Review of Recent LNG Research at HSL and Possible Future R&D Topics

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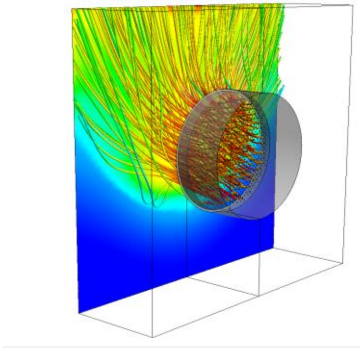
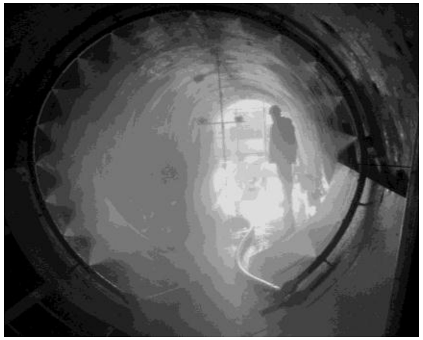
Outline

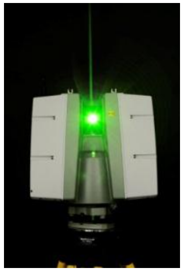
- Introduction to HSL
- Recent research on LNG hazards
  - LNG pool fires
  - Review of vapor cloud explosion incidents
  - LNG spills
- Potential LNG R&D topics

Introduction to HSL

- Directorate of UK Health and Safety Executive (HSE)
- Multi-disciplinary laboratory
  - Fire and process safety
  - Computational modeling
  - Exposure control
  - Toxicology etc.
- Approx. 400 staff
- 550 acre test site
  - Fire galleries and burn hall
  - Largest impact track in EU
  - Anechoic chamber etc.



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LNG Pool Fires: Background

- Phoenix large-scale LNG pool fire experiments conducted by Sandia National Laboratories in 2009
- Two tests involved ignited LNG spills on water
  - 21 m diameter LNG pool
  - 83 m diameter LNG pool
- 83 m pool - unexpected results
  - Fire did not extend across LNG pool surface
  - Fire significantly higher than predicted
  - Very little smoke

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LNG Pool Fires: Background

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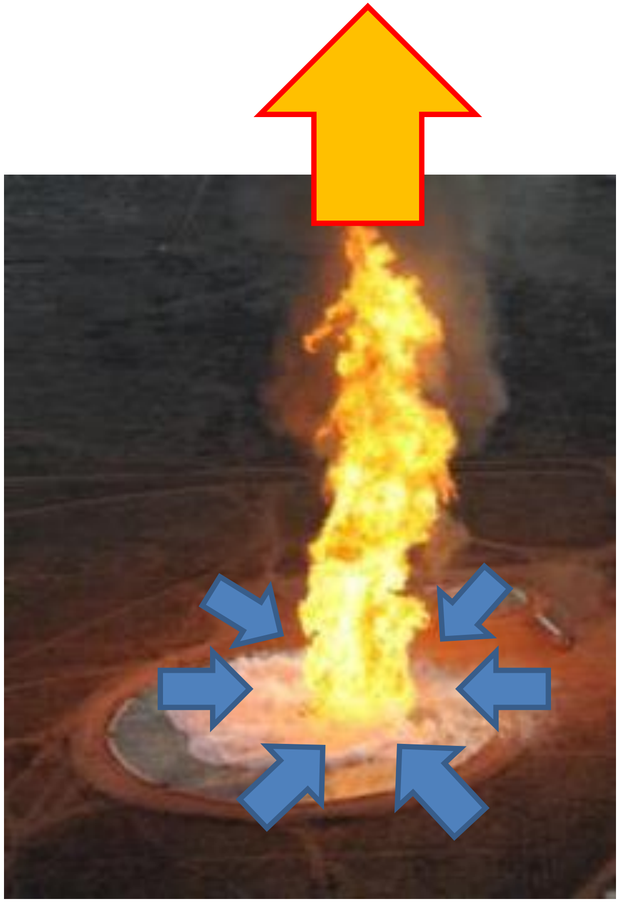
- Hypothesis (proposed by Shell Research Ltd)
  - Strong thermal updraft from large fire
  - High speed inwards flow of air/vapor into the base of the fire
  - Flames unable to spread outwards from central ignition location
- Video analysis
  - 2-3 m/s flow into base of fire
  - Sufficient to arrest flame spread?
- Investigation at HSL funded by Shell Research Ltd
  - CFD modeling
  - Flame spread experiments



