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Vapour cloud assessment for overfilling incidents

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Jaipur October 29th 2009

12 dead, >50 injuries, Mass evacuation

Cloud diameter approx 1000m

Upward spray from a pipe under tank pressure (<1 bar)

Duration of leak ~75 minutes

Caribbean Petroleum Corporation (Puerto Rico)

23rd October 2009

Cloud diameter approximately 500m

Substance: Gasoline

Cause: Tank overfilling (Ship to Shore transfer)

Buncefield and other incidents have shown that very large vapour clouds can be caused by liquid leaks

(Especially tank overfilling, releases of volatile liquids at elevation or upward facing sprays)


05:34:38 AM
11 12 2005 SUN
PLAY
Pause
1
Tower 1


11 12 2005 SUN
PLAY
Pause
05:48:07 AM
1
Tower 1


05:56:11 AM
11 12 2005 SUN
PLAY
Pause
1
Tower 1


11 12 2005 SUN
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Pause
05:36:28 AM
8
Tower 8


11 12 2005 SUN
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Pause
05:44:28 AM
8
Tower 8


11 12 2005 SUN
PLAY
Pause
05:45:28 AM
8
Tower 8


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8
Tower 8

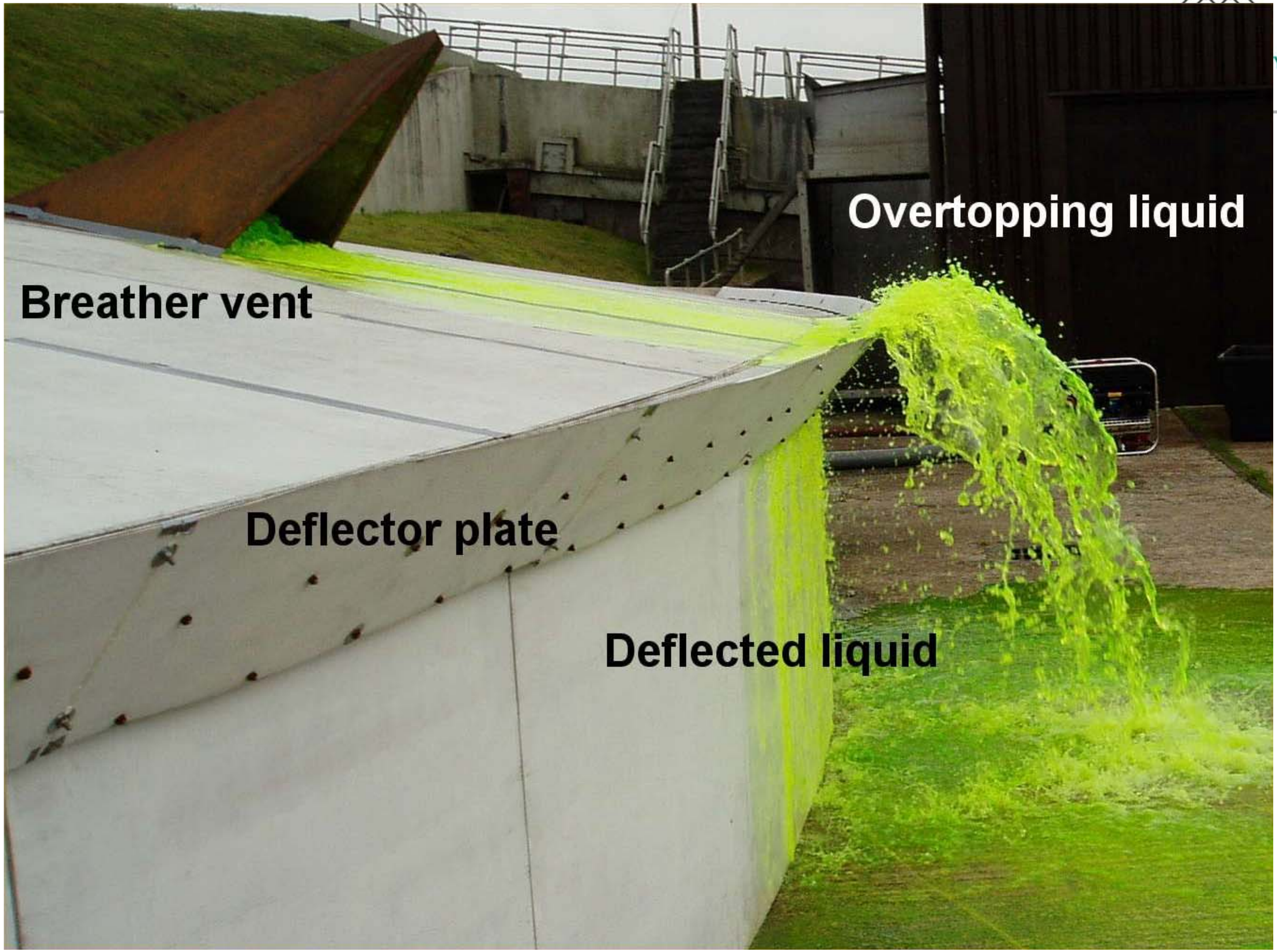
Calculating vaporisation in the casacde

How is the liquid released?

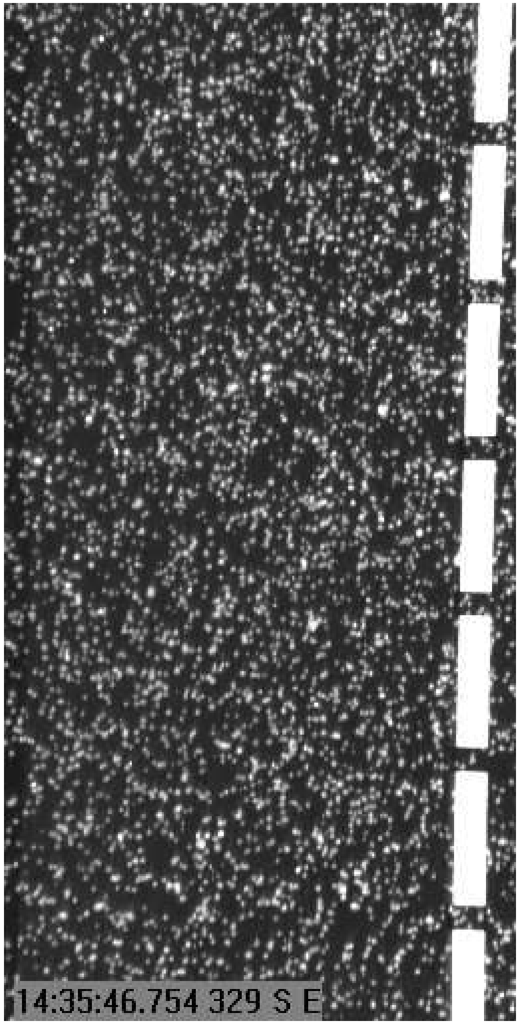
How does it break up as it falls?

