A brief history of LNG and natural gas hazard research - what are the remaining challenges?

Geoff Chamberlain,
Waverton Consultancy Ltd
55th UKELG meeting
26 April 2016

There is much to cover in 20 minutes

- LNG source term.
- Dispersion, passive and jet.
- RPT
- Pool formation and fires
- Jet fires
- BLEVEs
- Deflagration and detonation.
- ~~Cold brittle failure~~
- ~~Asphyxiation~~
- ~~Roll over~~

LNG source terms

- Jets – liquid, spray, 2 phase.
- Many models, but little validation. Liquid outflow may persist along long pipes.
- A pool is assumed to form. But pressurised LNG may not ‘rain out’.
- Effect of waves and currents on pool spreading.
- Effect of RPTs.
- Effect of scale.
- Heat transfer rate to LNG.
- Ice formation. Favoured by still, shallow water.
- Water ingress into LNG tanks of ships.
- See HSE RR789.

Summary of largest LNG spill tests

Project	Spill Size, m^3	Rate, m^3/min	Pool radius, m	LFL distance, m
Esso 1972	0.8 - 10.8	9 - 17.5	7-14	400
Maplin 1980	5 – 20	1.5 – 4	10	190
Avocet 1978	4.2 - 4.5	4	6. - 7.2	220
Burro 1980	24 – 39	11.3 - 18.4	5	420
Coyote 1981	8 – 28	14 – 19	NA	310
Falcon 1987	20.6 - 66.4	8.7 - 30.3	NA	380
Phoenix 2011	58 - 198.5	7.3 - 115 (51-802 kg/s)	10.4 - 42	NA

Summary of accident and sabotage scenarios

Scenario	Breach size, m^2	Spill rate, m^3/min
Accidental collision	0.5 - 2	300
Intentional	0.5 - 12	1500

Dispersion – dense gas

- Many models
- CFD – FEM3
- Lagrangian non-linear Puff Model – SCIPUFF
- Shallow-Layer model – TWODEE
- 1D Integral models – SLAB, HEGADAS, DEGADIS, GASTAR.
- Empirical models – based on Gaussian puff/plume models.

- Daish, R.E. Britter, P.F. Linden, S.F. Jagger, and B. Carissimo (2000) “SMEDIS: scientific model evaluation of dense gas dispersion models”, Int J Environment and Pollution Vol. 14 No1-6, 39-51.

Dispersion - jet

- 5kg/s at 3.5 to 7 bar, 25 mm hole, horizontal, no rain out and LFL up to 80 m.

RPT

- Spontaneous, delayed, triggered.

- Spontaneous condition: $0.9 \leq T_w/T_c \leq 1.0$
- Pure CH_4, $T_c \approx -83^oC$, $T_{slt} \approx -106^oC$

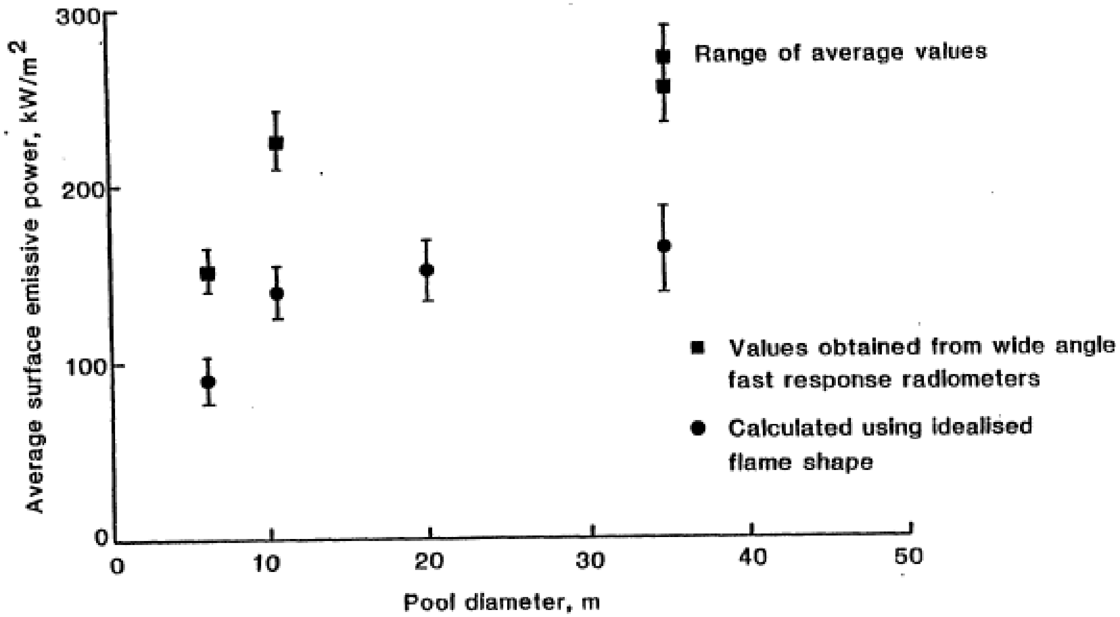
- Delayed RPT, predicted methane < ~40%, but not so for large tests.

