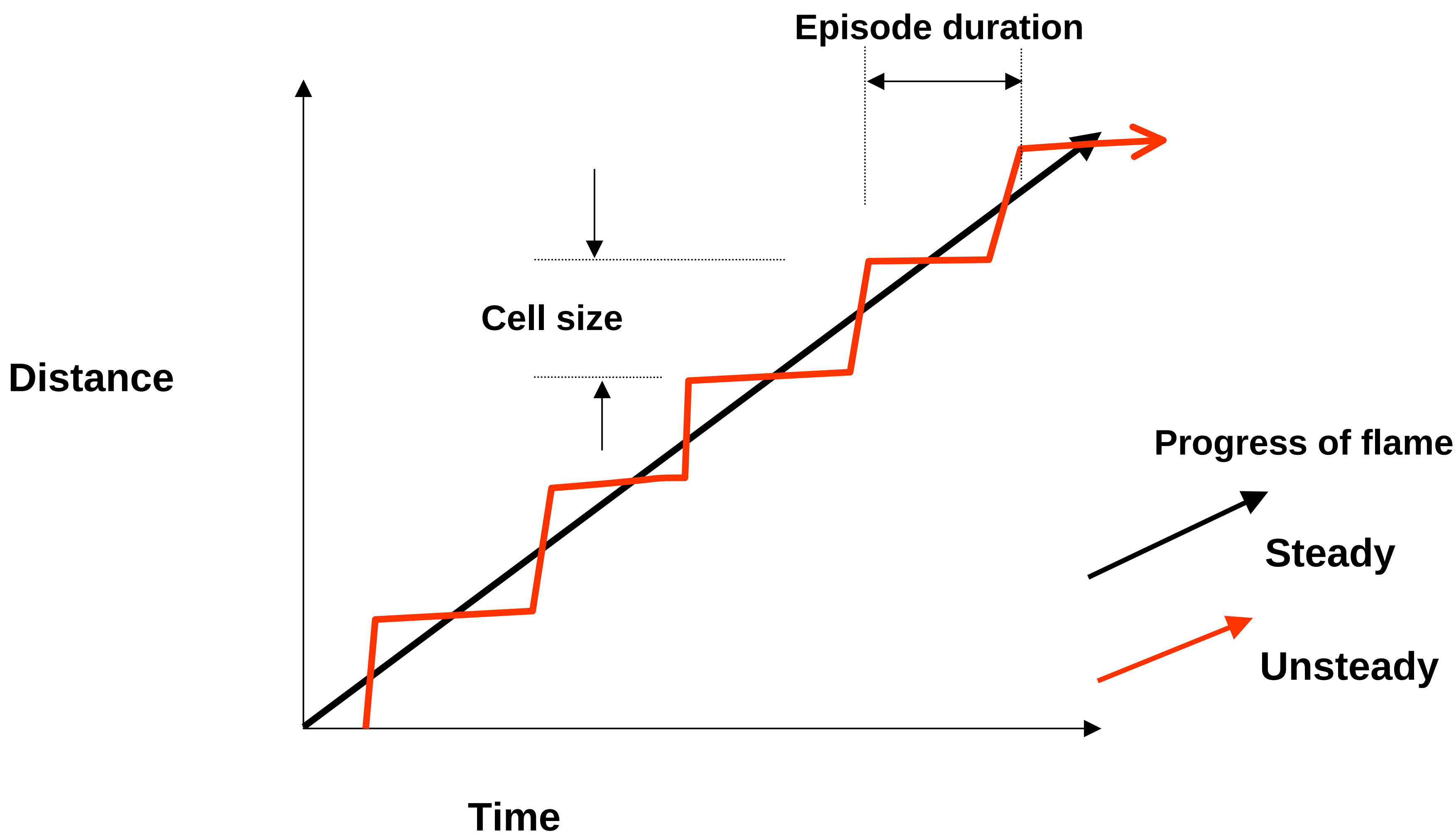
High overpressure (>2000 mbar) everywhere in the cloud.