How much air is drawn into the cascade?

How much liquid vaporises?


Overtopping liquid
Breather vent
Deflector plate
Deflected liquid

Droplet size in the cascade



Gasoline

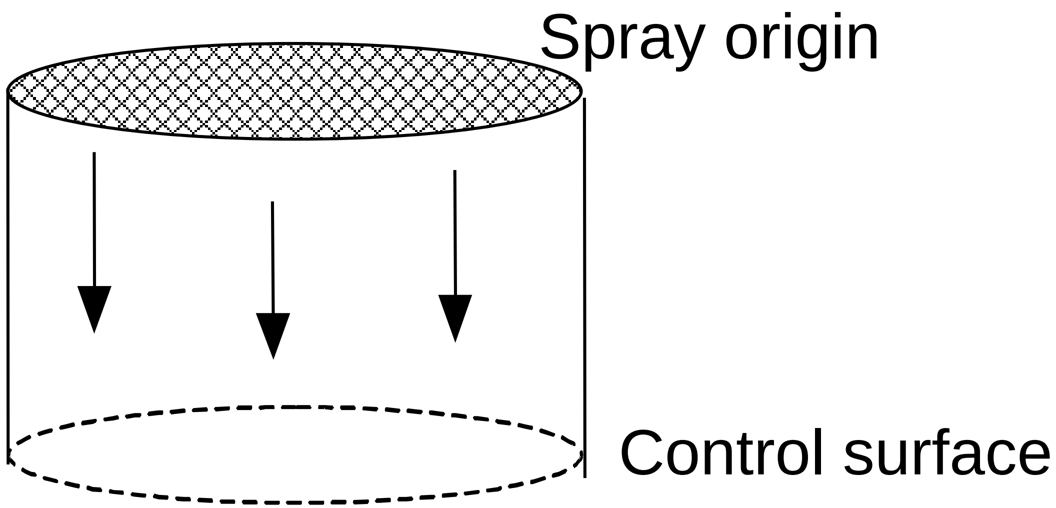
- **Small, even sized drops**
- **Diameter approximately 2mm.**

Water

- **Wide range of droplet sizes**
- **Up to 6mm diameter**

	Surface tension (N/m)	**Density (kg/m3)**
Water	0.0727	998
Hexane	0.0184	667

Air flow driven by gravity driven liquid cascade

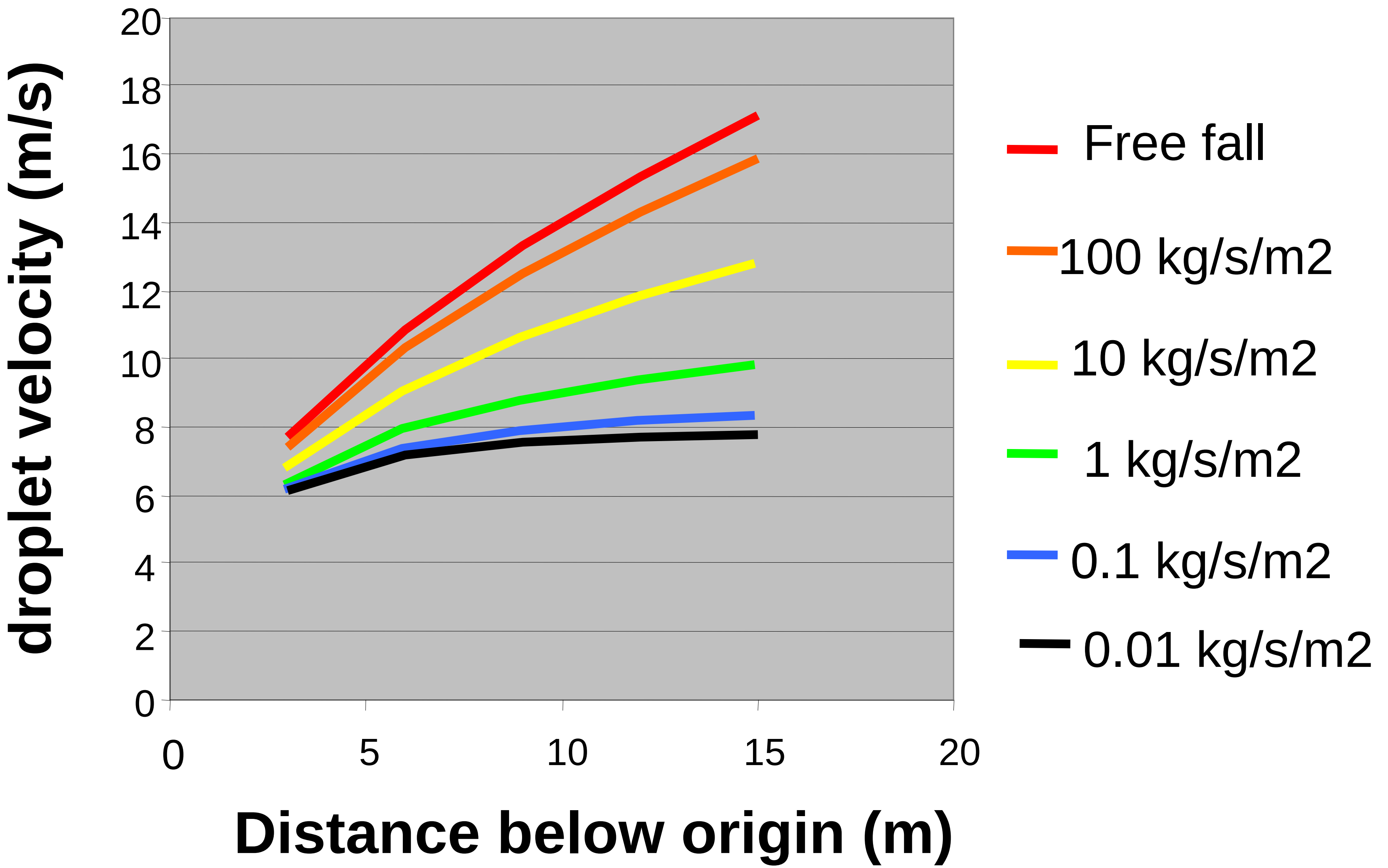


This is a straightforward mechanics problem (much easier than a turbulent gas jet)