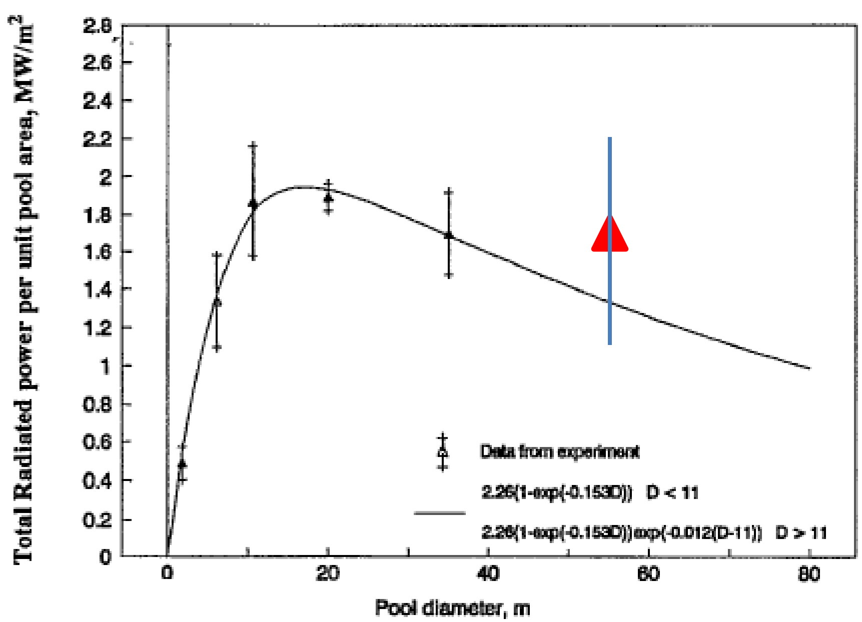
- Triggered RPT, by explosives, waves, momentum of spilled LNG, RPT elsewhere.

- Energy released sufficient to deform but not to breach ship.

- No RPTs with liq. propane or hydrogen.

