Area classification of flammable mists: summary of joint-industry project findings

Simon Gant*, Richard Bettis, Simon Coldrick, Graham Burrell, Roger Santon and Brian Fullam, Health and Safety Executive (HSE)
Kyriakos Mouzakitis, Anthony Giles and Philip Bowen, Cardiff University

Hazards 26 Conference, 24-26 May 2016
Contents

- Background and Motivation
- Aims of Joint Industry Project
- Scope
- Research Programme
  - Literature Review
  - Fluids Classification
  - Experiments
  - Modelling
- Analysis of Area Classification Guidelines
- Possible Future Work
Background

- **ATEX/DSEAR** – Employers must:
  - Identify and classify areas of the workplace where explosive atmospheres may occur
  - Ensure that appropriately certified equipment is used in the hazardous zones

- **For flammable gases and dusts:**
  - Hazardous area classification guidance in BS EN 60079, IGEM/SR/25, IP15

- **For flammable mists from high-flashpoint fluids ...?**
  - BS EN 60079-10-1 Annex D: limited guidance on flammable mists (only qualitative, not quantitative)
  - IP15: “there is little knowledge on the formation of flammable mists and the appropriate extents of associated hazardous areas ... Further research is needed”
Joint Industry Project

Aims:

- To undertake scientific research that can be used to develop formal guidance on:
  - Formation of flammable mist
  - Mitigation measures
  - Area classification zone and extent
  - Protected equipment concepts, and equipment selection

- To develop practical criteria that define the likelihood of mist formation that can be used as part of an area classification exercise
Joint Industry Project

**Scope:** Mists/sprays/aerosols of liquids that are below their flashpoint at ambient temperature:

- Lubricating oil
- Vegetable oil
- Hydraulic oil
- Light fuel oil
- Heavy fuel oil
- Heat transfer fluid

**Outside scope:**

- Flashing fluids, e.g. propane
- Low flashpoint fluids, e.g. gasoline
Joint Industry Project

- **Sponsors**: HSE, ONR, RIVM, GE, Siemens, EDF/British Energy, RWE, Maersk Oil, Statoil, BP, ConocoPhilips, Nexen, Syngenta, Aero Engine Controls, Atkins, Frazer Nash, Energy Institute

- Budget: £477k

- Kick-off meeting: 5 December 2011

- Final meeting: 9 July 2015
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Literature Review

- Address the following questions:
  1. When is a mist flammable?
  2. How do you generate a flammable mist?
- Survey information on: LEL, MIE, MIC, MESG, MHSIT
- Briefly survey mitigation measures
- Help define possible future directions for Hazardous Area Classification of mists
- Published:
  - HSE Research Report RR980 (134 pages long)
  - IChemE Hazards XXIII paper, 2012
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Fluids Classification

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**Outside scope:**

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- Low flashpoint fluids, e.g. gasoline
Fluids Classification

Temperature increase from 12°C to 67°C

Based on 1 mm diameter orifice at 10 bar
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Experiments

- **Objectives**
  - Investigate flammability of spray releases relevant to area classification
  - Produce data for validating models
  - Examine feasibility of go/no-go categorization of mist flammability

- **Methodology**
  - Test 3 different types of fluids
  - Use hole size characteristic of leak
  - Test range of relevant pressures
  - Determine LEL from measurements of:
    - Ignition
    - Droplet size
    - Droplet concentration
  - Examine effects of raising fluid temperature
  - Vertical downward release
  - 1 Joule spark ignition
Experiments

- Kerosene (Jet A1), Light Fuel Oil, Hydraulic Oil
- Base range: 5 to 20 barg
- Additional tests at 70°C for Light Fuel Oil