Observation 2:

Subsonic (average) rate of flame spread (150 m/s)

Deduction: Episodic (cellular) combustion

Cellular or episodic combustion



Direct evidence for cellular combustion

Radiative enhancement of flame spread in a homogenous gas/dust mixture

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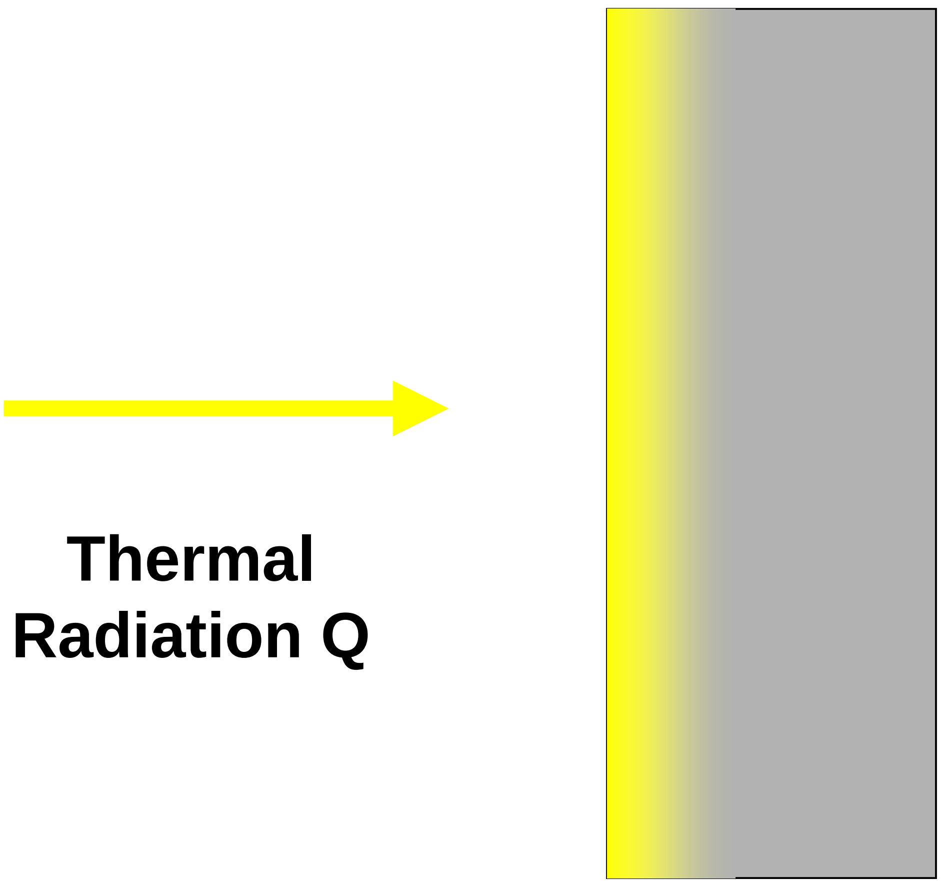