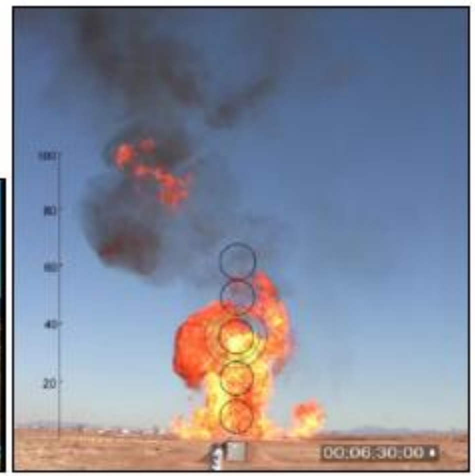
LNG Pool fires - average SEP

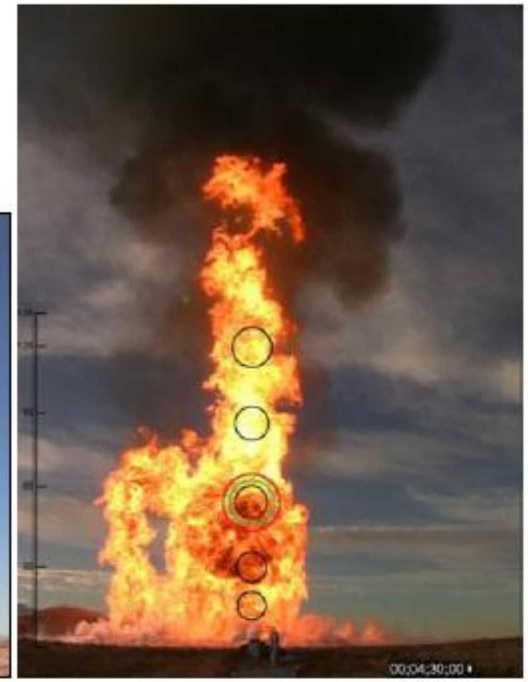




LNG Pool Fires – Phoenix Tests

Burn rate = 0.146 kg/m^2/s





LNG - 10 m SNL 2005

LNG - 21 m SNL 2009

LNG - 83 m SNL 2009

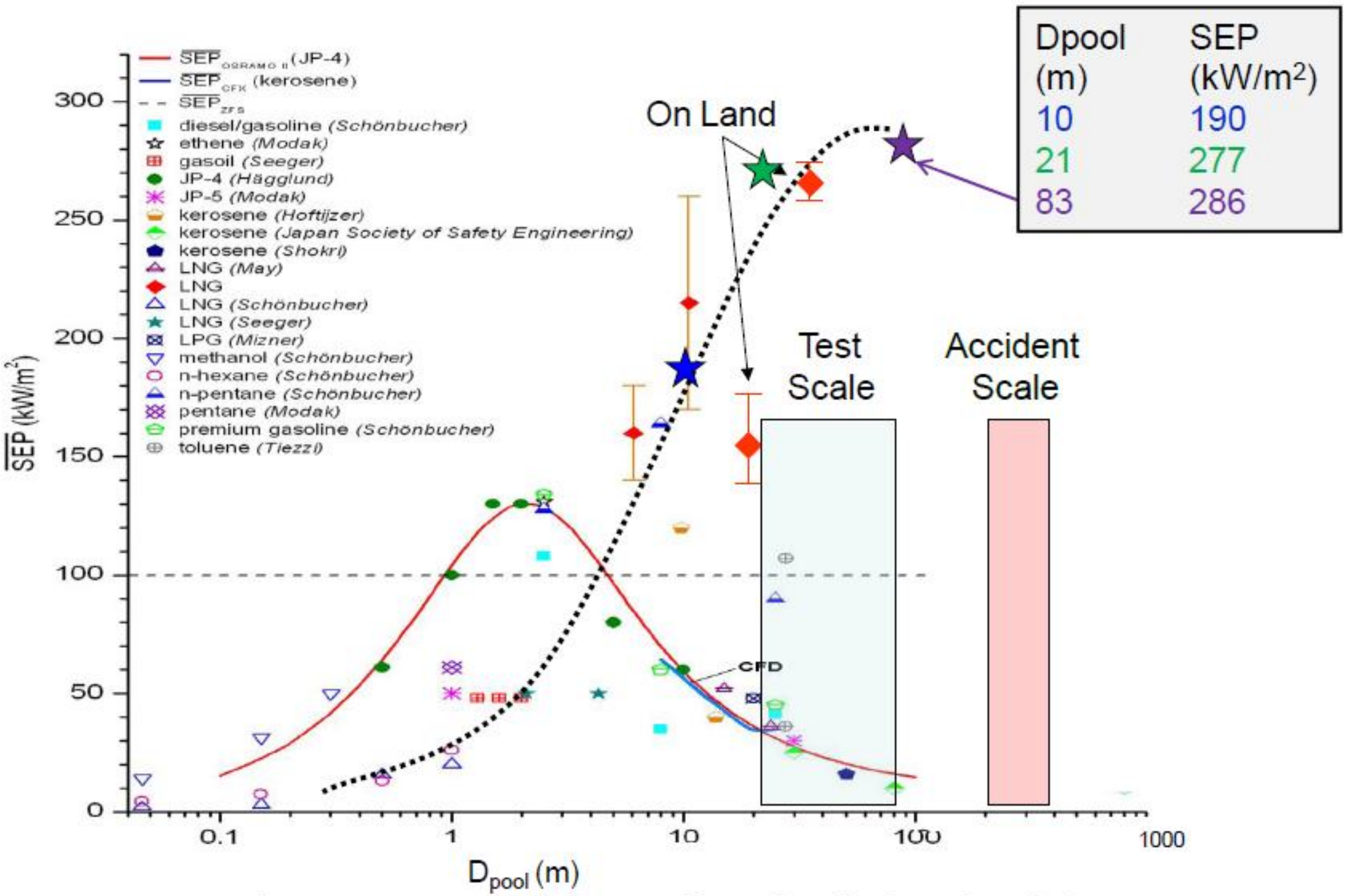


Figure 2 SEP vs. pool diameter for various hydrocarbon fuels.

LNG Pool Fires – Phoenix Tests

- 50.8 kg/s average discharge rate.
  - Equiv diameter 20.7 m
  - Average length 70 m
  - Average height 34 m
  - Average F factor 0.21±0.4
- 802 kg/s average discharge rate.
  - Equiv diameter 83 m
  - Average length 146 m
  - Average width 15 m above pool, 56 m
  - Average F factor 0.24±0.8
  - Flame did not attach to pool edges.

LNG Pool Fires – Phoenix Tests

Ice and hydrate formation shown after the test.

LNG Pool Fires

- Large spills on shallow, still water create ice and hydrates. Not so important for deep, wavy water.
- Fire does not attach to edges of pool.
- Fire will attach to structures in the water, e.g. ship, harbour wall.
- No evidence of smoke shielding, hence high SEP.

LNG jet fires

- 5 kg/s LNG horizontal release, jet fire 25 m.
- This is similar to a 5 kg/s natural gas flame.
- No rain out.

