Investigation of Cargo Tank Vent Fires on the GP3 FPSO.

Part 1: Identification of Ignition Mechanisms and Analysis of Material Ejected from the Flare

Part 2: Analysis of Vapour Dispersion

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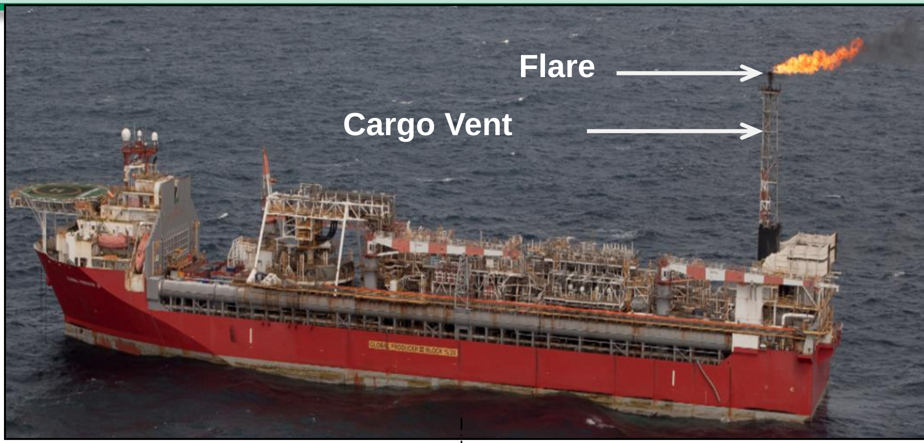
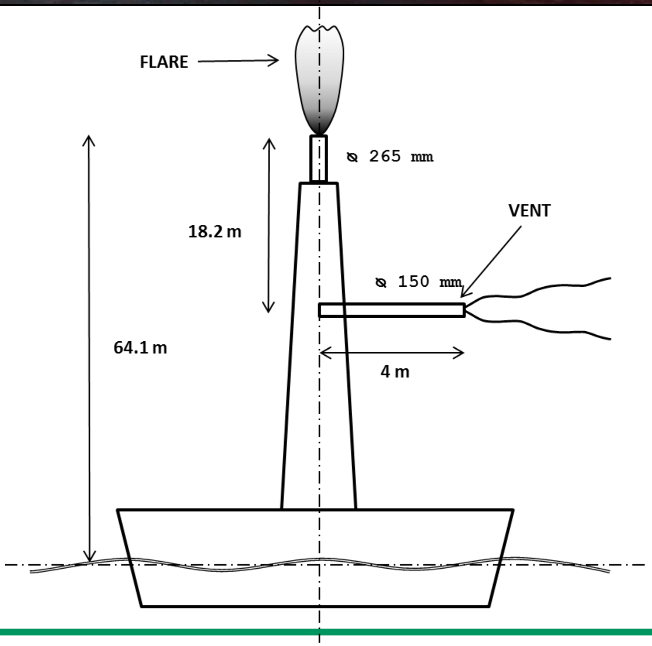
Hazards 26 Conference, 24-26 May 2016

GP3 Operation

- Global Producer III (GP3)
  - FPSO owned and operated by Maersk Oil UK
  - Dumbarton, Lochranza and Balloch fields in UKCS
- Crude capacity of 500000 bbl
  - Approx. 2-3 week loading cycle
- Lighter hydrocarbons vaporise
  - Cargo hold ~ 40 °C to minimise wax formation
- Venting occurs when cargo tank pressure reaches 600 mmH_2O - at 400 mmH_2O the vent closes
- Composition changes during loading cycle
  - initially inerted tending toward 100% flammable
- Venting frequency and duration varies through loading cycle.
- Vent is a 150mm pipe located part way up of the flare tower, 18m below the flare tip





GP3 Incidents

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- 4 ignitions of the cargo vent over the past 5 years
- A fire occurred at the GP3 cargo vent outlet in April 2010
  - Fire occurred in calm and stable atmospheric conditions
  - Ignition source unknown
  - Vent modified and mitigation measures installed
- Three further fires occurred in 2013 and 2015

Incident	Date	Wind Speed (knots)	Wind Speed (m/s)	Wind Direction (deg)
1	April 2010	Unrecorded	Unrecorded	Unrecorded
2	February 2013	4	2.0	285
3	April 2013	3	1.5	261
4	May 2015	9 (unconfirmed)	4.5	280

HSL Investigation of Ignition Mechanisms

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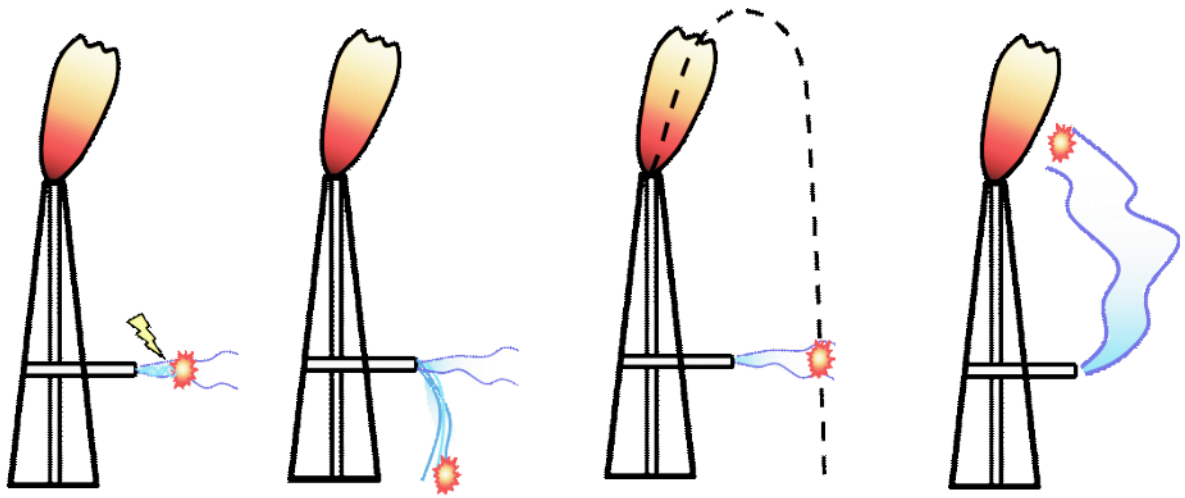
- In June 2013, Maersk commissioned HSL to assess the cargo vent dispersion behaviour and identify potential ignition sources
- Background analysis & reviewed previous CFD modelling of ignition incidents – identified that ….

- 6 feasible routes to ignition
- 2 were discounted (equipment spark and radiation)
- 4 remaining ignition mechanisms were assessed further:



Ignition Mechanisms

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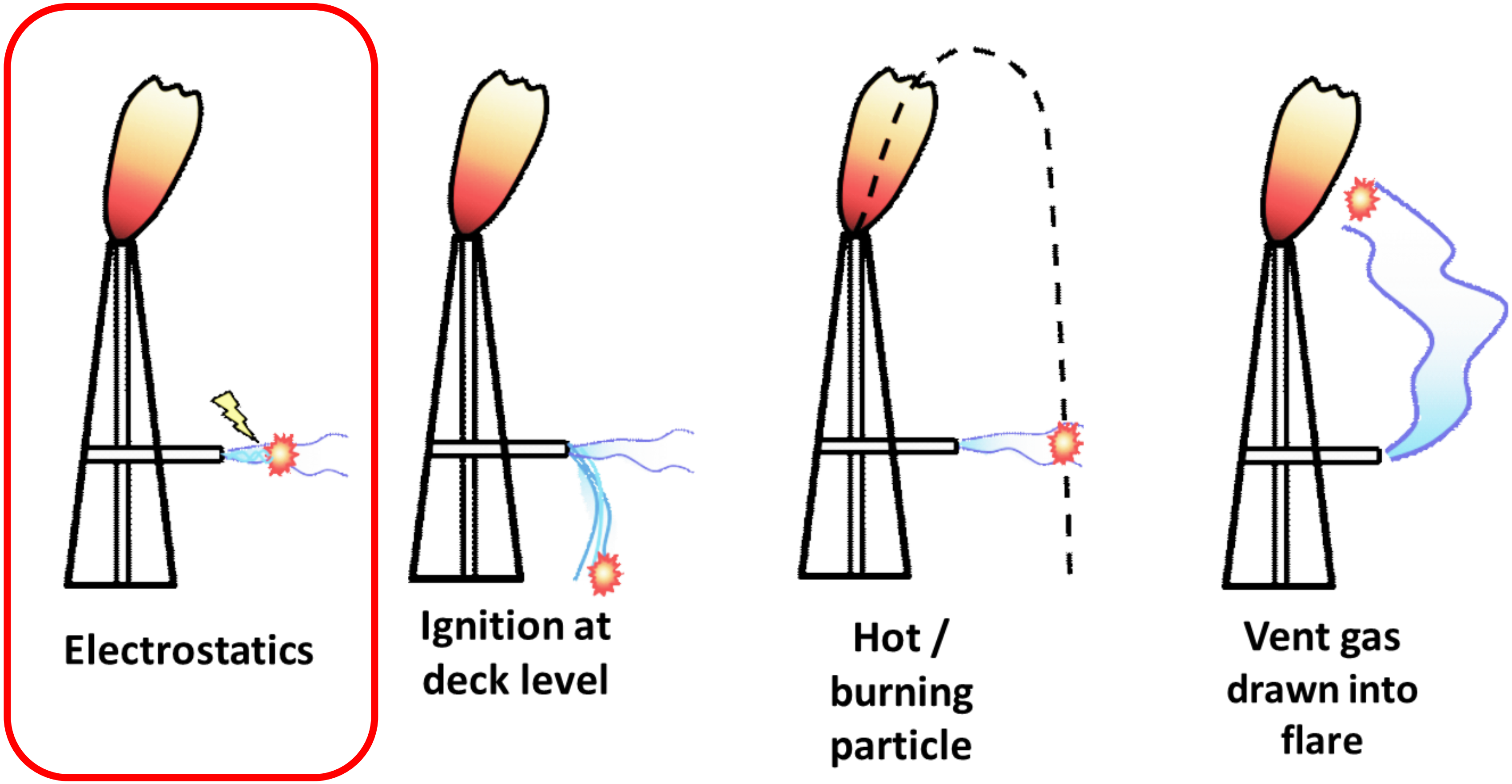
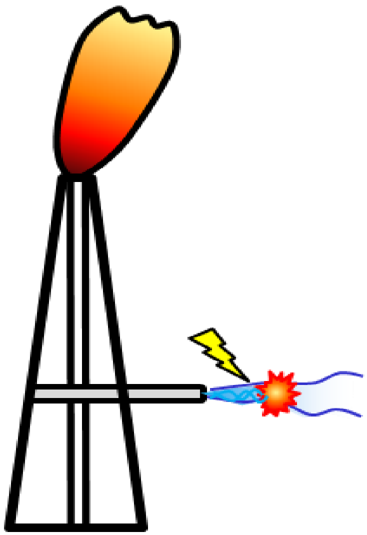