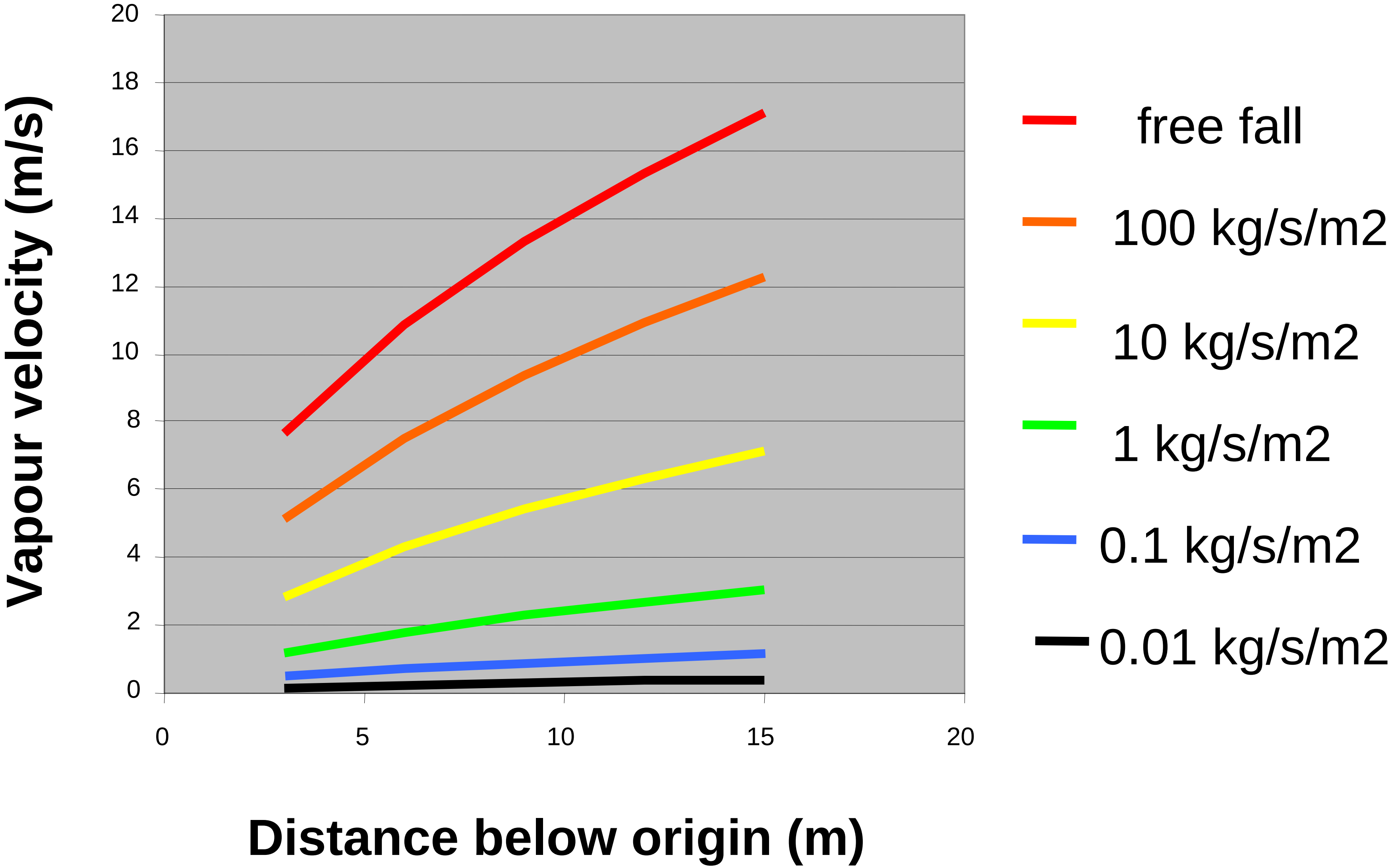
There are no empirical constants

Hazards XX Conference (2007): "***Liquid dispersal and vapour production during overfilling incidents***"