Natural Gas Jet Fires

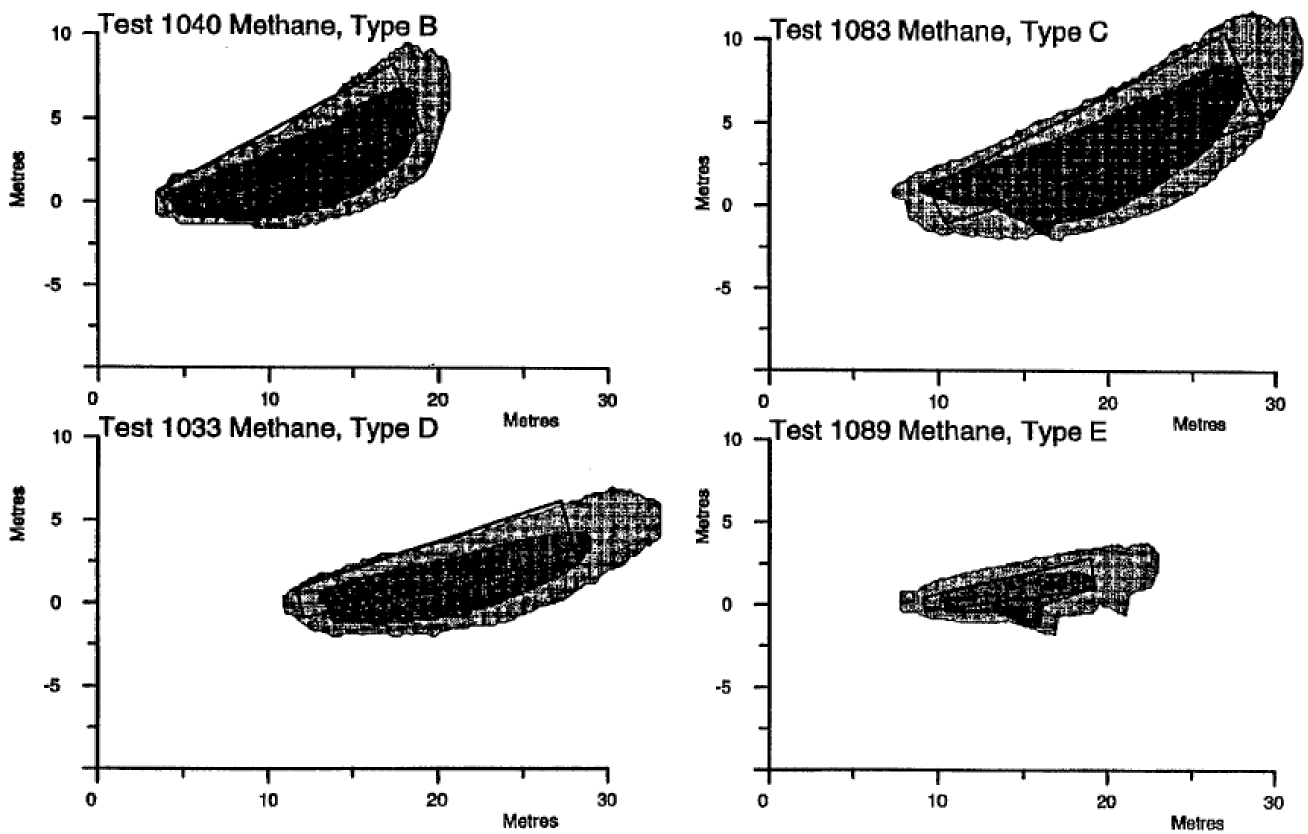
- Many tests in the 1 – 70 kg/s range,
- Flame lengths 10 – 70 m,
- F factors around 0.12 - 0.25
- SEP ≈ 300 kW/m^2

Natural Gas Jet Fires – effect of scale?

- Consider a NG pipeline full bore break.
- What is the flow rate and time dependence?
- What is the flame size and shape?
- Effect of crater for buried pipelines?

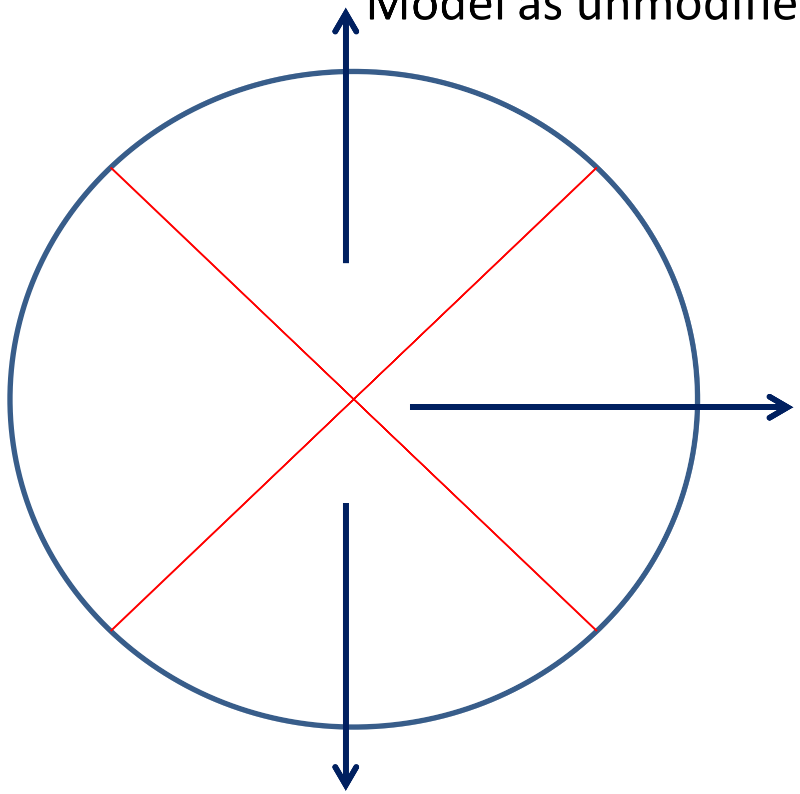
Natural Gas Jet Fires at Large Scale

- The flame becomes buoyancy dominated about halfway along its trajectory. (Ricou and Spalding 1961).