Electrostatic Ignition

Postulated Ignition Mechanism

- Evidence of liquid discharge from the vent line
- Electrical discharge between multiphase flow providing ignition source



Approach

- Review
  - Previous report on electrostatic ignition potential on GP3
  - Comprehensive listing of mechanisms.
  - Lack of "input data" limited the assessment
- Assessment
  - GP3 fluid samples
  - Methods and data for assessment (order of magnitude) of electrostatic ignition sources via calculations

Electrostatic Ignition Source Review

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Spark discharge

- Not if equipment is earthed
- Possible from charged slug of conducting liquid
- Measurements indicate it is insulating

Propagating brush discharges

- Can be very energetic
- Depends upon area and thickness of insulating layer and degree of charging
- Insufficient insulation material present

Brush discharge

- from electrically insulating item of equipment
- No large insulators in area
- from slug of charged insulating liquid
- No data available
- On ship testing could be hazardous
- Cannot be ruled out

Corona discharges

- Unable to ignite alkanes

Lightning-type discharges from charged droplet clouds

- Not likely even for worst-case scenario
- Insufficient charged cloud

Ignition Mechanisms

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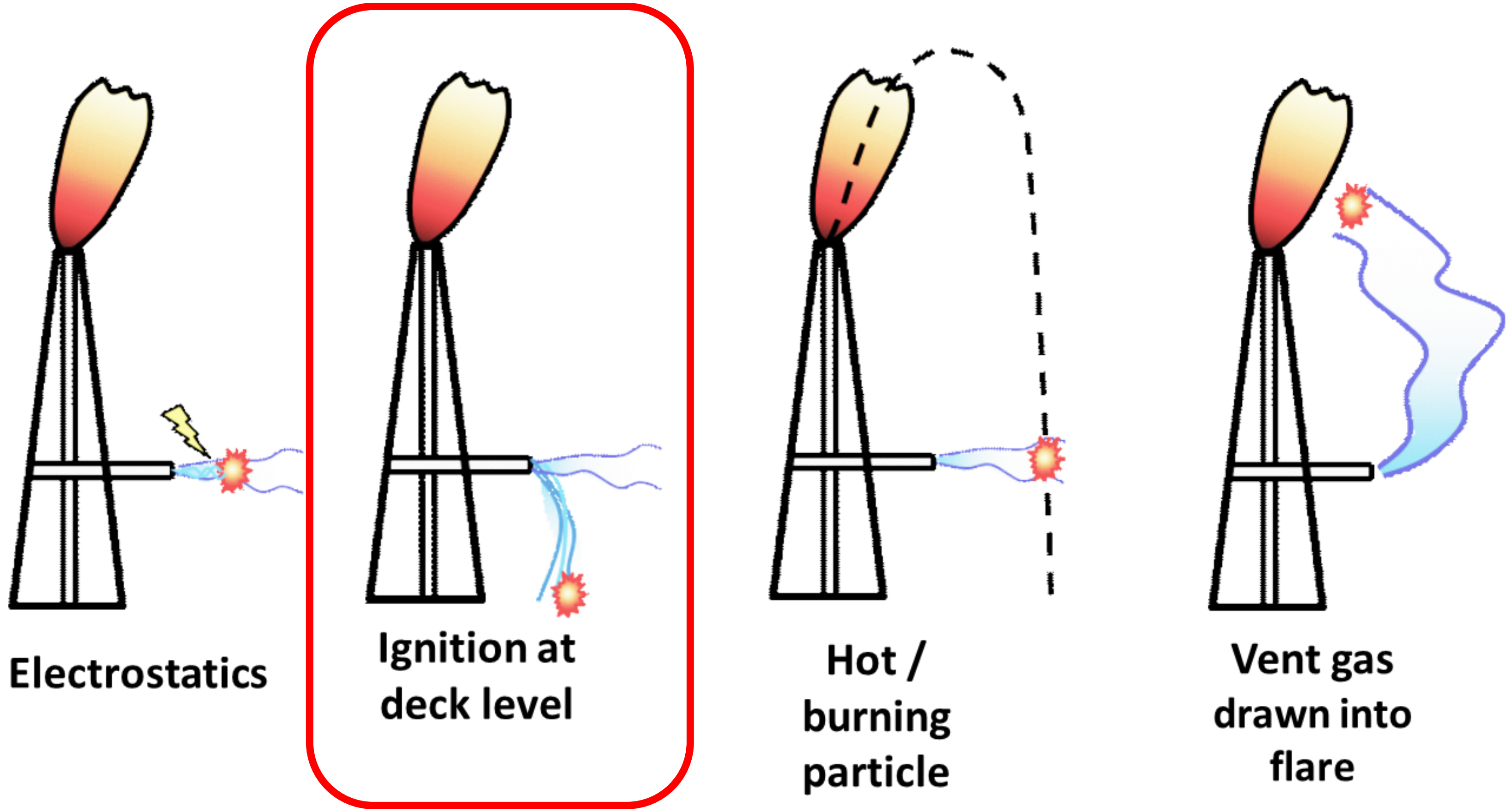

Ignition at Deck Level

Postulated Ignition Mechanism

- Evidence of liquid discharge from the vent line
- Hot surfaces vaporise /ignite rain out hydrocarbons
- Flame burns back to the vent through the rainout droplets

Approach

- Analysis of vent flow and composition of condensed liquids
- CFD simulations of rainout examined the effect of droplet size, wind direction and wind speed

Ignition at Deck Level

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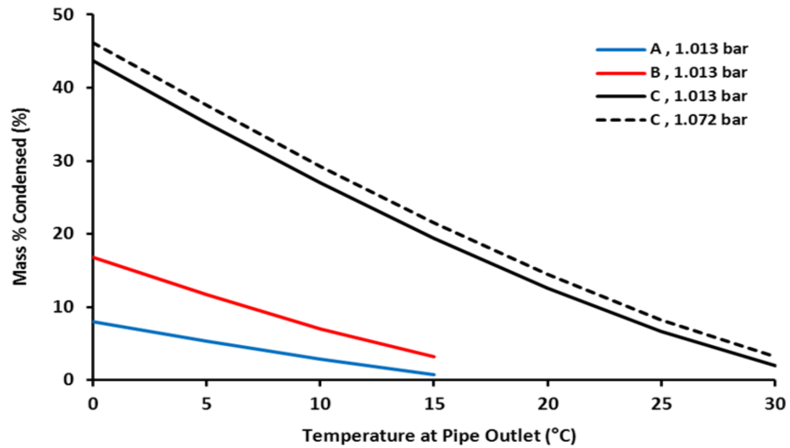

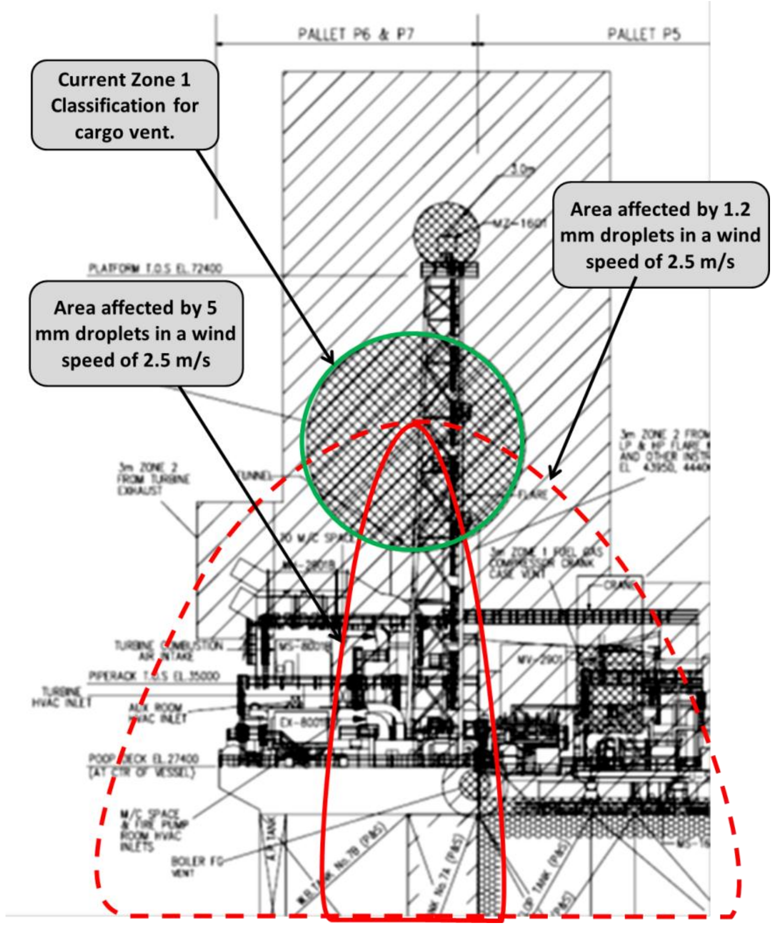

- Warm saturated vapour could condense within vent pipe
- Wetted area increased by smaller droplets and/or higher wind speeds
- Rainout could occur onto hot diesel engine exhausts and turbine heat recovery units