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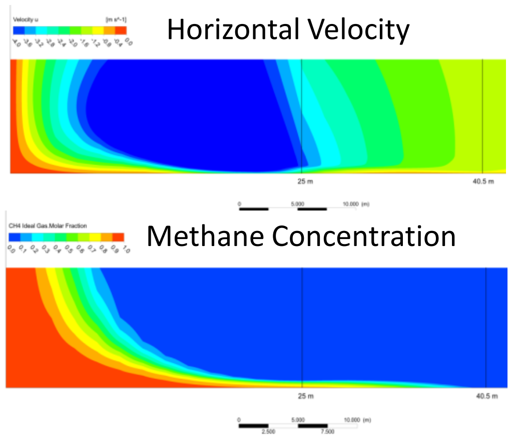
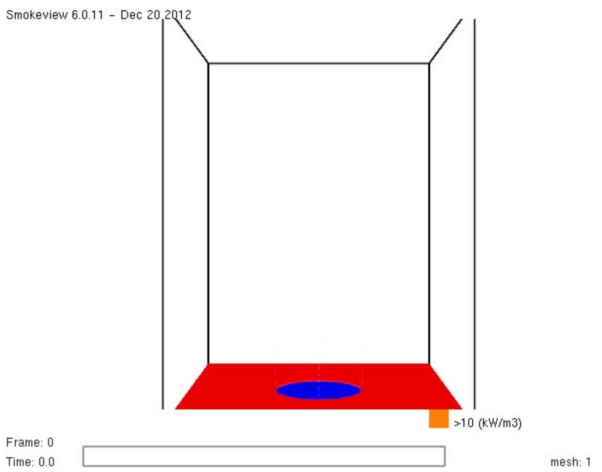
LNG Pool Fires: Modeling

- CFD modeling aim
  - To predict the speed of air/vapor entrained into the base of the fire in the Phoenix test
- CFD models tested
  - Ansys-CFX: volumetric heat source
  - FDS: combustion model
- Conclusion
  - Speed of entrained air/vapor flow

    Ansys-CFX = 3.7 m/s

    FDS = 3.2 m/s
  - Phoenix test provides only one data point
  - Mid-scale experiments proposed





LNG Pool Fires: Experiments

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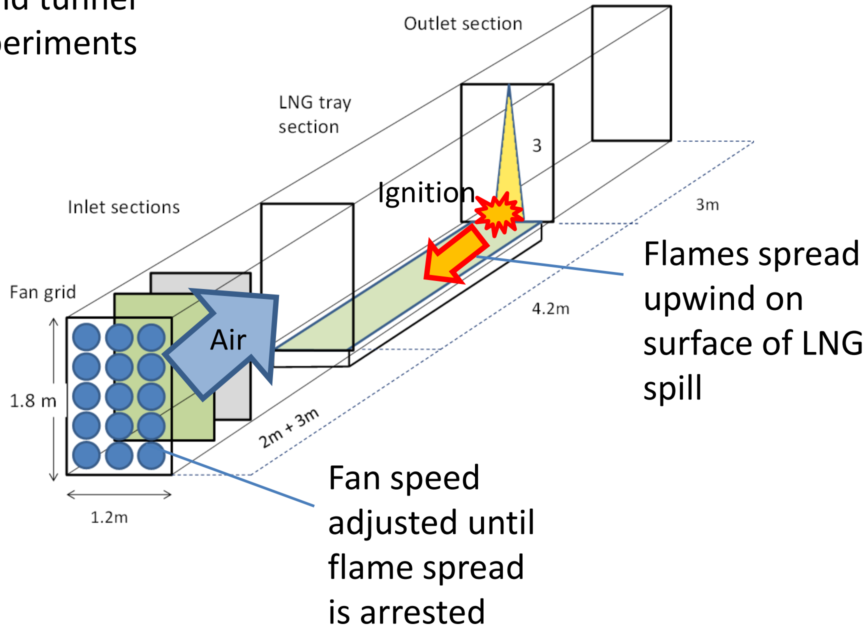
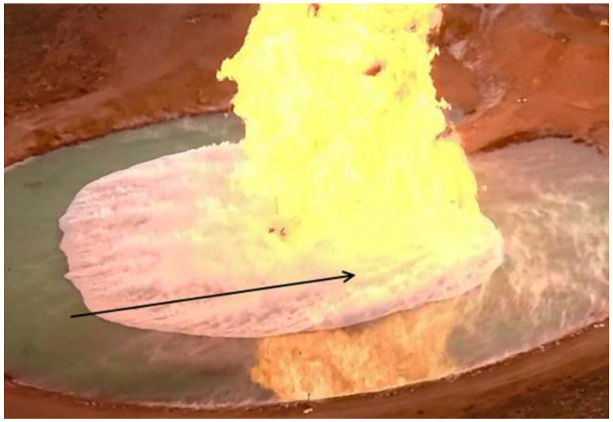
Wind tunnel experiments