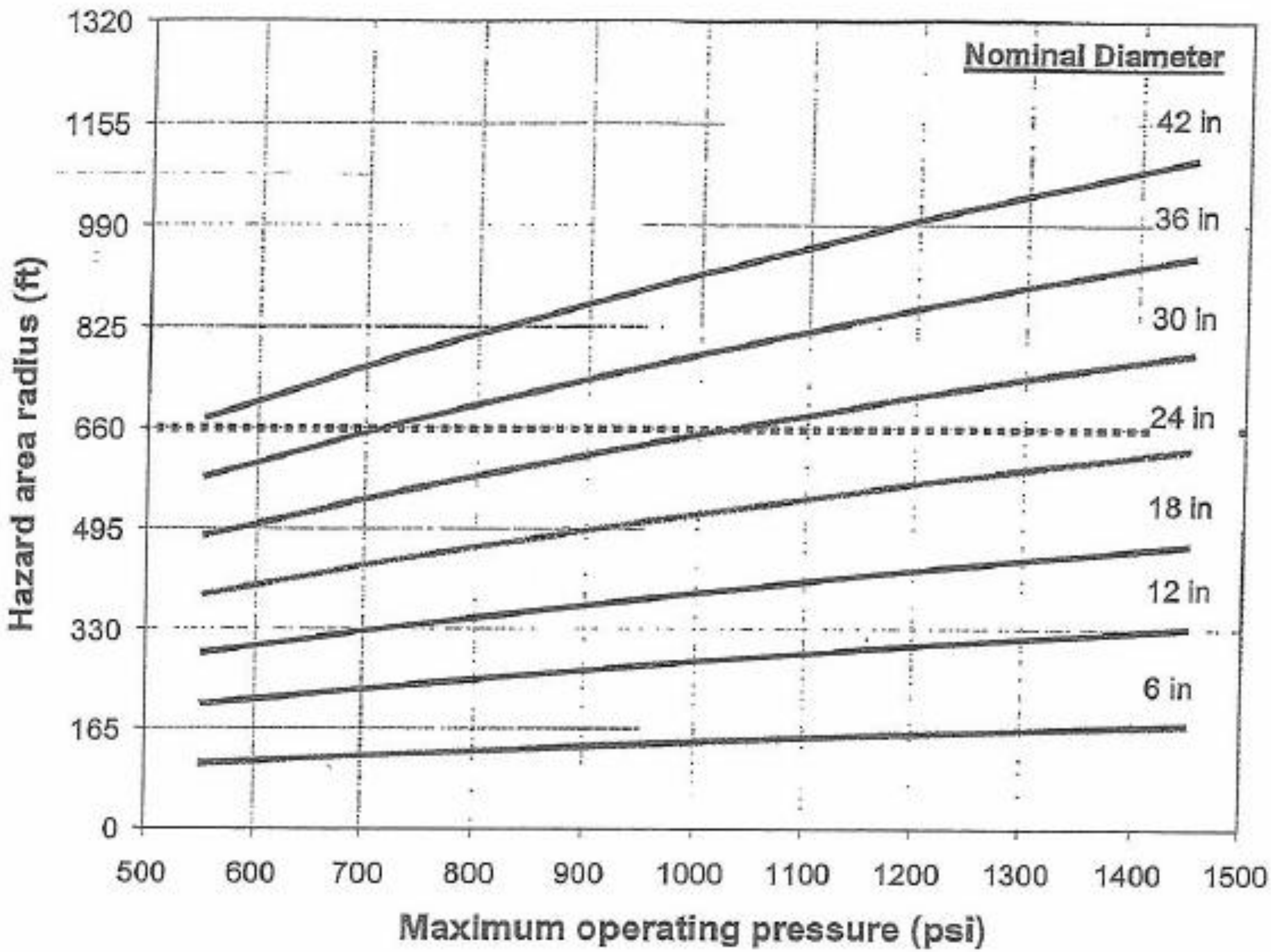


Buried Natural Gas Pipelines

- Craters – OGP434-7, 2010



GRI of Canada proposed hazard radii for full bore natural gas pipeline ruptures.



LNG BLEVEs

- LNG stored at atm. P will not BLEVE.
- 2 accidents both in Spain involving pressurised storage in a road tanker.
- 2002, tanker overturned, 20 min to BLEVE.
- 56 m^3, design P. 7 bar, 4-6 mm thick SS single wall, 85% full.
- Failure attributed to liquid expansion.