Ignition at Deck Level

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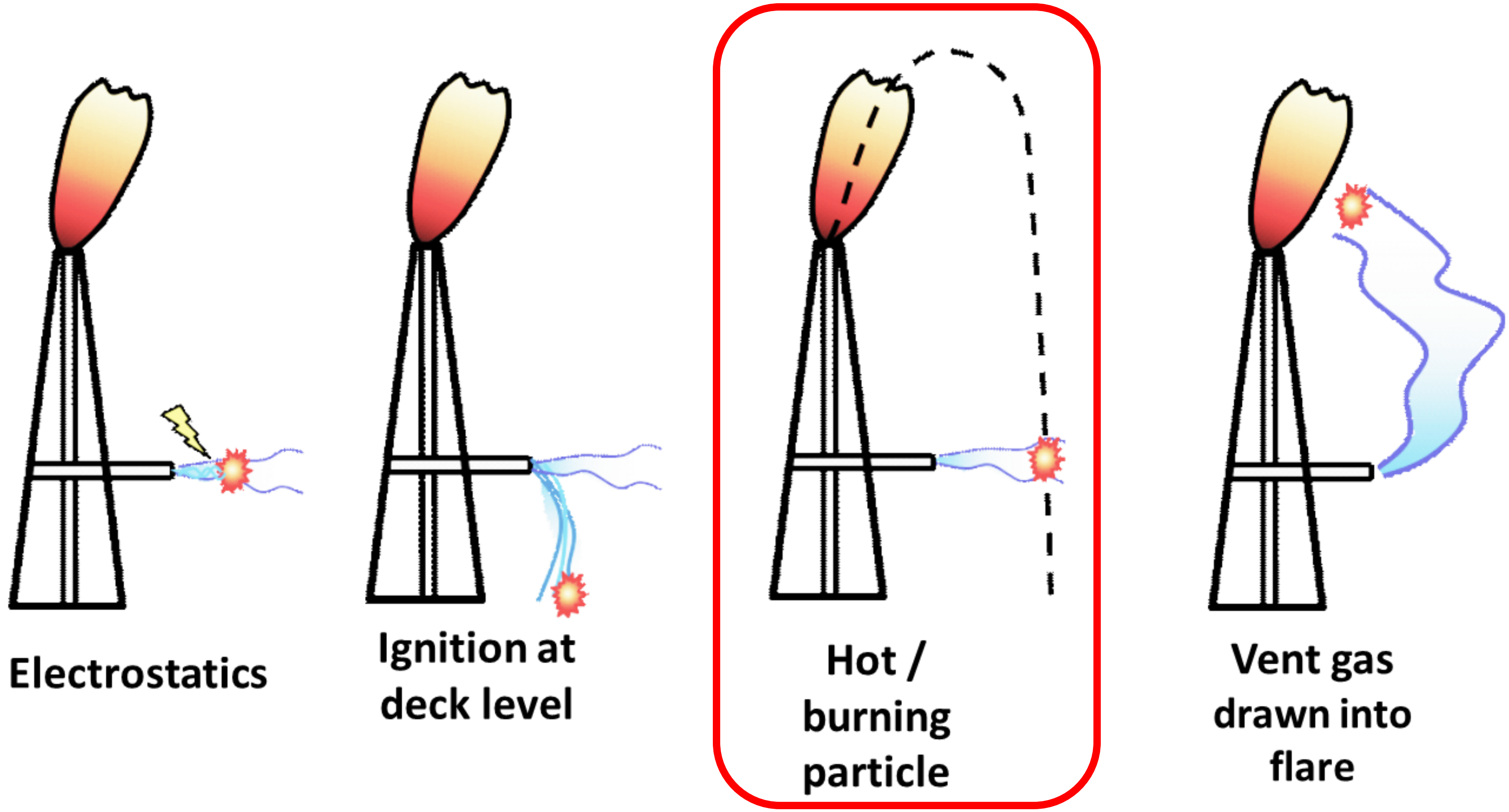
Progress

- Cargo vent pipe was insulated and trace heated in 2014
- Subsequent analysis showed that warm vapour mixed with air will not condense or rainout
- No further reports from GP3 of liquid rainout from the cargo vent
- Further ignition incident took place in 2015

Conclusion

- Hazard has been removed
- Liquid rainout does not explain all of the ignition incidents.

Ignition Mechanisms



Hot / Burning Particle

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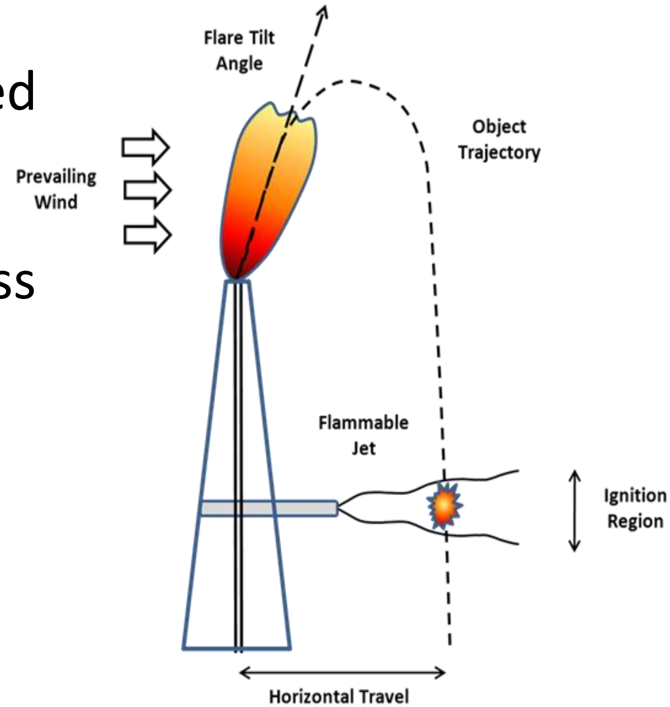
Postulated Ignition Mechanism

- Combustible particle (liquid or solid) is ejected through, and ignited by, the flare
- Prevailing conditions allow the particle to pass through the flammable region from the dispersing cargo vent
- The particle has sufficient heat to ignite the flammable mixture



Approach

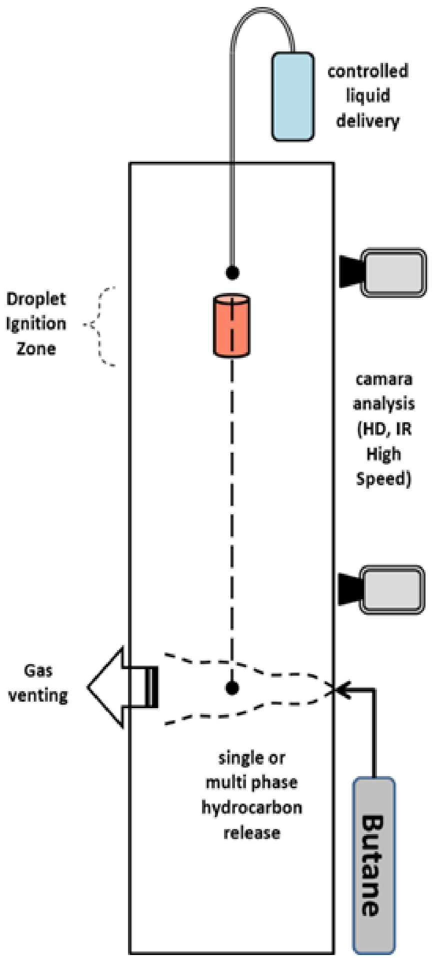
- Theoretical analysis of feasibility
- Experimental tests to answer any uncertainties

Hot / Burning Particle

- Vague evidence liquid / solids falling from the flare
  - Oil deposits near base of flare tower
  - Damage to flare tip
- Theoretical analysis showed
  - Could fall through the flammable region
  - Could provide sufficient energy (simple model)
- Uncertainties:
  - material composition; droplet ignition / combustion,
  - liquid break-up during free fall
  - Energy transfer – cross flow, convection
- Proposed experiments conducted to address the uncertainties

Hot or Burning Particles: Experimental

- Assess the combustion / extinction behaviour of liquid droplets during free fall (up to 8m)
  - Investigate two phase mixture ignition
  - Repeat investigations with solid particles of varying size
- Simulated vent release
  - Butane
  - Match GP3 release velocity
- Heptane droplets
- Solids metal cubes
- Other possible material
- Identified ignition response
  1. No ignition
  2. Ignition and extinction
  3. Burn back to source



Class 3 Ignition:

- Burn back to source

Burning Droplets - Experimental Results

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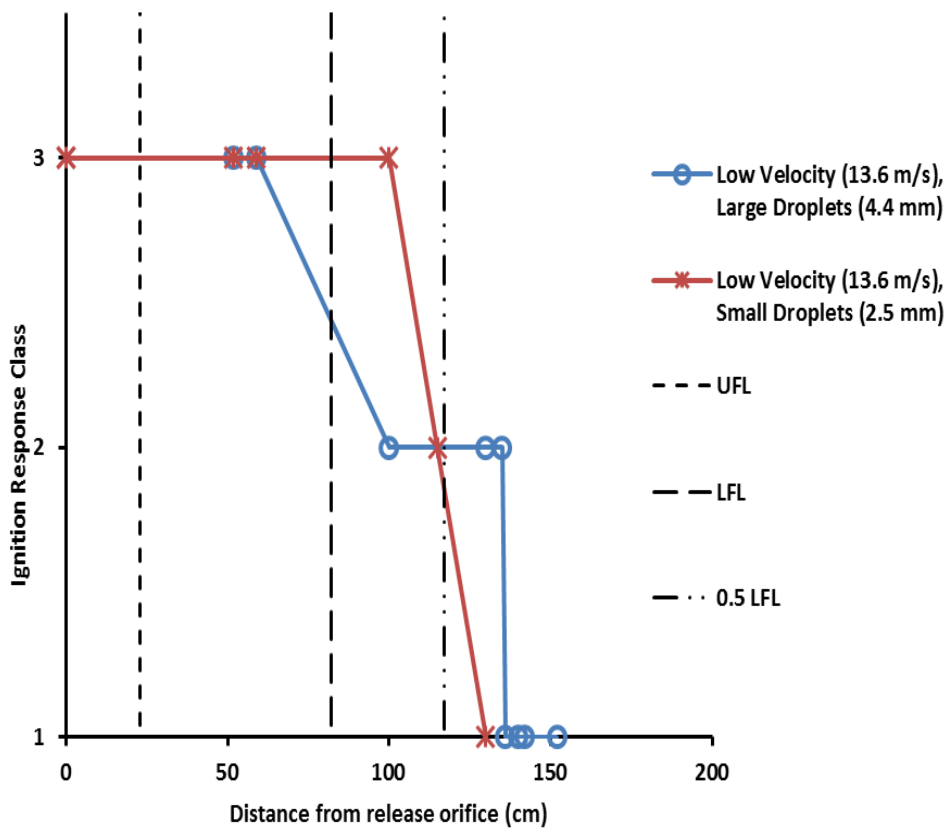
Low vent flow rate (v =13.6 m/s).