Droplet dynamics in cascade of varying mass density



Air flow driven by sprays of varying mass density

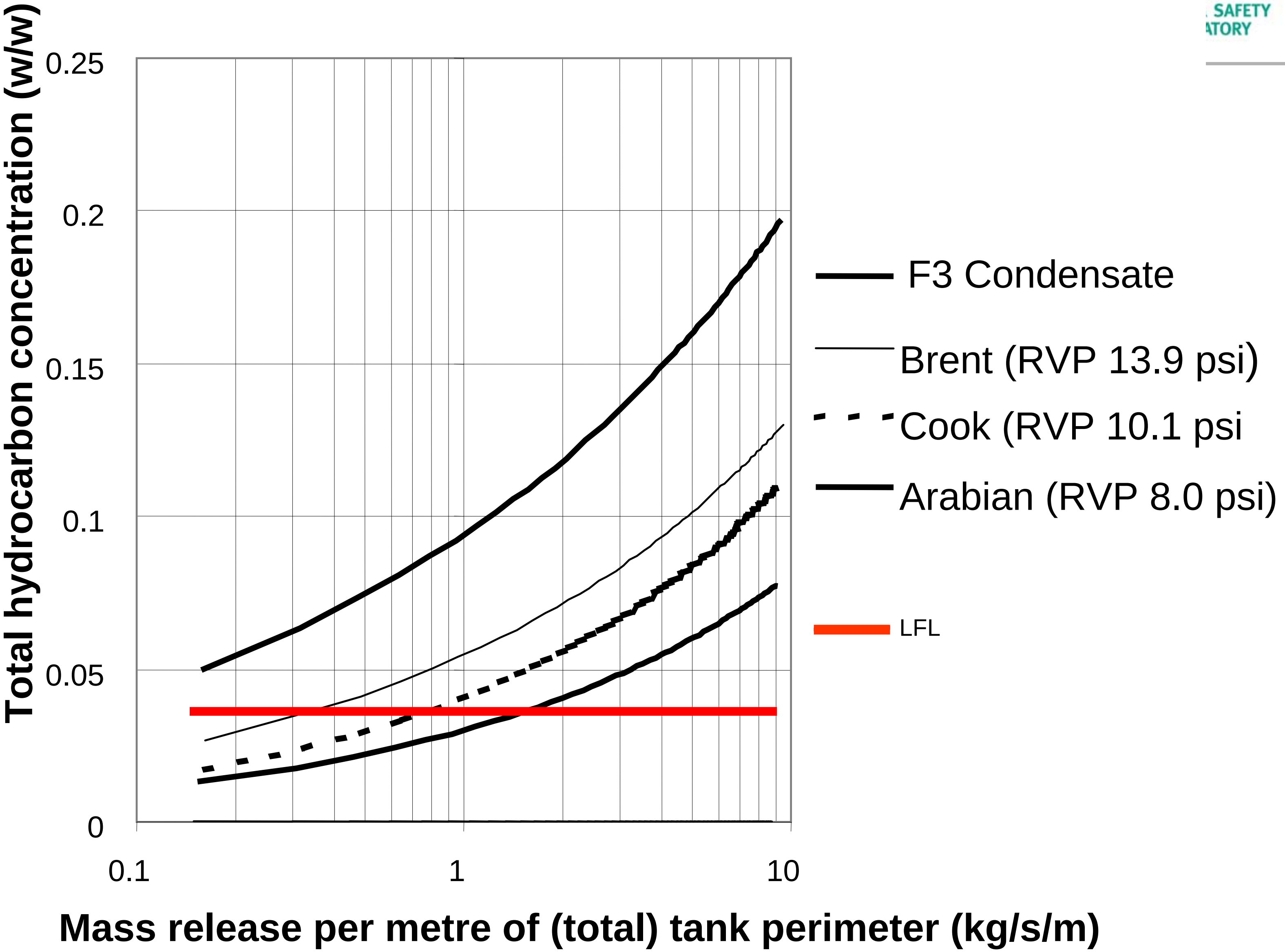


This analysis gives the amount of air drawn into the liquid cascade

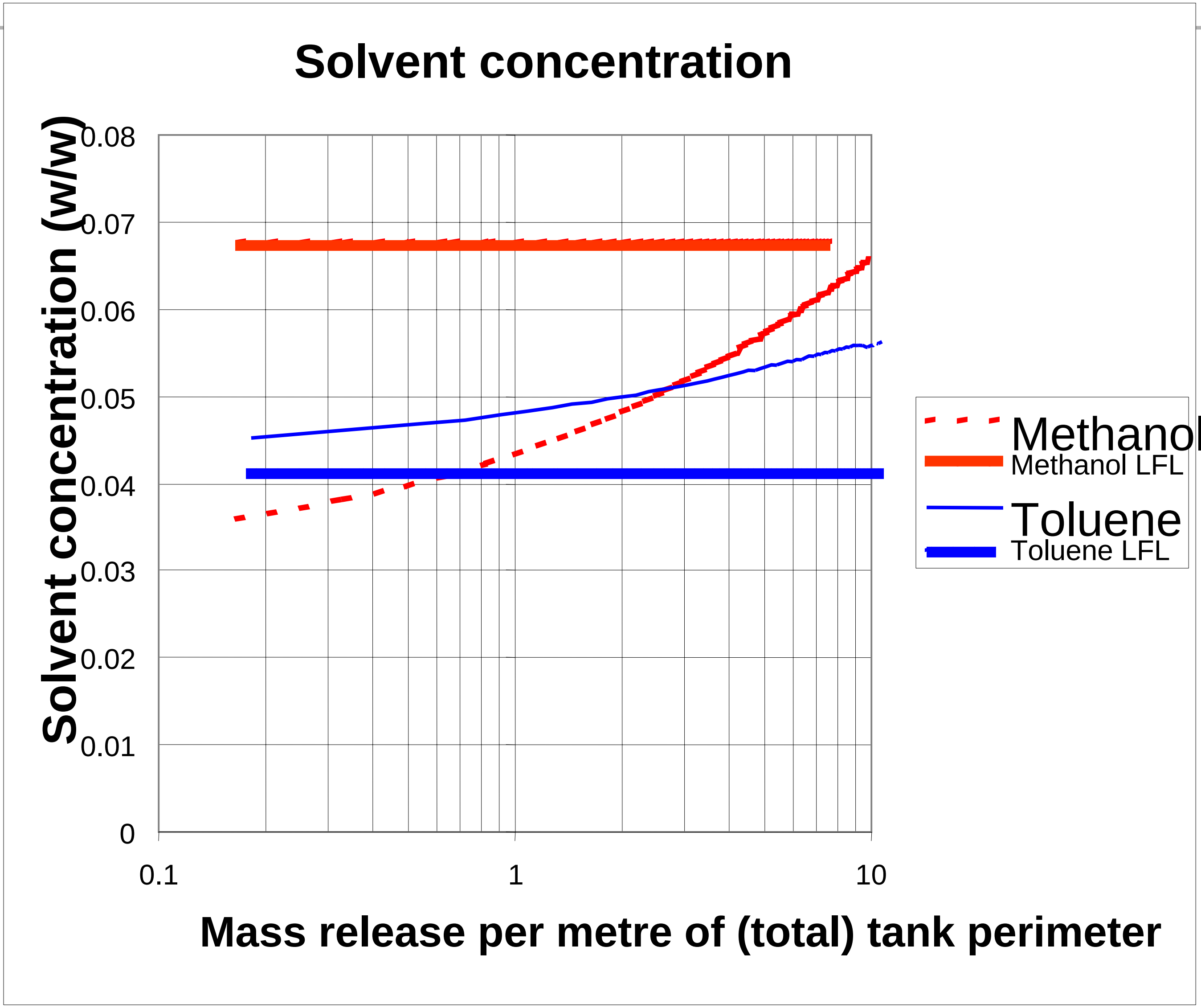
If we assume thermodynamic equilibrium is reached, we can calculate the vapour concentration at the foot of tank

A given tank is overfilled at a specified rate with a specified liquid.

Can a significant flammable vapour cloud be formed?