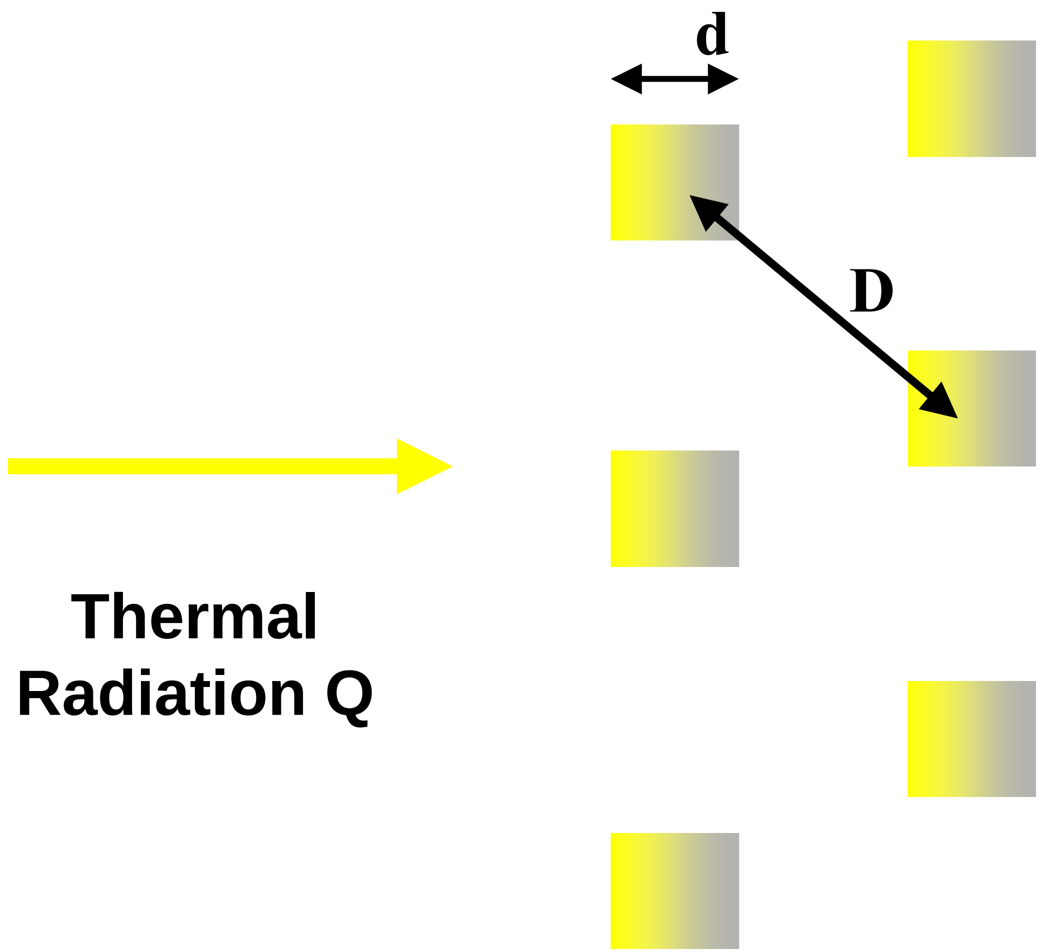
Assume dust does not contribute to heat capacity

Burning velocity

$$\frac{Q}{C_p \Delta T_{ign} \rho_{air}}$$

About 1 m/s

Dust concentrated in pockets



Burning velocity

$$\left(\frac{D}{d}\right)^3 \frac{Q}{C_p \Delta T_{ign} \rho_{air}}$$

Dust concentrated in pockets

Burning velocity

$$\left(\frac{D}{d}\right)^3 \frac{Q}{C_p \Delta T_{ign} \rho_{air}}$$

d can be as small as 10mm

(any smaller and conductive losses prevent ignition)

If D is around 100mm the maximum burning velocity can be very high

What dust concentration is required?

$$\frac{I}{I_0} = e^{-mK_m L}$$

For soot $K_m \sim 5\ m^2/g$

Efficient trapping of radiation in a 10 mm deep layer requires a mass concentration of

$m = 1/(5 \times 0.01) = 20\ g/m^3$

What dust concentration is required?

For very fine particulate like soot the amount of dust required does not significantly add to the heat capacity of the air.

Coarser mineral dusts have to be present at higher concentration to be effective in trapping radiation.

What dust concentration is required?

Overall the minimum dust mass densities required are low.

For soot, d = 10mm and D = 100mm

$$\rho_{overall} = 20\ (10/100)^3 = 0.02\ g/m^3$$

If dust from the ground is mixed into a 5m deep cloud a (minimum) ground level dust lofting of about 0.1 g/m^2 is required.

What pressure is developed?