LNG BLEVE accident 2011

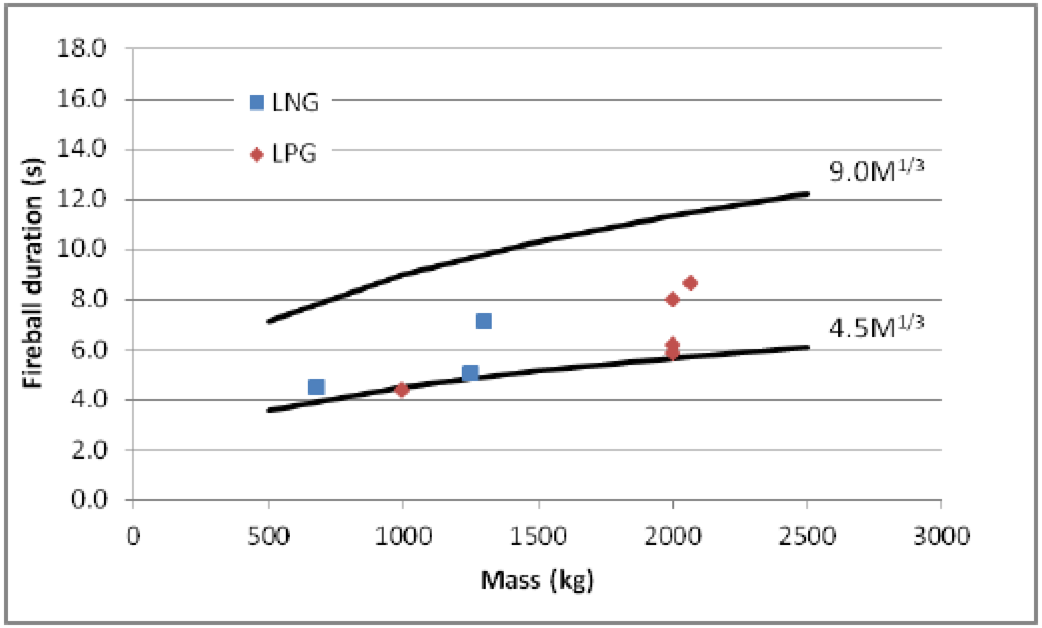
- Same design as before.
- BLEVE in 71 mins. Caused by failure of vessel wall by flame impingement.
- 150 m diameter fireball.

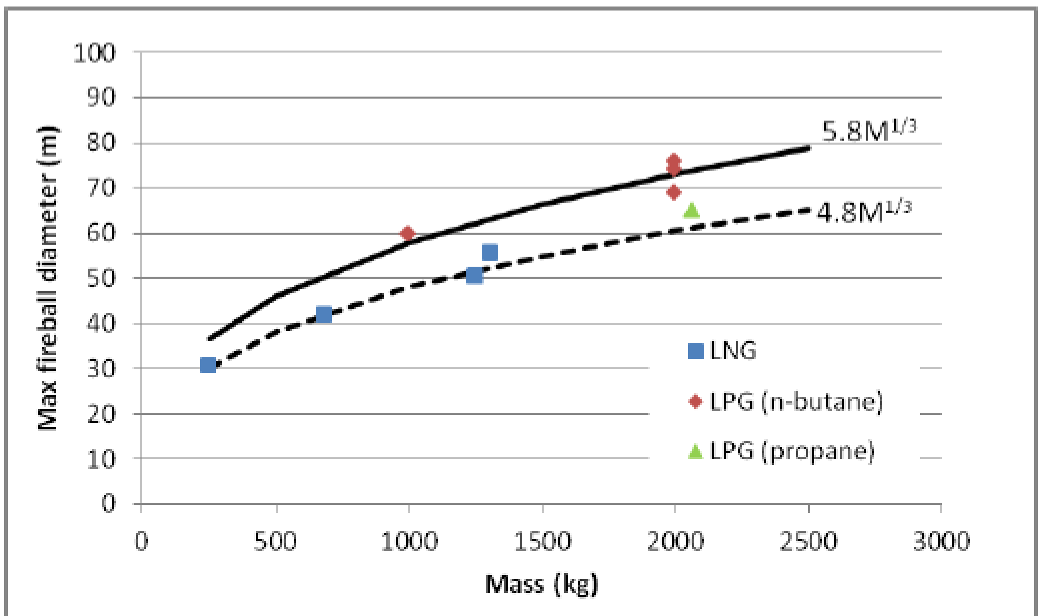
LNG BLEVEs – Shell Tests

- 5 m^3 vessel, 6.1-13.6 barg, vessel rupture on top surface by explosive charge.

37% fill, 13 barg | 67% fill, 6.1 barg | 69% fill, 13.6 barg

LNG BLEVES – fireball duration and diameter





LNG BLEVES – Fireball Surface Emissive Power

Experiment #	SEP Range (kW m^{-2})	SEP 3 s after rupture (kW m^{-2})
2	450-650	540
3	250-350	290
4	400-550	475

SEP higher than for LPG BLEVEs, (less smoke obscuration).

LNG BLEVEs – Shell work

- Empirical models based on LPG are conservative, but not overly so.
- Thermal radiation levels are slightly less than LPG BLEVEs.
- Overpressure is also slightly less owing to lower expansion velocities.