- Droplets were easily ignited and burned through the 8 m drop height
- Release easily ignited jet within the LFL region
- Ignition also occurred between LFL and ½ LFL
- Similar behaviour observed at all droplet sizes and release flow rates
- Two phase release showed similar results

Burning Droplets - Experimental Results

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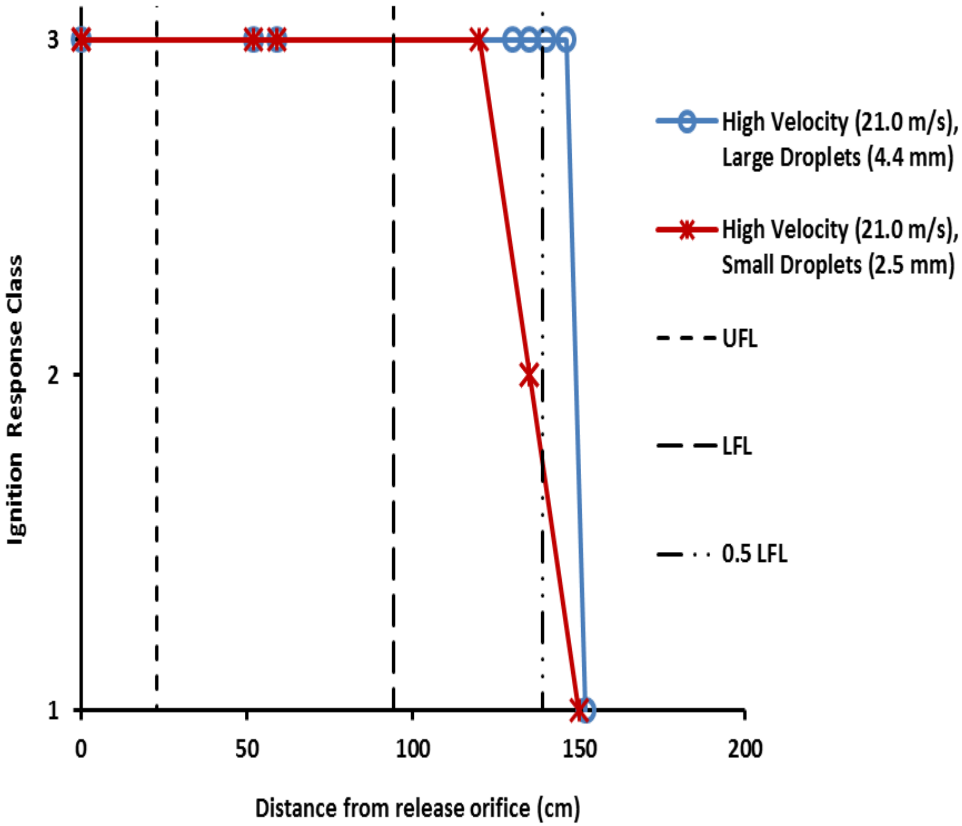
High vent flow rate (v =21.0 m/s).



- Droplets were easily ignited and burned through the 8 m drop height
- Release easily ignited jet within the LFL region
- Ignition also occurred between LFL and ½ LFL
- Similar behaviour observed at all droplet sizes and release flow rates
- Two phase release showed similar results

Burning Droplets - Experimental Results

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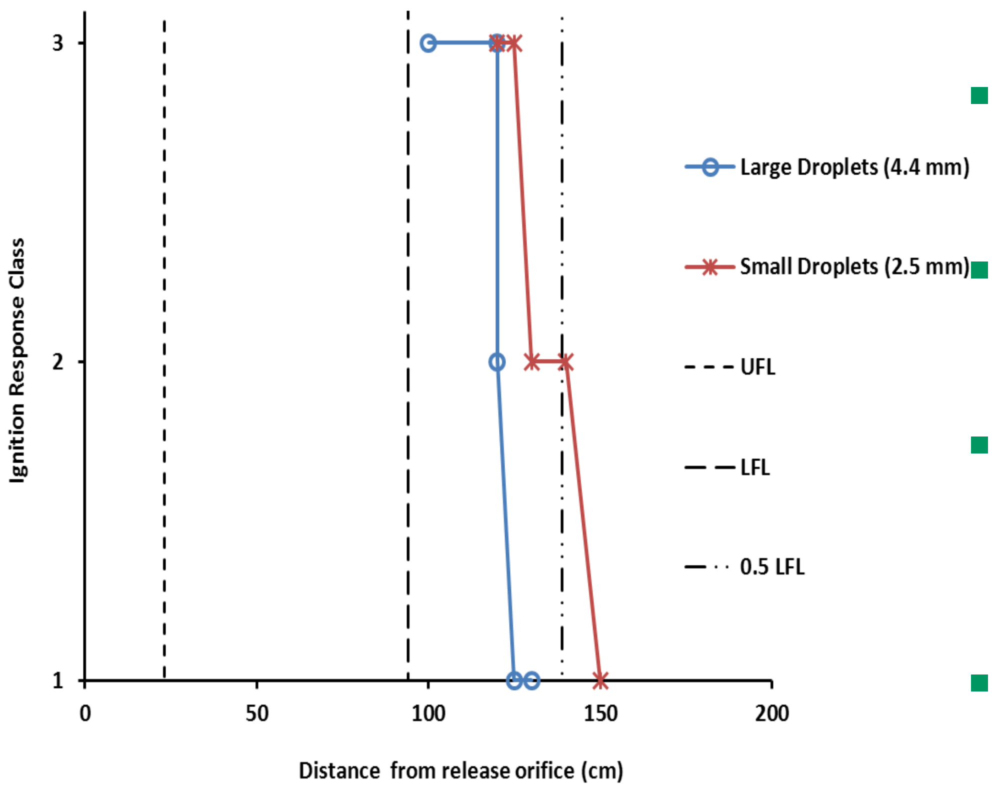
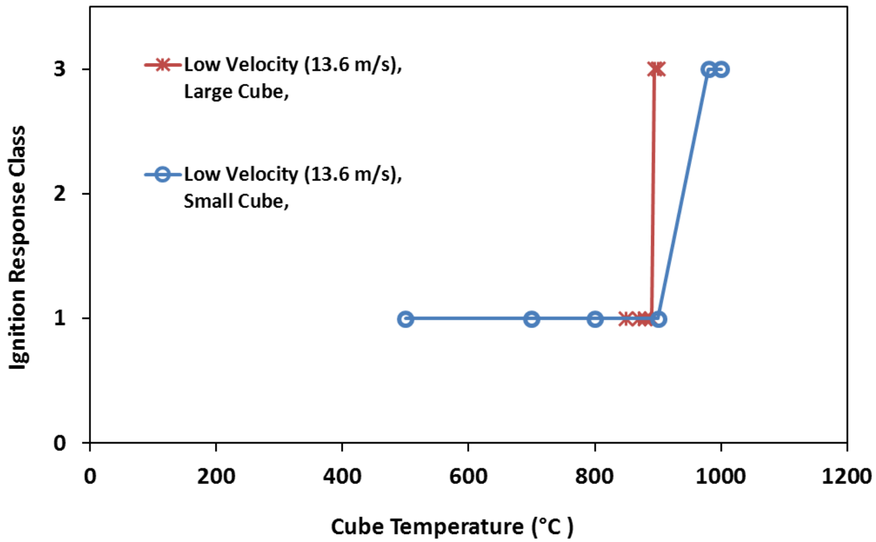
Two Phase flow (v =21.0 m/s).

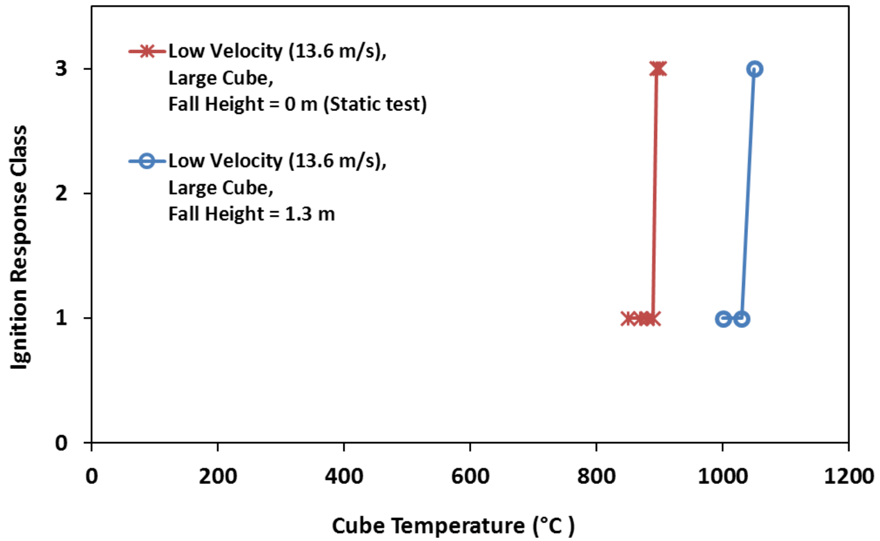


- Droplets were easily ignited and burned through the 8 m drop height
- Release easily ignited jet within the LFL region
- Ignition also occurred between LFL and ½ LFL
- Similar behaviour observed at all droplet sizes and release flow rates
- Two phase release showed similar results