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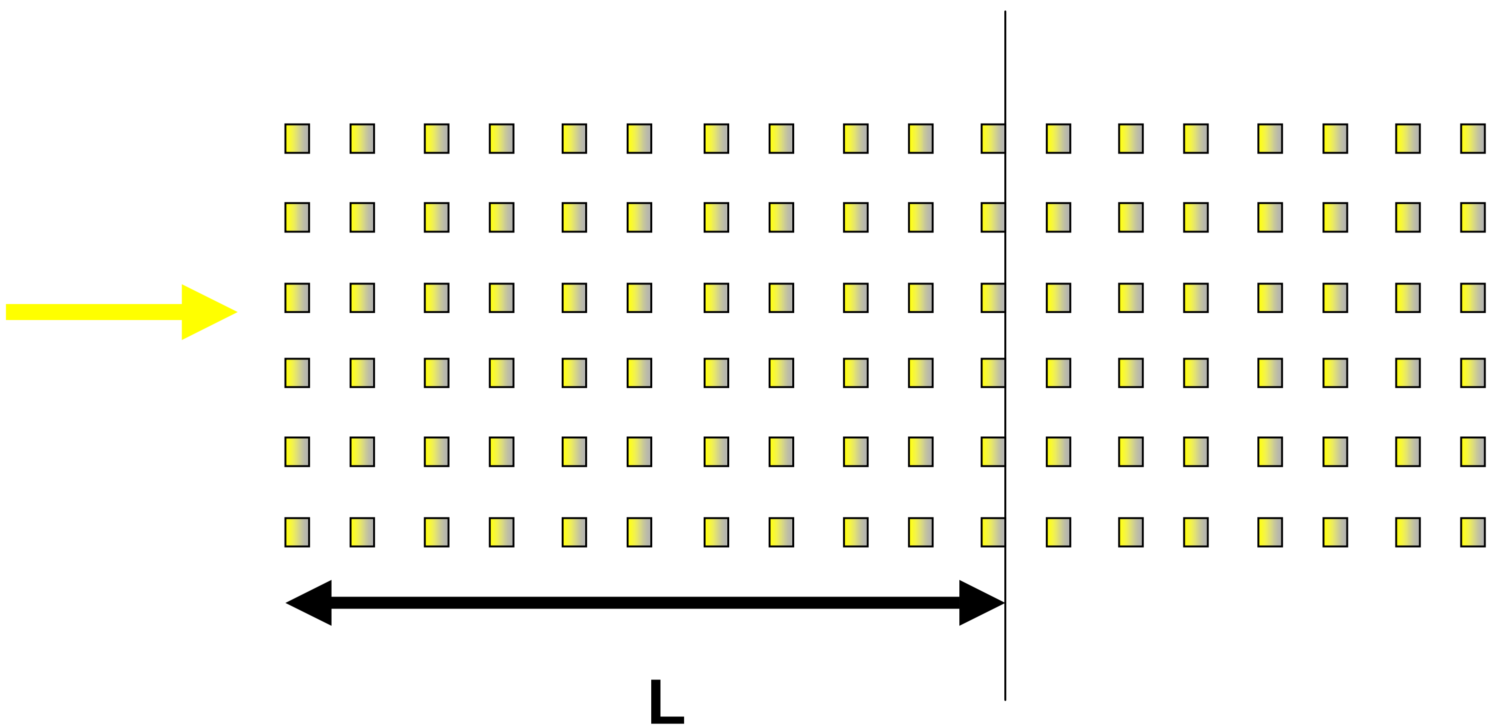
Not much

(if the average flame speed is the observed value of 150 m/s and the flame proceeds steadily)