Natural Gas Deflagrations and Detonations

- Very few major explosions with natural gas/methane. Mainly from pipeline failures.
- But many domestic incidents. Confinement rather than congestion, seems to be a key player.

Natural Gas Deflagrations and Detonations

- Many experiments performed.
- Damaging deflagrations when methane is confined.
- Congestion must be severe for damaging blast.
  - 45 m, 40% blockage, 1.5 m spacing, steady flame of 80 m/s.
- Jet ignition into congestion, can sustain high flame speeds (1000 m/s → 500 m/s), but not detonation.

Methane/Natural Gas Detonations

- Methane, ambient, stoichiometric in air
  - Initiation energy 22 kg tetryl, natural gas 3.5 kg.
  - Cell size 190-350 mm.
  - Critical explosion diameter 4 m.
  - Bradley et al. (2008) theorise that no DDT is possible in ducts (assumed no reflected, transverse shock waves).
- BUT, experiments carried out in the GETF (73m long, 1.05m wide duct with baffles) with natural gas show:
  - Sustained detonations 8-10.8% NG/air.
  - $L_{ddt}/D \approx 16\text{-}23$
  - Cell size λ 27-50 cm $\pm$ 30%
  - $D/\lambda > 1$
  - $L_{ddt}/\lambda > 5\text{-}7$

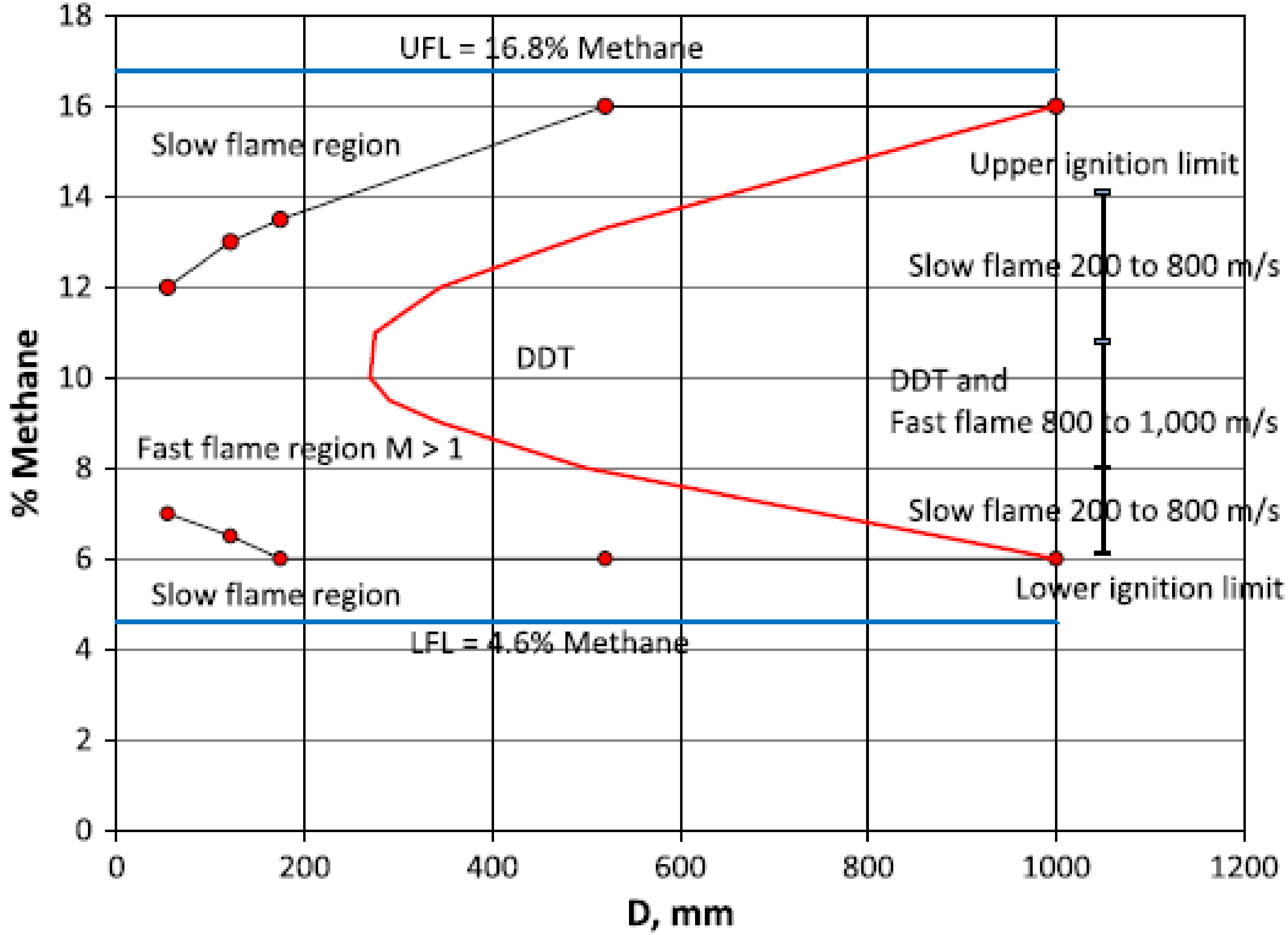


Fig. 13. Slow flame, fast flame, and DDT limits as function of composition and tube diameter at normal conditions $p = 1$ bar and $T = 293$ K (after Kuznetsov et al. [27]). Natural gas–air data from these tests added at $D = 1050$ mm.