Solid Cubes - Experimental Results

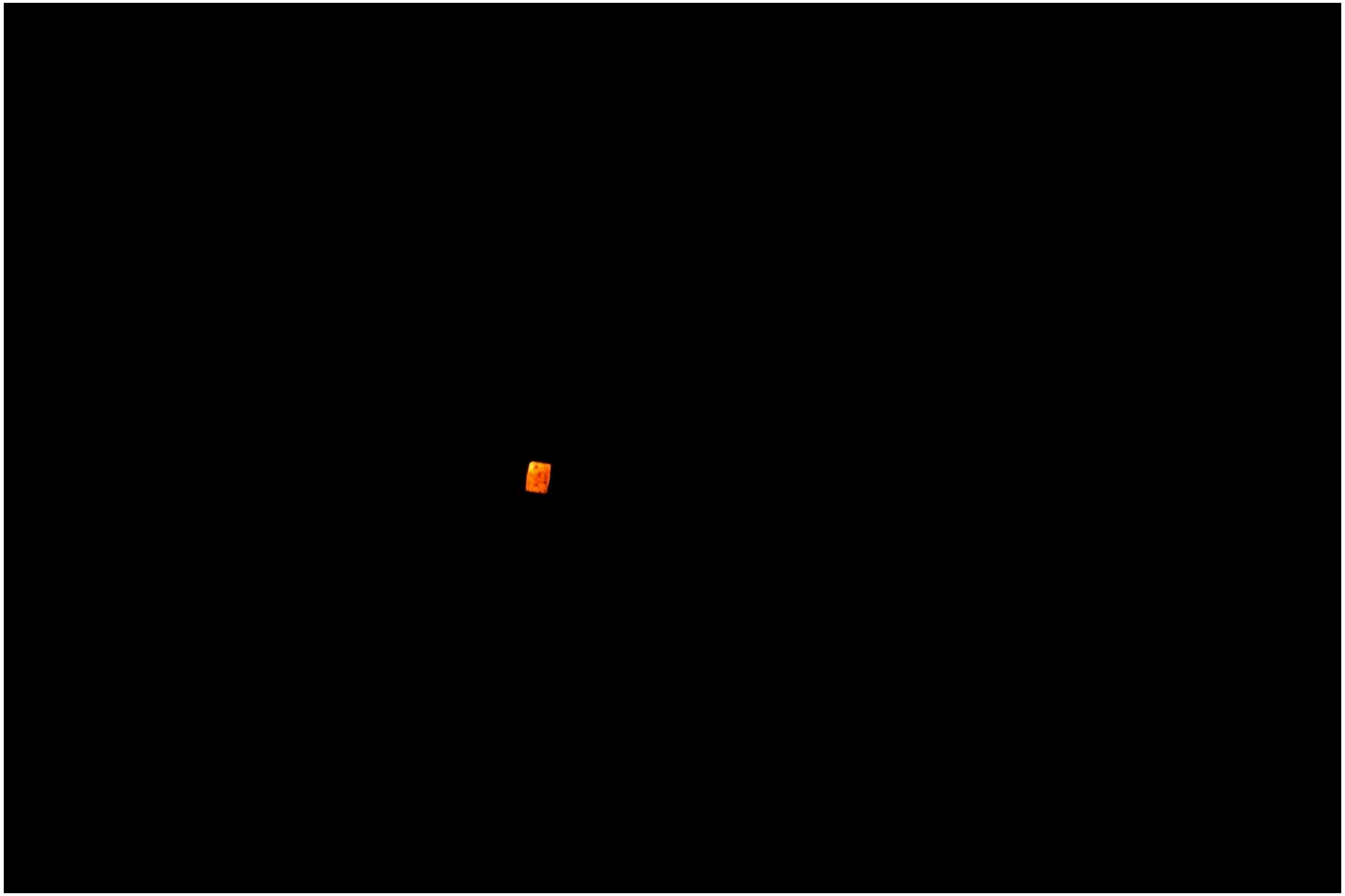


Static test in the stoichiometric region



Comparison of ignition tests from ground level or dropped from 1.3 m above the release plane.

- Cube temperatures have to be substantially above the AIT
- Elevated releases require a higher temperature



Hot or Burning Particles: Summary

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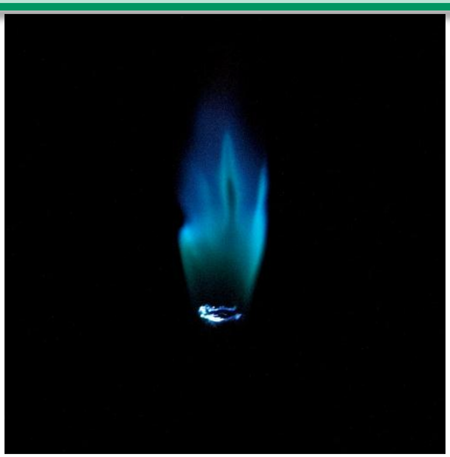
- Burning droplet experiments showed that:
  - Heptane droplets easily ignited when passing through a burner flame
  - Droplets continued to burn through a height of 8 m
  - Burning droplets ignited single- and two-phase clouds of butane, which had comparable velocity to cargo vent vapour cloud on GP3
- Analysis and observation suggested that a droplet would continue to burn through a drop height similar to GP3 (18 m)



Burning droplet of heptane

Flame front propagation after ignition by falling droplet

Hot or Burning Particles: Summary

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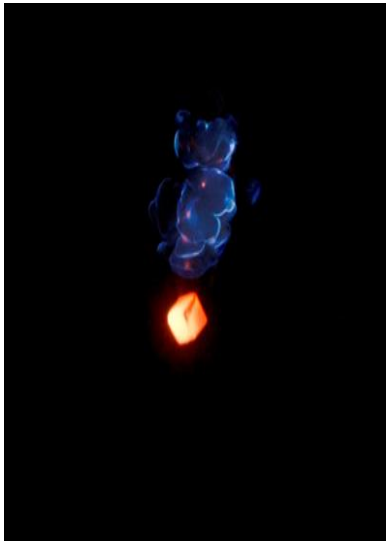
- Hot particle experiments showed that:
  - Metal cubes heated above 895 °C would ignite the vapour cloud
  - Unlikely for such a high temperature metal particle to occur on GP3, or be maintained after free-fall from the flare

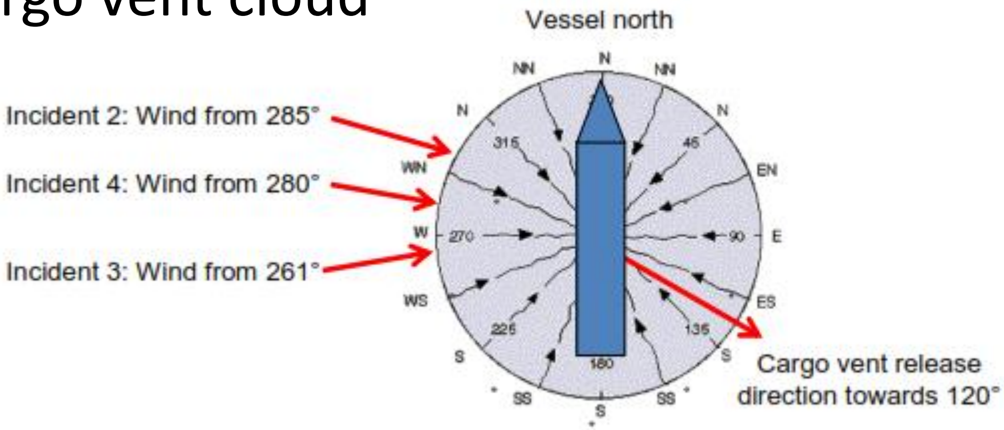
- Burning plastics experiments showed that:
  - Burning droplets could ignite the vapour cloud
  - Droplets may be extinguished during free-fall (depending upon volatility)



Ignition kernel formation in the wake of a hot metal cube

Conclusion

- Analysis of the GP3 ignition incidents showed that the prevailing wind would have tilted the flare over in the direction of the cargo vent cloud



- Ignition of the cargo vent from burning droplets falling through the gas cloud is a feasible ignition mechanism

Ignition Mechanisms

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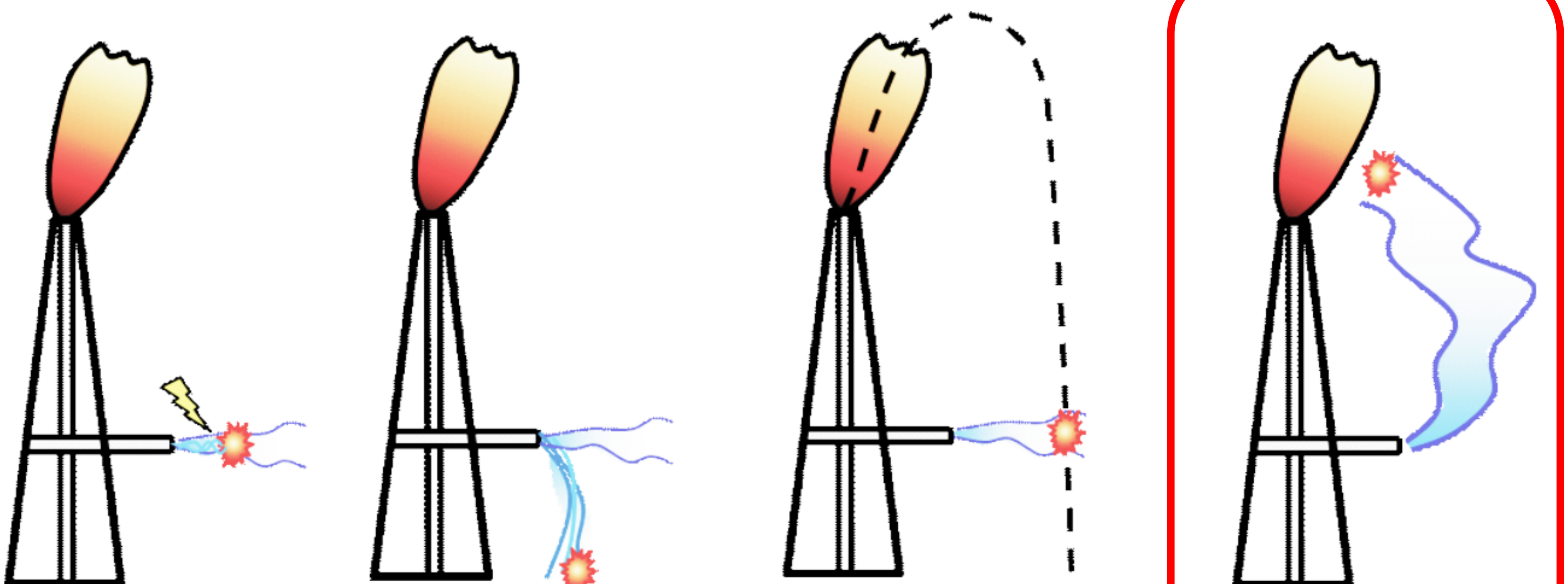