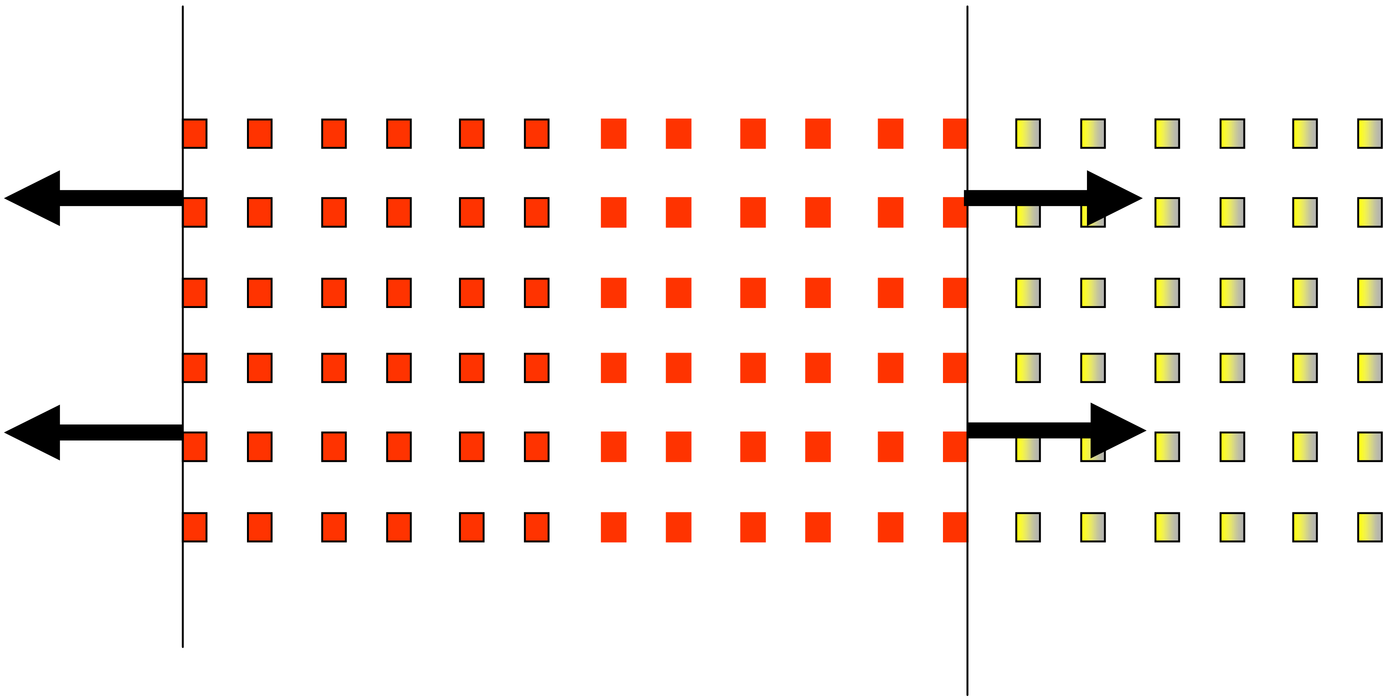
What if the combustion is episodic?

Ignition of flame kernels occurring near simultaneously in a volume ahead of the flame front (depth L).



The ignited cell expands with a velocity of order

$$V_{exp} = V_{flame} \cdot L/D$$



Magnitude of induced pressure

$$V_{exp} = V_{flame} \cdot L/D$$

Example:

Distance between dust pockets D = 100mm

Size of explosion cell L = 5m

V_{flame} = 10 m/s

Expansion of outer edge of explosion cell = 500 m/s

This is sufficient to induce pressures of several bar.

Conclusions

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Understanding detonation is important – especially the conditions that may trigger DDT in relative unconfined systems.

But Buncefield and Jaipur were not detonations. The explosions were episodic but the physical mechanisms involved remain unclear.

Those with an interest in practical plant safety ought to be addressing this problem with at least the same level of energy devoted to DDT.

Research is warranted in the following areas

- Ignition of dust/gas mixtures by thermal radiation

  (underway at Imperial College)

- Dust entrainment close to violent, unconfined gas explosions

- Variations in dust mass density in relevant turbulent flows

- Stability of combustion where there are multiple radiative ignitions ahead of the flame front.

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The surprising ability of turbulence to render an initially homogenous distribution of ambient particles very inhomogeneous is likely to have consequences in several fields and deserves further study.

Bracco, P. H. Chavanis, and A. Provenzale

Particle aggregation in a turbulent Keplerian flow

Physics of Fluids (1999) Vol 11, No.8