- Main findings
  - Flame stabilised when air flows were 2.8 and 3.2 m/s
  - Flame progressed further along low speed areas adjacent to walls
  - Stabilised conditions equated to turbulent flame speed of 2 m/s

LNG Pool Fires: Conclusions

- Inwards flow of air/vapor exceeds 2 m/s when pool diameter > 20 m
- Implies maximum LNG pool fire diameter on open water is 20 m
  - BUT … obstacles, such as the loading boom in Phoenix tests, would allow the fire to spread > 20 m
  - Wind speeds > 2 m/s will move the pool fire towards the downwind edge of the spill area
- Main finding: it may be overly simplistic to assume whole pool spill area will be on fire
  - Thermal radiation may be lower on upwind side and higher on downwind side than is currently predicted



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LNG Pool Fires

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- Further information

  - Atkinson G., Betteridge S., Hall J., Hoyes J. and Gant S.E. "Experimental determination of the rate of flame spread across LNG pools", IChemE Hazards 26 Conference, Edinburgh, UK, 24-26 May 2016

  - Betteridge, S., Hoyes, J., Gant S.E. and Ivings, M. "Consequence Modelling of Large LNG Pool Fires on Water", IChemE Hazards 24 Conference, Edinburgh, UK, 7-9 May 2014

  - Kelsey A., Gant S.E., McNally K., and Betteridge S. "Application of global sensitivity analysis to FDS simulations of large LNG fire plumes", IChemE Hazards 24 Conference, Edinburgh, UK, 7-9 May 2014

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Review of Vapor Cloud Explosions (VCEs)

- Aim: to review historical severe unconfined VCE incidents
  - Characterise the events and identify common factors
  - Improve our understanding of vapor 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

Buncefield (2005)

Jaipur (2009)

Puerto Rico (2009)

Amuay (2012)

Review of VCEs: Main findings

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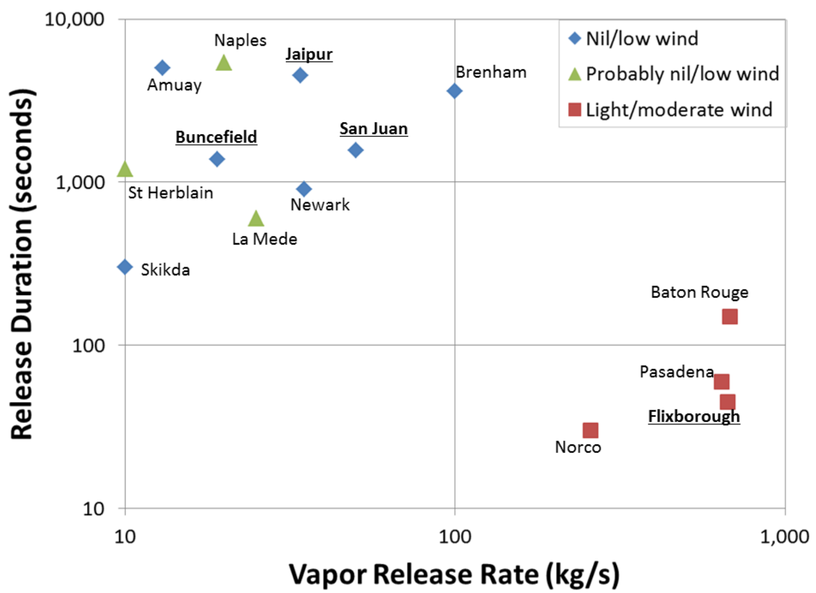
- Occurrence of VCE incidents
  - No unconfined VCE incidents with methane, only with higher hydrocarbons
  - Most VCE incidents involved vapor clouds that spread in all directions around source, indicating the events took place in very low wind speeds
  - Only a few incidents showed burned area extending solely in the downwind direction