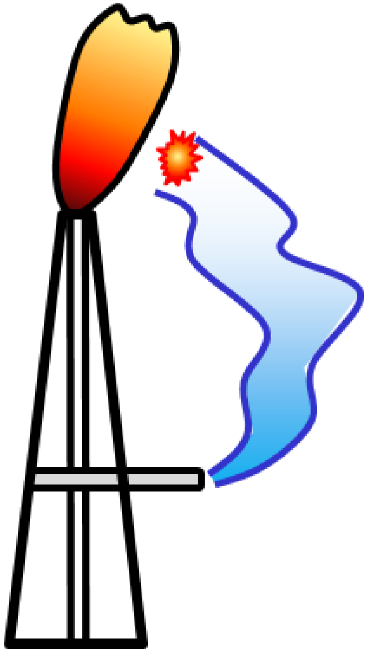
Electrostatics

Ignition at deck level

Hot / burning particle

Vent gas drawn into flare

Vent Gas Drawn Into the Flare



Postulated Ignition Mechanism

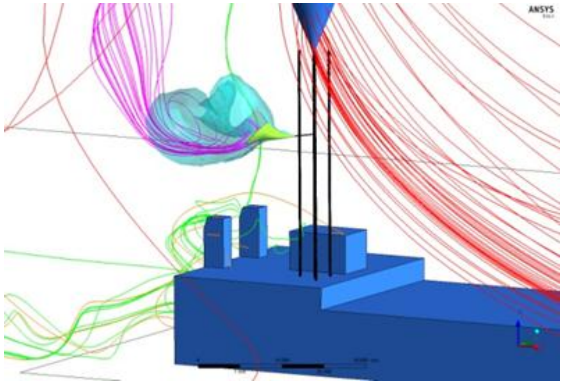
- Heat from the flare affects the local flow behaviour and causes the vented vapour to be drawn towards the flare
- In low wind speeds the vented vapour is not diluted / dispersed and a flammable mixture persists up to the flare
- The flare directly ignites the vapour and the flame burns back to the cargo vent outlet

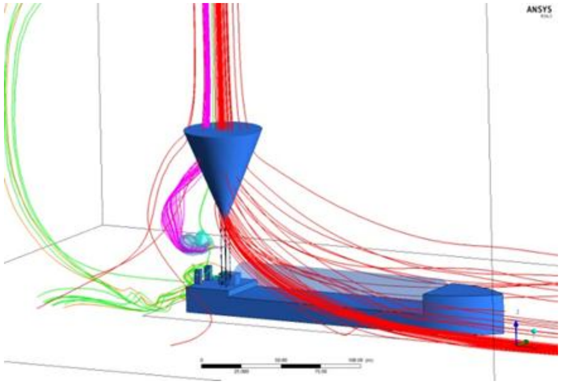
Approach

- CFD modelling of vent gas dispersion
- Experiments to inform model validation and interpretation

Preliminary Gas Dispersion Analysis

- Review of previous CFD dispersion work and further simulations





CFD sensitivity tests
Wind speed = 0.25 – 2 m/s
Wind angle = 20° - 170°
Flare rate = 0 – 230 kg/s
Exhausts on/off
Hot surfaces on/off
Deck obstructions on/off

- Flammable vapour drawn towards the flare in some cases, but the vapour diluted to <50% LEL before it reached the flare
- Complex dispersion behaviour in very low wind speeds
  - Sensitive to presence of hot surfaces, exhaust gases and the flare
- Time-varying turbulent fluctuations not resolved by CFD model

Further Gas Dispersion Analysis

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To address uncertainties in CFD modelling:

- Experiments
  - Indoor tests to map extent of flammable cloud
  - Outdoor tests using 1:10 scale model of GP3 vent and flare
- Refine CFD model
  - Validate CFD model against experiments
  - Perform further simulations of GP3 using detailed geometry from CAD data supplied by Maersk

Indoor Gas Dispersion Experiments

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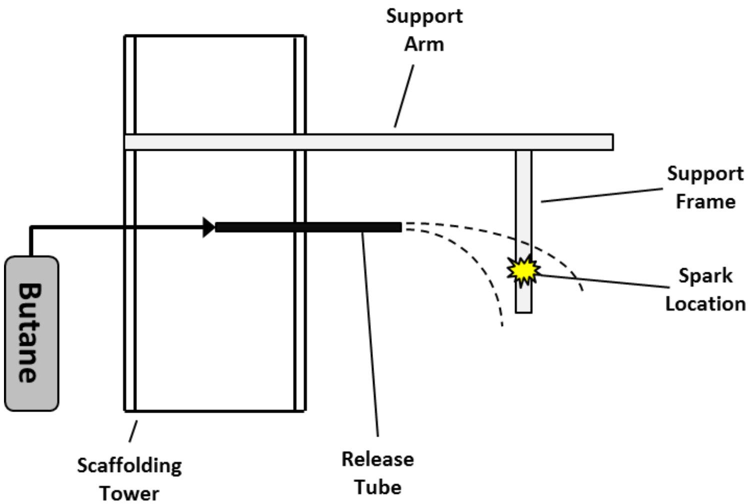
- Experiments conducted in HSL Burn Hall (quiescent atmosphere)



FLIR GasCam image

- Froude number preserved for reduced scale gas releases
  - Same ratio of inertial to buoyancy forces as gas release on GP3
  - Butane flow rate = 5 l/min, hole diameter = 7.2 mm, release velocity = 2 m/s
- 10 ignition tests at each location
- 5 cm vertical/horizontal spacing between ignition points

Indoor Gas Dispersion Experiments

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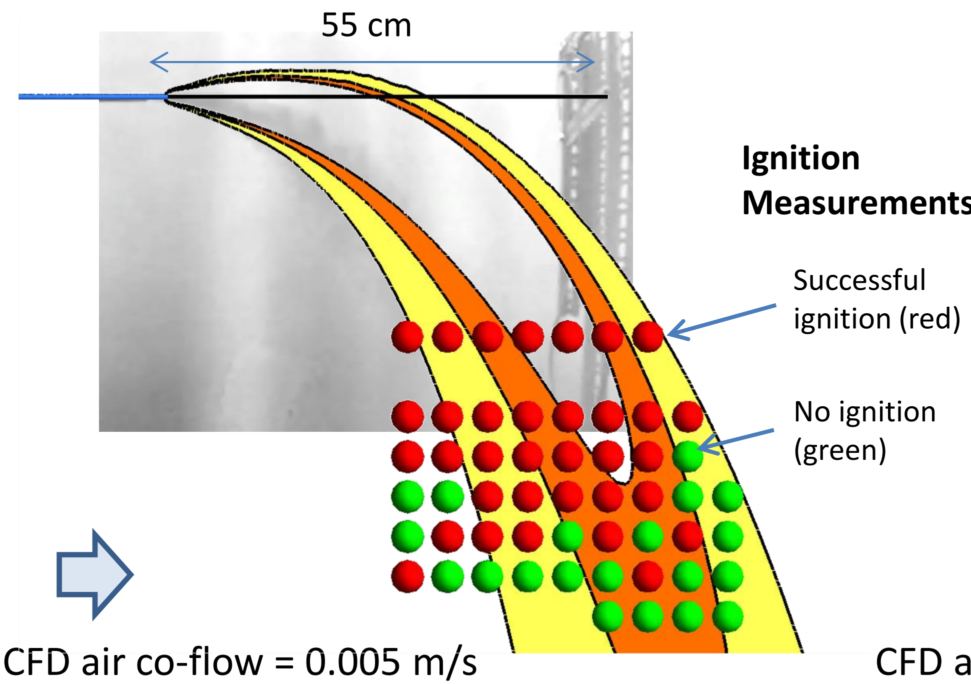

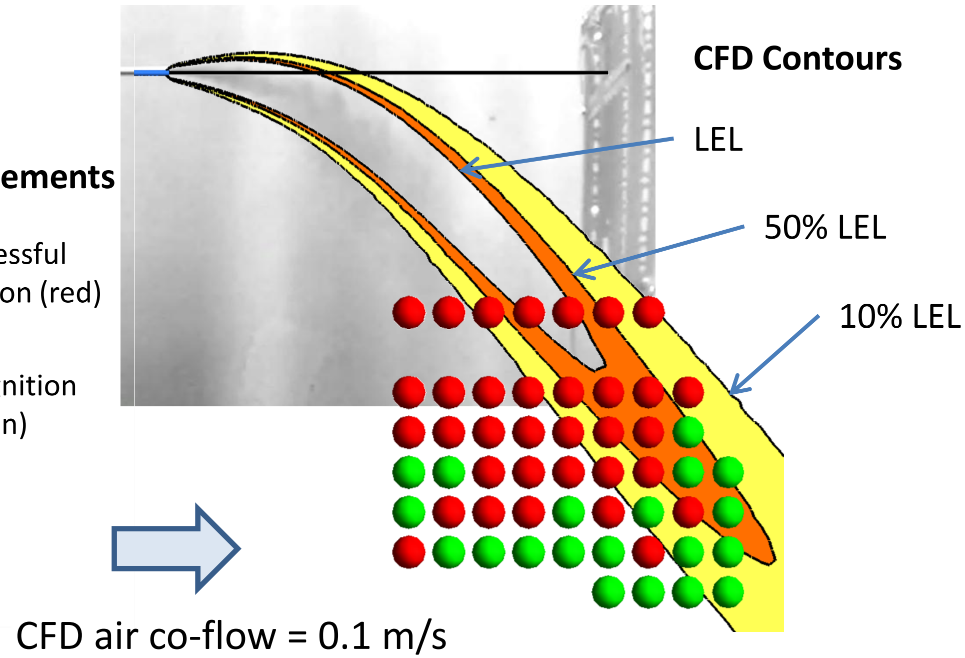

- Predicted 50% LEL cloud does not encompass all ignition locations
- Dispersion behaviour very sensitive to background air movements