Total hydrocarbon concentration (w/w)
0.25
0.2
0.15
0.1
0.05
0
0.1
1
10
Mass release per metre of (total) tank perimeter (kg/s/m)
F3 Condensate
Brent (RVP 13.9 psi)
Cook (RVP 10.1 psi
Arabian (RVP 8.0 psi)
LFL

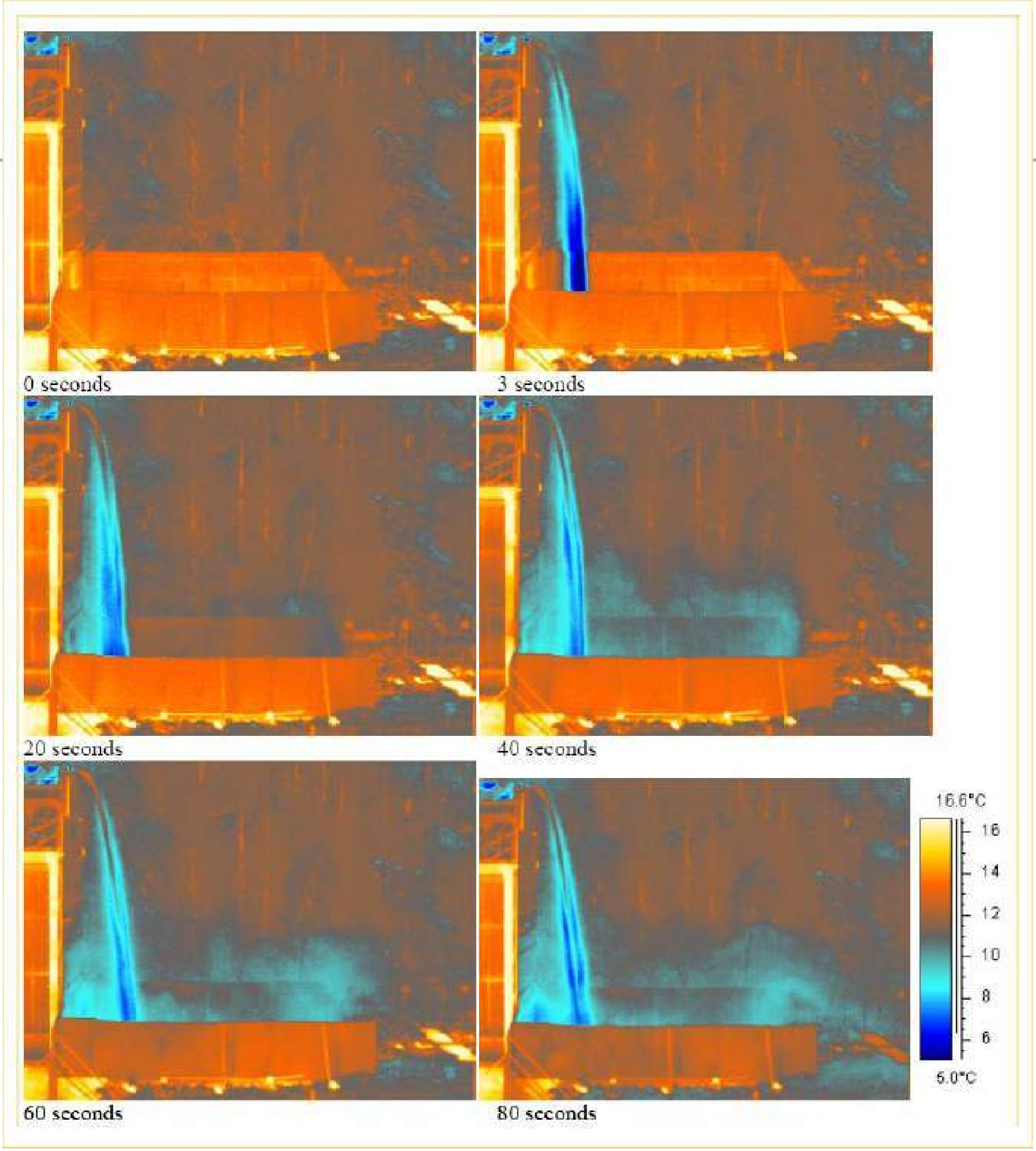


Solvent concentration
Solvent concentration (w/w)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.1
1
10
Mass release per metre of (total) tank perimeter
Methanol
Methanol LFL
Toluene
Toluene LFL

Key areas addressed in the new experimental and modelling work:

- Heat and mass transfer – how good is the equilibrium assumption?
- Near field dispersion
- Far field dispersion