Natural Gas Deflagrations and Detonations – BFETS JIP 1995

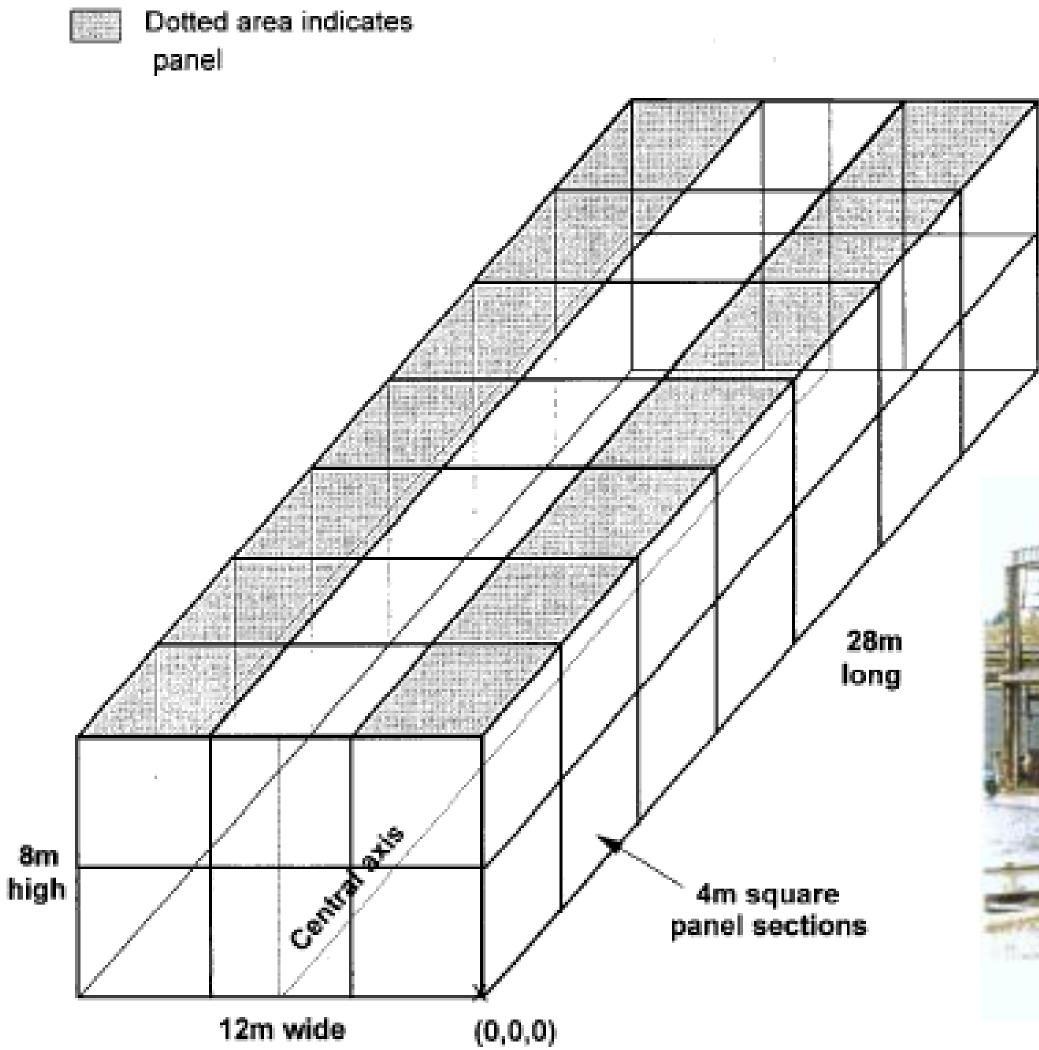


Figure 3.4(a): View of Equipment Layout 02 from North East

Natural Gas Deflagrations and Detonations – BFETS JIP 1995

- With ignition at one open end:
- Maximum overpressures up to 65 bar. Duration < 1 ms.
- Several tests, overpressures 13 to 22 bar at end of rig. Durations <1 ms.
- DDT?

Summary 1 – LNG/natural gas knowns

- Dispersion to LFL if source term is known.
- RPT overpressures.
- LNG pool fires up to 60 m diameter.
- LNG and natural gas jet fires up to 100 kg/s.
- LNG BLEVES.
- Deflagrations, confined and congested.

Summary 2 – LNG/Natural gas Challenges

- Source terms.
- Effect of waves, water depth, RPT, wind on pool and fire size.
- Scaling :
  - pool sizes,
  - pool fire size,
  - Natural gas jet fires from full bore pipe ruptures,
  - Deflagration to natural gas/methane detonation in ducts and congested plant.