Outdoor Gas Dispersion Experiments

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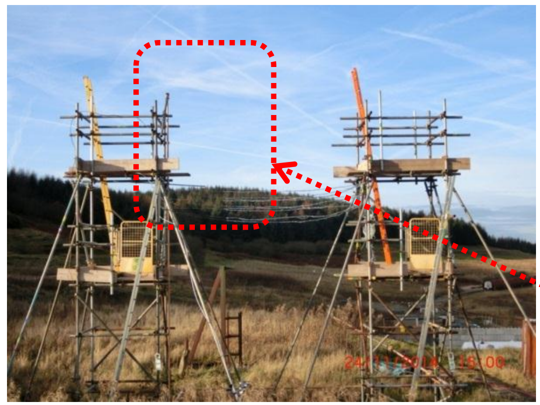

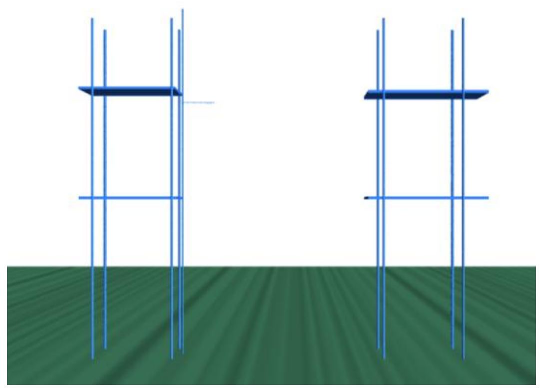

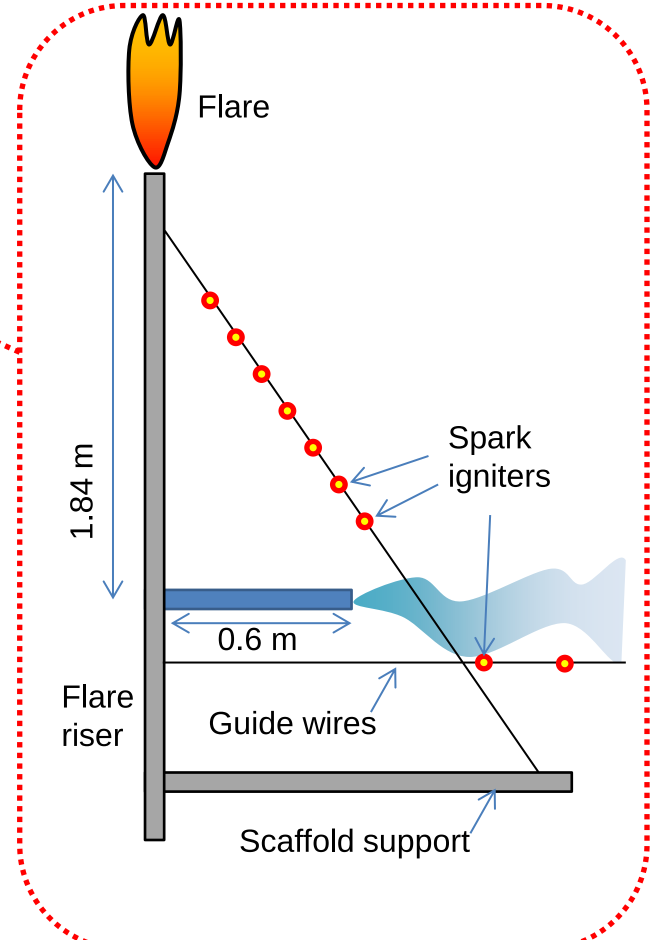

1:10 scale model of GP3 vent and flare

Scaling of Outdoor Experiments

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- Froude number preserved in 1:10 scale gas releases

	Full Scale	1:10 Model Scale
Gas Release Mass Flow (kg/s)	0.375	0.0012
Release Diameter (m)	0.15	0.015
Release Speed (m/s)	11	3.5
Target Wind Speed (m/s)	2.5	0.8

- Maintain the same ratio of the buoyancy flux between the vented vapour and the flare at full scale and reduced scale

- Tests performed with:
  - Butane gas (FLIR GasCam and ignition tests)
  - Carbon dioxide and smoke (flow visualization)

CFD Modelling of Outdoor Experiments

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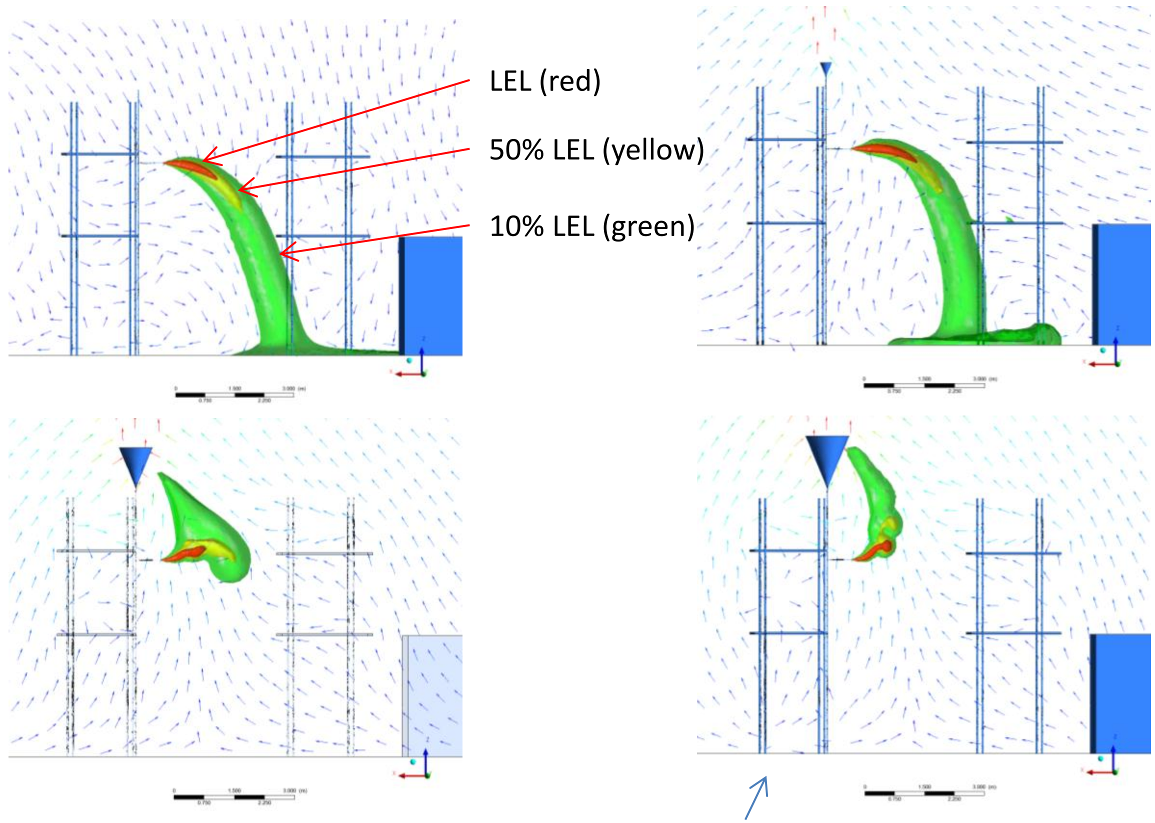
Initial CFD sensitivity tests (no comparisons to measurements)

No flare

Low flaring rate



Medium flaring rate

High flaring rate

Very low wind speed (0.005 m/s) in all cases shown here

Model predicted gas was not drawn to flare in higher wind speed of 0.5 m/s

Outdoor Gas Dispersion Experiments

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- Two experiments conducted over long periods (1 – 2 hours) in different wind conditions
- Test 1
  - Wind opposing gas release (counter-flowing)
  - Wind speed = 1.4 m/s on average (but variable)
  - Gas cloud ignited once by spark located 33 cm above/in-front of vent pipe
- Test 2
  - Wind in same direction as gas release (co-flowing)
  - Wind speed = 0.6 m/s
  - No ignitions
- Video footage showed flare on/off had no influence on dispersion

Experiments: Test 1

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Wednesday 10th June

- Prevailing wind from the north
- Approximately 1-2 m/s

Expt Conditions:

- Flare = 200 g/s (high flow condition)
- Vented gases:

  Butane = 40 l/min (high flow condition)