- VCE consequences
  - Ignition of large flammable vapor clouds produced high over-pressures and extensive damage in nearly all cases, even in open unconfined areas
  - Only one flash fire incident: Donnellsen (Iowa) LPG pipeline, probably due to rich vapor concentrations



Review of VCEs: Conclusions

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- Possible explanation for trends in occurrence of VCE incidents
  - Nil/low wind speeds occur less frequently than windy conditions…
  - … but small leaks are much more likely than catastrophic failures
  - Balance of probabilities: more incidents occurred in nil/low wind speeds
  - Incident sites also lacked working gas detection/shutoff systems
  - Limited ignition sources (a large cloud could develop before igniting)

- Implications
  - Importance of gas detection/shutoff systems and other layers of protection
  - Significance of small sustained releases in nil/low wind speeds
  - Proposed basis for risk assessment: ignition of a large cloud with a concentration well within the flammable range will produce a severe explosion

- Other issues
  - Lack of consensus among experts on explosion mechanism: deflagration/detonation

Review of VCEs

- Further information

  – Atkinson G., Cowpe E., Halliday J. and Painter D. (2016) “A historical review of vapour cloud explosions”, Mary Kay O’Connor Process Safety Symposium, Texas A&M, College Station, Texas, 25-27 October 2016

  – Atkinson G., Hall J. and McGillivray A (2016) “Review of vapor cloud explosion incidents”, Health and Safety Laboratory Report MH/15/80 http://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=111

  – Atkinson G. (2016) “Vapor Cloud Explosion (VCE) Historical Review”, PHMSA Public Workshop on Liquefied Natural Gas (LNG) Regulations, Washington D.C., 19 May 2016, http://primis.phmsa.dot.gov/meetings/MtgHome.mtg?mtg=111

  – Multimedia packages available from PHMSA for Buncefield, Jaipur, Flixborough and San Juan incidents

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LNG Spills: Aims

- Improve understanding of the physics of LNG spills on land
- Conduct experiments to provide data for validating:
  - Liquid spread models (non-volatile)
  - Models of spreading vaporising pools
- Validate HSE's models of spreading vaporising pools (GASP)

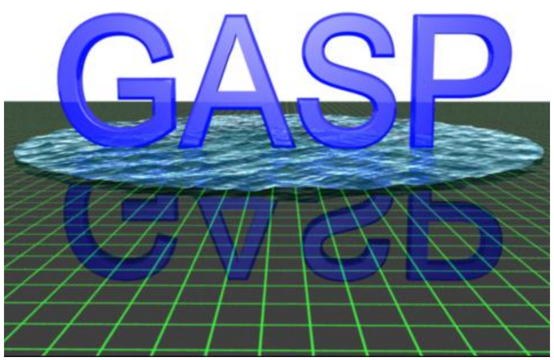
LNG Spills: Experiments

- Three fluids: water, liquid nitrogen, LNG
- Instantaneous and continuous releases
  - Instantaneous volumes: 10 – 30 liters
  - Aspect ratio of cylinder: 1:1 – 5:1
- Wet and dry concrete test pad (10 × 10 m)
- 33 configurations with up to 3 repeats

- Measurements
  - Two rakes of 16 thermocouples above surface to measure spreading rate
  - 6 thermocouples embedded in the concrete at depths of 10 – 30 mm
  - 3 thermocouples within release cylinder
  - Video

LNG Spills: Progress

- Analyses of experimental data nearing completion
- GASP modeling nearing completion
- SPLOT liquid spill model sensitivity tests ongoing
- Completion date: March 2017



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Potential LNG R&D Topics

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- LNG tank design and consequence modeling
  - Jet fire impingement tests

- LNG Spills
  - Sloping bunds, impoundments, gravel pits
  - Use of floating insulating blocks to reduce LNG vaporization rate
  - Vapor fences and water sprays/curtains for vapor dilution

- Vapor Cloud Explosions
  - Large-scale tests:
    - 100m+ radius vapor fence filled with flammable vapor from LPG fountain
    - Study effect of elements that might trigger transition to severe explosion (sheds, pipework etc.)
    - Also useful for LPG source terms and low wind dispersion - both urgently needed
  - Small-scale tests:
    - Detonation tests on columnar objects (struts, small pipes, etc.)
    - Fundamental studies of the fluid mechanics of flow driven by a localized explosion - boundary layer detachment and roll up, lofting of particles etc.

Acknowledgements

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