Sometimes the cloud is visible



Sometimes thermal imaging is required

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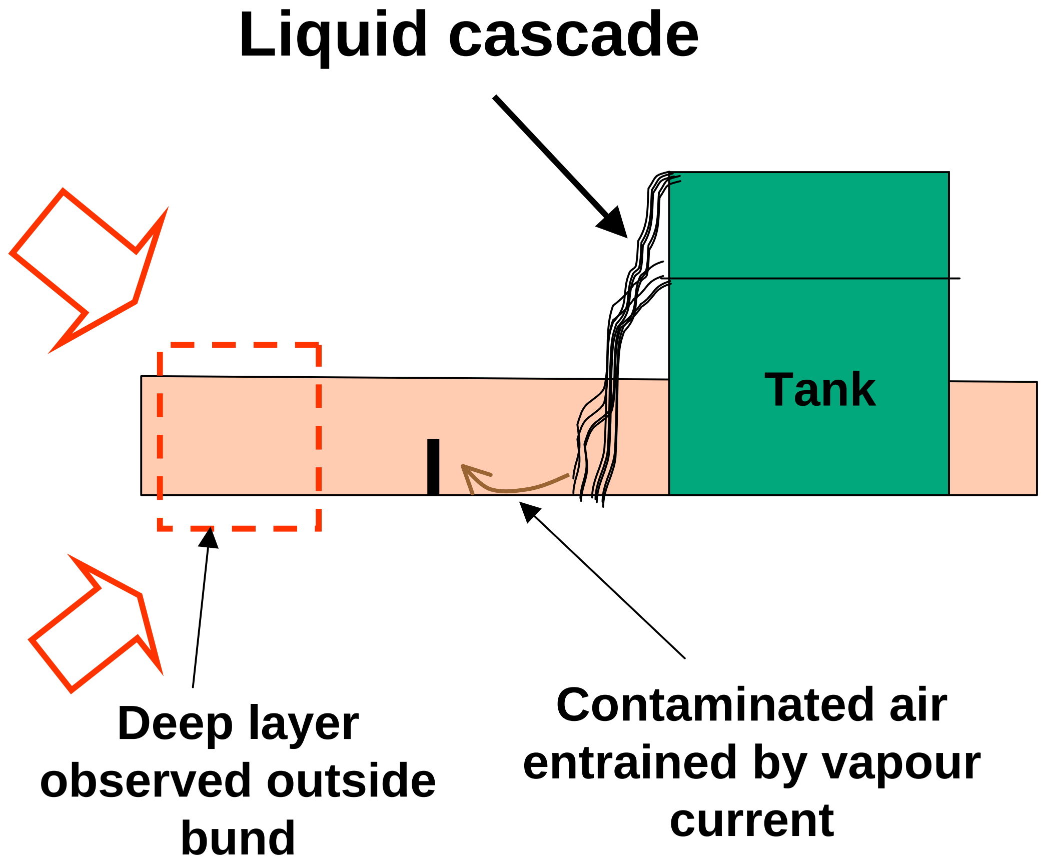
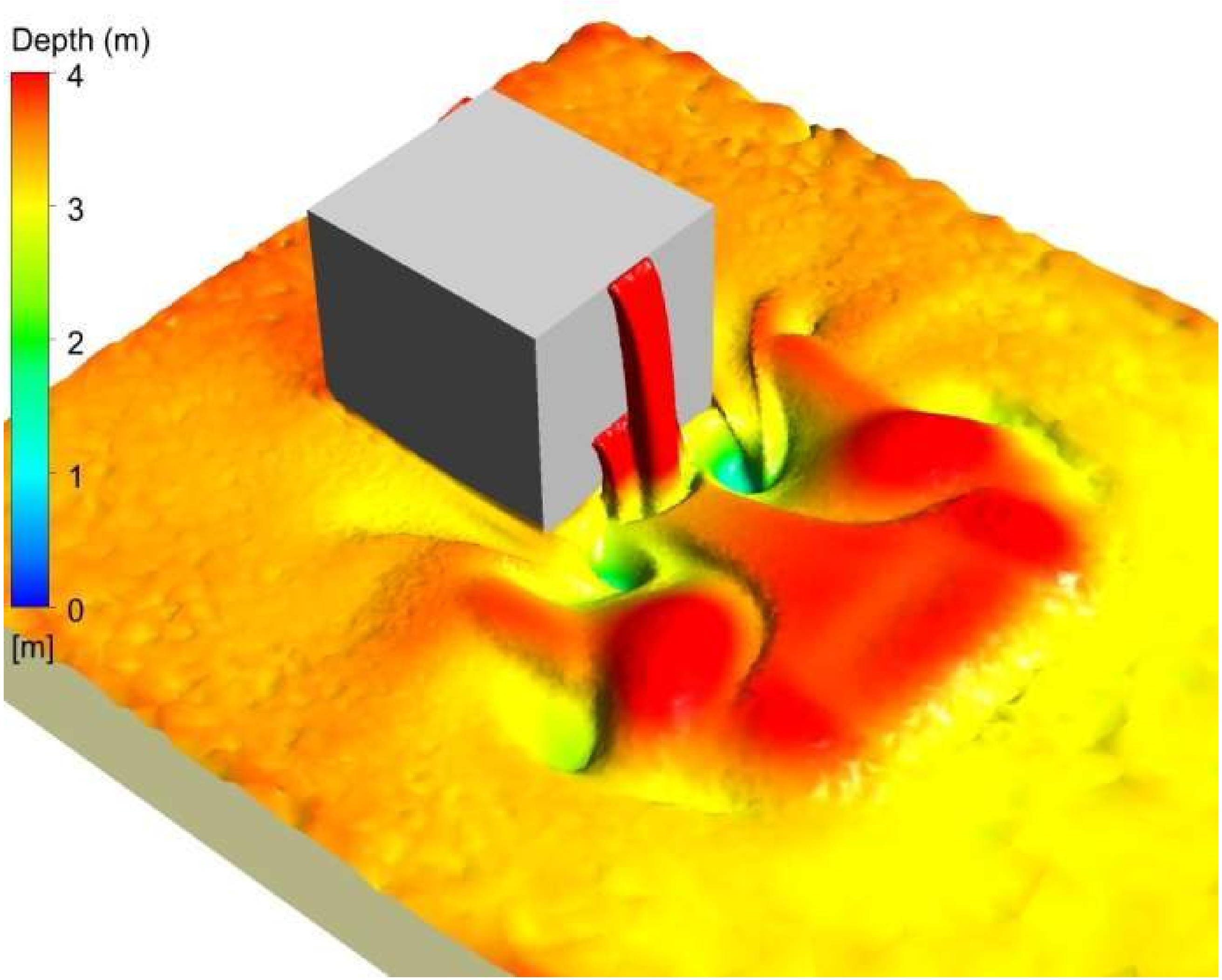
How effective is the vaporisation process?

Measurements of liquid and vapour temperatures in full scale experimental cascades.

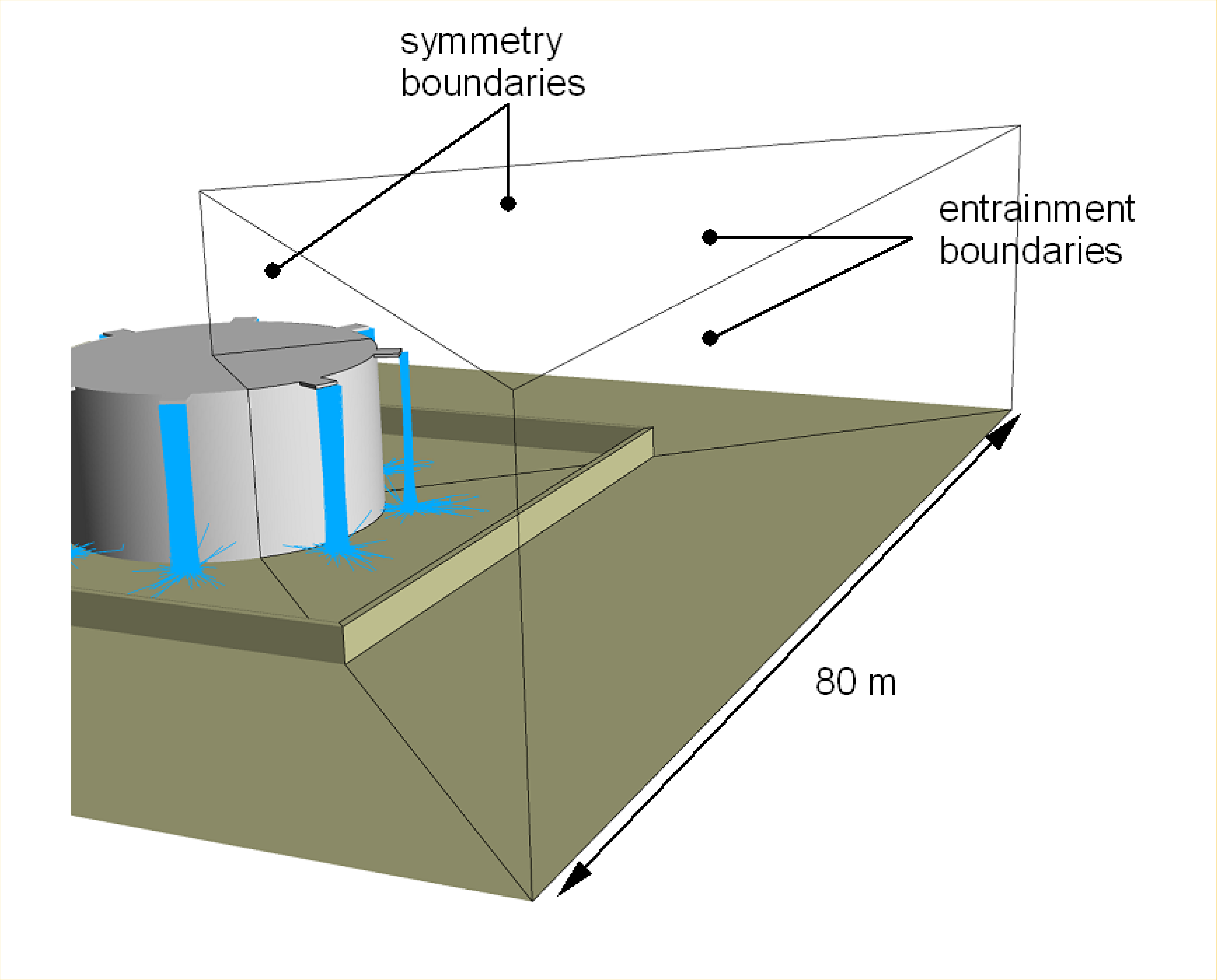
Near field dispersion: Is entrainment of air suppressed by the deep accumulating vapour cloud ?