  Smoked seeded CO_2 = 42 l/min

Outdoor Gas Dispersion Experiments

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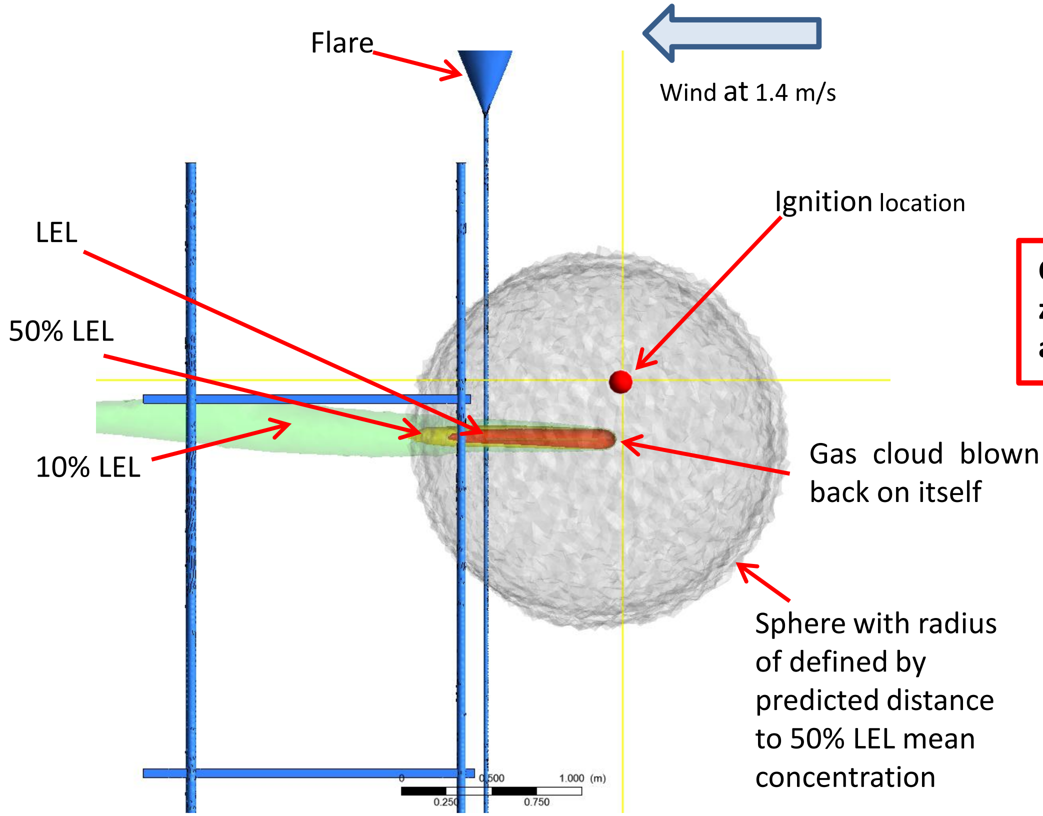
CFD results for Test 1



CFD model predicted zero gas concentration at ignition location

Flammable Sphere Approach

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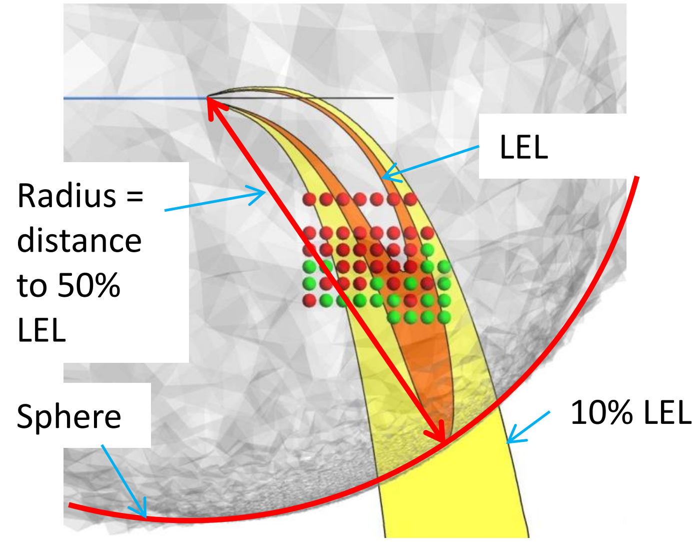
New approach proposed to determine flammable cloud size

- Flammable cloud defined as a sphere around the release point with radius equal to the predicted distance to the 50% LEL mean gas concentration
  - Fluctuations in wind speed and direction may cause a flammable mixture anywhere within the sphere
- 50% LEL sphere successfully predicts all ignition locations identified during the HSL experiments
- Similar concept to the spherical regions for hazardous area classification zones in EI15



- The approach is conservative: it tends to over-estimate size the flammable cloud

Final CFD Modelling of GP3

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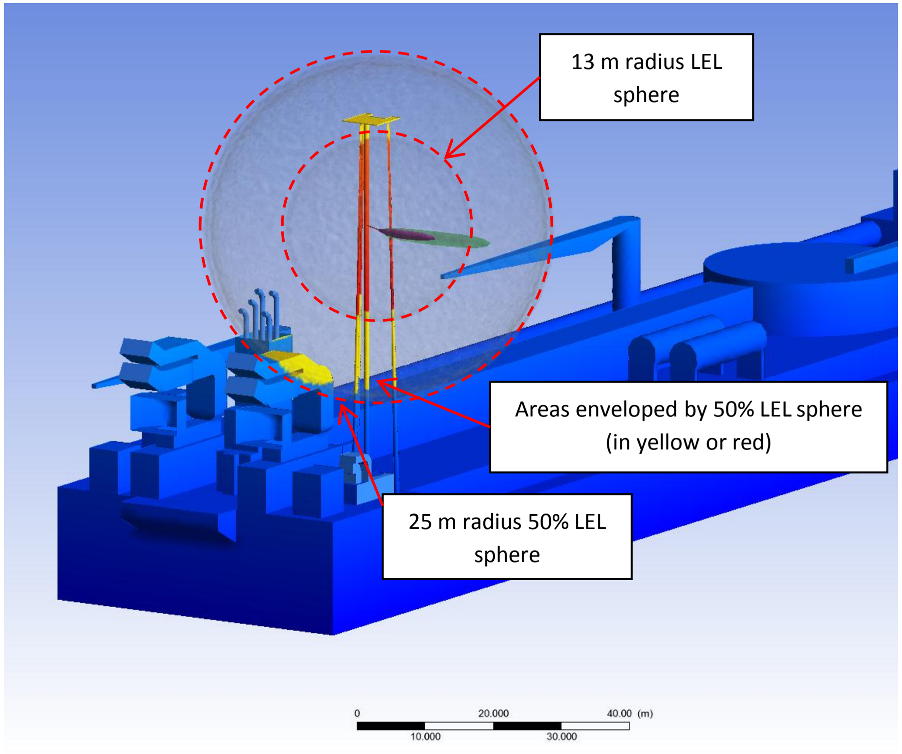
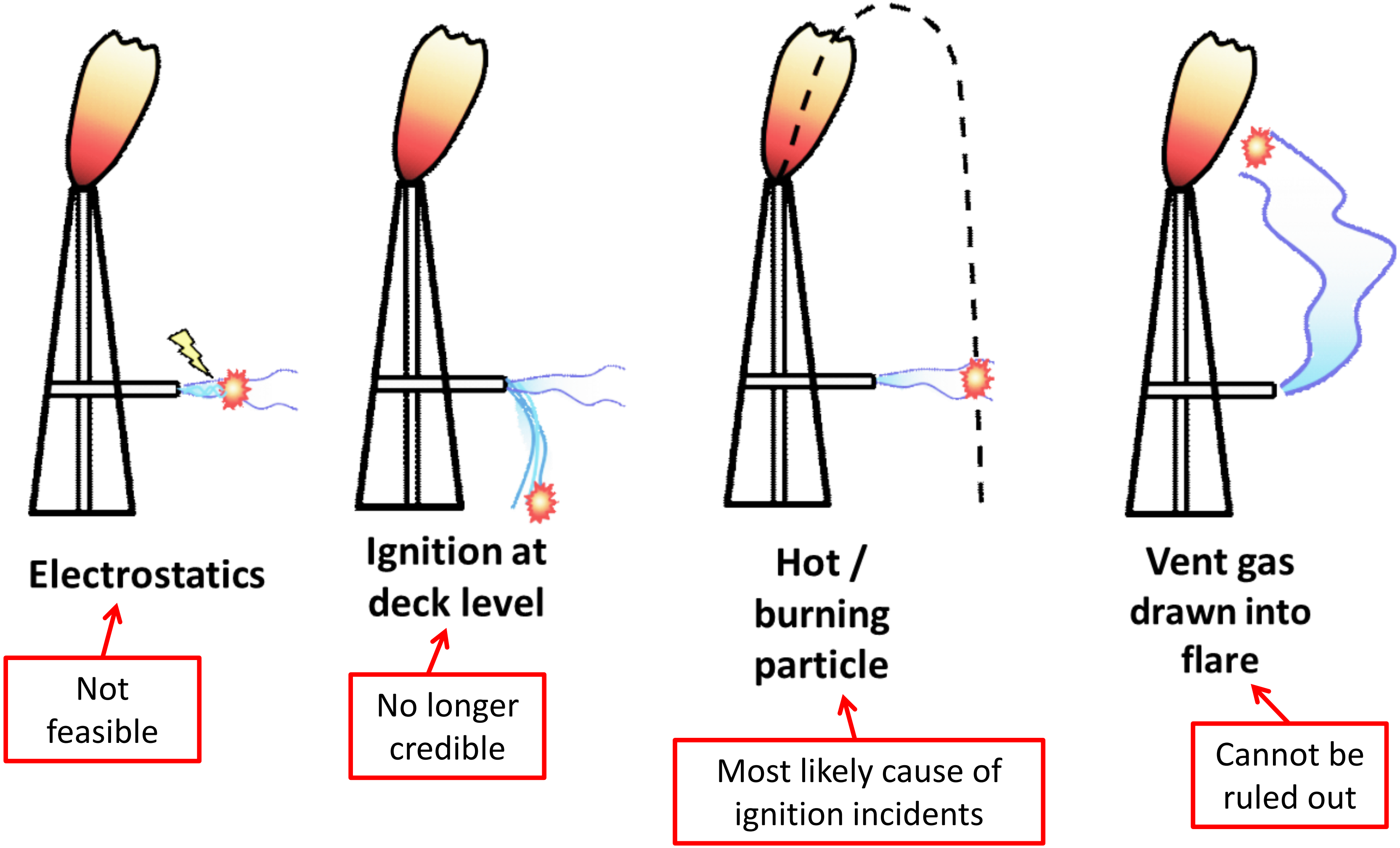
- CFD simulations performed for the GP3 Ignition Incidents 2, 3 and 4
  - Wind conditions unknown for Incident 1
- Results indicate that flare may have been the ignition source
- But … sphere approach to define extent of flammable cloud is conservative, it will tend to over-predict cloud size
- **Conclusion**: Ignition mechanism cannot be ruled out as the cause of the incidents



CFD results for second GP3 ignition incident

Overall Conclusions



Acknowledgments

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- Phillip Hooker, Andrew Newton, Darrell Bennett, Louise O'Sullivan (HSL), Stefan Ledin (DNV GL)
- David Piper (Maersk Oil North Sea UK Limited)
  - Maersk Oil provided a full range of data and internal reports to support the investigation activities.
  - Supported the dissemination of the incident details and investigation findings at Hazards 26.

Any Questions?

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