Ignition locations
## Experiments

<table>
<thead>
<tr>
<th>Spray Geometry</th>
<th>Fluid</th>
<th>Pressure (barg)</th>
<th>Temperature</th>
<th>Ignited?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free spray</td>
<td>Jet A1</td>
<td>1.7, 2, 3, 4, 5, 10, 15, 20</td>
<td>Ambient</td>
<td>At all pressures</td>
</tr>
<tr>
<td>Free spray</td>
<td>Hydraulic oil</td>
<td>5, 10, 15, 20, 30, 70, 110, 130</td>
<td>Ambient</td>
<td>No, but some “flashes” at highest pressures</td>
</tr>
<tr>
<td>Free spray</td>
<td>Light fuel oil</td>
<td>5, 10, 15, 20</td>
<td>Ambient</td>
<td>No</td>
</tr>
<tr>
<td>Free spray</td>
<td>Light fuel oil</td>
<td>5, 10, 15, 20</td>
<td>70 °C</td>
<td>At all pressures</td>
</tr>
<tr>
<td>Impinging</td>
<td>Hydraulic oil</td>
<td>5, 10, 15, 20</td>
<td>Ambient</td>
<td>No</td>
</tr>
<tr>
<td>Impinging</td>
<td>Light fuel oil</td>
<td>15, 20</td>
<td>Ambient</td>
<td>At 20 barg only</td>
</tr>
<tr>
<td>Impinging</td>
<td>Light fuel oil</td>
<td>5, 10, 15, 20</td>
<td>70°C</td>
<td>At all pressures</td>
</tr>
</tbody>
</table>

**Diagram:**

- Red: Atomization breakup
- Blue: Sinuous breakup
- Light blue: Jet A1
- Yellow triangle: Hydraulic Oil
- Green circle: Ambient LFO
- Purple diamond: Heated LFO

- None fully ignited
- Some ignition “flashes”
- All ignited

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CFD Modelling

- **Objectives**
  - To develop and validate a CFD model using the GTRC data
  - To compare CFD model predictions to EI15 guidelines

- **Methodology**
  - Test combinations of CFD sub-models (cone angle, primary/secondary atomization) for the GTRC tests with Jet A1 at 20 bar
  - Select “best” combination of sub-models to then compare to all experiments for Jet A1, hydraulic oil, LFO and LFO heated
  - Examine agreement with data across range of experiments
CFD Modelling: Effect of cone angle

Droplet concentration (g/m$^3$)

Good agreement with ignition locations

Droplet SMD (μm)

Poor agreement with droplet size on centreline

Cone angle has little effect
Summary of CFD Validation

- Atomised sprays (e.g. Jet A1 at 20 bar)
  - GTRC measurements considered most reliable here
  - CFD model with DNV Phase III JIP RR droplet size correlation gave results within factor-of-two of measurements for concentration and diameter

- Non-atomised sprays (e.g. light fuel oil at ambient temp.)
  - Fewer reliable measurements of droplet size and concentration
  - Uncertainties due to liquid stream rather than droplets
  - CFD model assumed atomised spray of droplets: poor agreement with measurements
  - Low likelihood of ignition in non-atomising sprays
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EI15 Code of Safe Practice