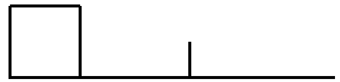
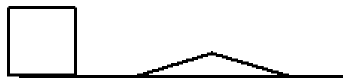
Even when a deep layer accumulates around the tank the vapour flow entrains some fresh air



Computational domain

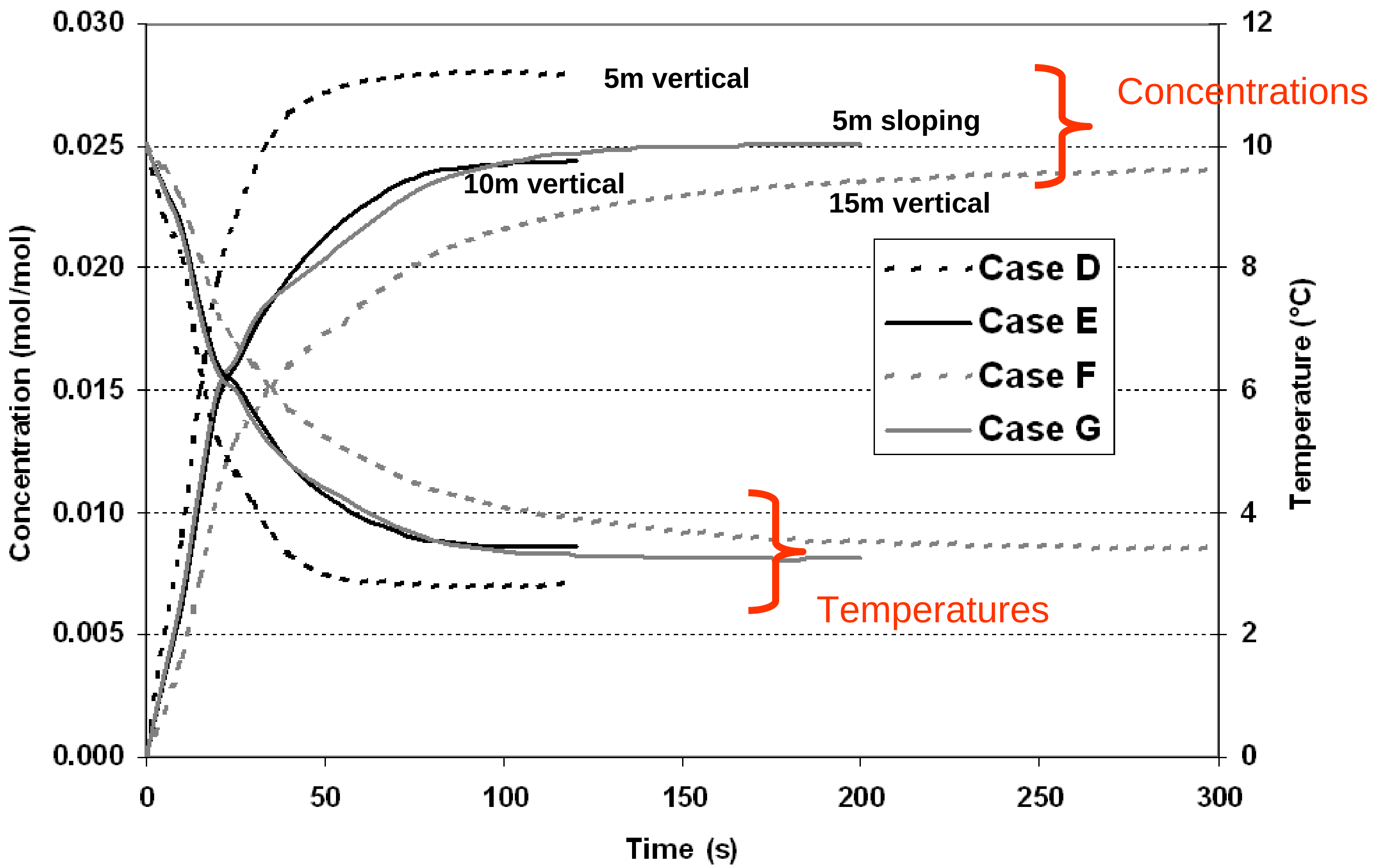


Test cases

Simulation	*Configuration*	
Case C	no bund	
Case D	bund at 5 m	
Case E	bund at 10 m	
Case F	bund at 15 m	
Case G	sloping bund at 5 m	
Case H	no bund, 4m wall surrounding domain	
Case I	no bund, 2.5m wall surrounding domain	

Effect of bund design on concentration in the cloud

(concentration at the tank foot ~0.05 mol/mol)



What is the relationship between the concentration in the cascade and that in the vapour cloud?

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Barrier height (m)	Cloud depth (m)	Distance to barrier (m)	Dilution factor (conc. in cascade/conc. in cloud)
4	5	30	1.5
2.5	3.6	30	2.1
2	-	5	1.8
2	-	10	2.0
2	-	15	2.0

Conclusions from the experimental and modelling work

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- Overfilling can be a well-defined source term and can be analysed with some confidence – compared other hazard modelling methods.

- Distribution of liquid discharge is the main uncertainty (especially for floating roof tanks)

- Long range dispersion in very light or zero winds is a major outstanding difficulty – site specific data can improve the value of modelling.

- These problems are worth the trouble - operators at gasoline depots should have an understanding of the way a vapour cloud is likely to develop in the event of an overfill.

Outline of the Vapour Cloud Assessment method

http://www.hse.gov.uk/research/rrhtm/rr908.htm

- Calculate the volume production rate for the specific tank / flow rate
- Calculate the concentration of fuel vapour at the foot of the tank
- Allow for near field dilution (reduces concentrations and increases volumes)
- Analyse long range slumping of the vapour cloud.

Example 1- A gasoline tank like Buncefield

Tank diameter D	25 m
Tank height H	15 m
Fuel flow rate F (Gasoline)	115 kg/s
Fuel temperature T_{fuel}	14°C
Air temperature $T_{ambient}$	0 °C
Duration of release	1400 s

Example 1- Air mass entrained

Tank diameter D	25 m
Tank height H	15 m
Fuel flow rate F (Gasoline)	115 kg/s
Fuel temperature T_{fuel}	14°C
Air temperature $T_{ambient}$	0 °C
Duration of release	1400 s

Mass entrainment in cascade $M_{air} = 90 kg/s \left(\frac{D}{25m}\right)^{0.75} \left(\frac{H}{10m}\right)^{0.45} \left(\frac{F}{115 kg/s}\right)^{0.25}$	108 kg/s

The standard gasoline used (from Buncefield)

n-butane[1]	9.6%	wt/wt
n-pentane[2]	17.2 %	wt/wt
n-hexane[3]	16%	wt/wt
n-decane[4]	57.2%	wt/wt

[1] as a surrogate for all C4 hydrocarbons
[2] as a surrogate for all C5
[3] as a surrogate for all C6
[4] as a surrogate for all low volatility materials

Concentration at the tank foot

Tank diameter D	25 m
Tank height H	15 m
Fuel flow rate F (Gasoline)	115 kg/s
Fuel temperature T_{fuel}	14°C
Air temperature $T_{ambient}$	0 °C
Duration of release	1400 s

Concentration at the tank foot $C_{fuel} = 17\%(w/w)\left(1.28\frac{M_{air}}{F}\right)^{-0.42} e^{0.011(T_{fuel}-10)} e^{0.0062(T_{ambient}-10)}$ = 17 % (w/w) (0.92) . 1.04 . 0.94	15.3% w/w

The rate at which the cloud volume is growing

Mass vaporised $M_{vaporised} = M_{air} .. C_{fuel} / (100 -. C_{fuel})$	19.5 kg/s
Mass splashed M_{splash} (kg/s)= 0.02 F	2.2 kg/s
Total mass addition rate to cloud $M_{cloud} = 2. (M_{air} + M_{vaporised} + M_{splash})$	259 kg/s
Volume addition rate to cloud $V_{cloud} = M_{cloud}/\rho_{ambient}$	199 m^3/s

Results

Concentration of fuel vapour in cloud C_{cloud} (kg/m^3) =($M_{vaporised}$ + M_{splash}) / V_{cloud}	0.11 kg/m^3 110 g/m^3
Range (after 1400s) to which cloud may hinder escape $R_{escape} = [1/ 2\pi\ V_{cloud}\ .\ T]^{1/2}$	210 m
Range to which low level cloud might be ignited $R_{ignition} = [1/ \pi\ V_{cloud}\ .\ T]^{1/2}$	297 m

Lower explosion limits

Substance	Mass concentration at the lower flammable limit at 0°C (g/m^3)
Butane	48
Pentane	46
Hexane	47
Heptane	47
Benzene	47
Methanol	103
Ethanol	70
Propanol	60
Acetone	70
MEK	62

Stoichiometric mixtures

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Substance	Mass concentration for a stoichiometric mixture at 0°C (g/m^3)
Butane	83
Pentane	84
Hexane	84
Heptane	84
Benzene	98
Methanol	187
Ethanol	140
Propanol	122
Acetone	134
MEK	120

The gasoline cloud is slightly rich with an equivalence ratio of 110 / 84 = 1.3

Results – Hazard ranges

Range (after 1400s) to which cloud may hinder escape (2m high cloud) $R_{escape} = [1/2\pi V_{cloud} . T]^{1/2}$	210 m
Range to which low level cloud might be ignited (1m high cloud) $R_{ignition} = [1/\pi V_{cloud} . T]^{1/2}$	297 m

These give an indication of the potential reach of the cloud at different heights. Note the cloud will not flow uphill from the tank foot by more than 3m.

The figure for the 2m high cloud matches the average radius and typical height of the Buncefield cloud quite well.

Use of the method for simple risk assessment

After 5 minutes (300 s) the range to which the cloud might extend over head height and impede escape would be:

$$R_{escape} = [\, 1/\, 2\pi\, V_{cloud}\, .\, 300\,]^{1/2} = 97 \text{ m}$$

This kind of analysis shows the need for prompt and effective evacuation in the event of an overfill in calm conditions.

Early warning to allow escape before the cloud arrives can greatly reduce risk. Staying put (even in a toxic refuge) is very dangerous if the cloud is flammable.

A similar tank and condition - but filled with methanol

Tank diameter D	25 m
Tank height H	15 m
Fuel flow rate F (Methanol)	115 kg/s
Fuel temperature T_{fuel}	14°C
Air temperature $T_{ambient}$	0 °C
Duration of release	1400 s

Results for the methanol tank compared to gasoline (in brackets)

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Concentration of fuel vapour in cloud C_{cloud} $(kg/m^3) = (M_{vaporised} + M_{splash}) / V_{cloud}$	35 g/m^3 (110 g/m^3)
Equivalence ratio of mixture in cloud	0.19 (1.3)
Range (after 1400s) to which cloud may hinder escape $R_{escape} = [\, 1/\, 2\pi\, V_{cloud} \,.\, T \,]^{1/2}$	197 m (210 m)
Range to which low level cloud might be ignited $R_{ignition} = [\, 1/\, \pi\, V_{cloud} \,.\, T \,]^{1/2}$	N/A (297 m)

Use of the method for simple risk assessment

There is no risk of a vapour explosion but there will be high concentrations of methanol to a range of around 200m after 1400 s.

Early warning would be of great benefit

Staying put in a toxic refuge would be the safest option in many cases.

What does HSE expect from industry?

- An understanding of the consequences of tank overfilling incidents in calm conditions.
- Inclusion of large vapour cloud scenarios in risk assessments
- Consideration of appropriate risk reduction measures (overflow protection, ROSOVs, gas detection, OB modification, ignition source control etc) to make risks ALARP