MODEL CODE OF SAFE PRACTICE PART 15
AREA CLASSIFICATION FOR INSTALLATIONS HANDLING FLAMMABLE FLUIDS

4th edition

Table C1: Fluid compositions and LFLs

<table>
<thead>
<tr>
<th>Stream component (mol %)</th>
<th>Fluid category</th>
<th>LFL (vol %)</th>
<th>Molecular weight (g/mol)</th>
<th>Boiling point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>N, Nitrogen</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.00</td>
</tr>
<tr>
<td>C, Methane</td>
<td>0.00</td>
<td>4.00</td>
<td>0.00</td>
<td>88.45</td>
</tr>
<tr>
<td>C2, Ethane</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>4.50</td>
</tr>
<tr>
<td>C3, Propane</td>
<td>70.00</td>
<td>0.00</td>
<td>1.00</td>
<td>3.00</td>
</tr>
<tr>
<td>C4, Butane</td>
<td>30.00</td>
<td>7.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>C5, Pentane</td>
<td>0.00</td>
<td>9.00</td>
<td>1.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C6, Hexane</td>
<td>0.00</td>
<td>11.00</td>
<td>3.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C7, Heptane</td>
<td>0.00</td>
<td>16.00</td>
<td>3.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C8, Octane</td>
<td>0.00</td>
<td>22.00</td>
<td>27.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C9, Nonane</td>
<td>0.00</td>
<td>0.00</td>
<td>25.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C10, Decane</td>
<td>0.00</td>
<td>25.00</td>
<td>38.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C11, Dodecane</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C12, Triodecane</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>H2O Water</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Hydrogen</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table C2: Physical parameters used in dispersion modelling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value used in EI15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature</td>
<td>30 °C</td>
</tr>
<tr>
<td>Storage/process temperature</td>
<td>20 °C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>70 %</td>
</tr>
<tr>
<td>Wind speed</td>
<td>2 m/s</td>
</tr>
<tr>
<td>Stability class</td>
<td>D</td>
</tr>
<tr>
<td>Surface roughness length</td>
<td>0.03 m</td>
</tr>
<tr>
<td>Release direction</td>
<td>Horizontal</td>
</tr>
<tr>
<td>Release height</td>
<td>For R1: 5 m For R2: 1 m</td>
</tr>
<tr>
<td>Release angle</td>
<td>For R1: horizontal For R2: unknown</td>
</tr>
<tr>
<td>Sample time</td>
<td>18.75 s</td>
</tr>
<tr>
<td>Reference height</td>
<td>10 m</td>
</tr>
<tr>
<td>Hazard distances</td>
<td>To LFL</td>
</tr>
</tbody>
</table>

Table 1.3: Fluid categories

<table>
<thead>
<tr>
<th>Fluid category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A flammable liquid that, on release, would vapourise rapidly and substantially. This category includes: (a) Any liquefied petroleum gas or lighter flammable liquid. (b) Any flammable liquid at a temperature sufficient to produce, on release, more than about 40 % vol. vapourisation with no heat input other than from the surroundings.</td>
</tr>
<tr>
<td>B</td>
<td>A flammable liquid, not in category A, but at a temperature sufficient for boiling to occur on release.</td>
</tr>
<tr>
<td>C</td>
<td>A flammable liquid, not in categories A or B, but which can, on release, be at a temperature above its flash point, or form a flammable mist or spray.</td>
</tr>
<tr>
<td>(i)</td>
<td>A typical methane-rich natural gas.</td>
</tr>
<tr>
<td>(ii)</td>
<td>Refinery hydrogen.</td>
</tr>
</tbody>
</table>
EI15 Code of Safe Practice

Table C4: Hazard radii $R_1$ and $R_2$ for pressurised releases

<table>
<thead>
<tr>
<th>Fluid category</th>
<th>Release pressure see note 4 (bar[a])</th>
<th>Hazard radius $R_1$ (m)</th>
<th>Hazard radius $R_2$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Release hole diameter</td>
<td>Release hole diameter</td>
<td>Release hole diameter</td>
</tr>
<tr>
<td></td>
<td>1 mm</td>
<td>2 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>4</td>
<td>8</td>
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<tr>
<td>50</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>G(i)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>G(ii)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>50</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>1</td>
</tr>
<tr>
<td>LNG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>2.5</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

Notes:
1. At the fluid storage temperature of 20 °C the nominal discharge pressure of 5 bar(a) is below the saturated vapour pressure of fluid category A. The saturated vapour pressure (6.8 bar(a)) was used to calculate the discharge rate and dispersion.
2. Distances to UFL for LNG releases at 5 m height. These distances have been modelled as methane, with typical LNG compositions varying between 93% - 90%. Typical rundown, storage and loading temperatures for LNG are in the range -170 °C to -165 °C; therefore releases from a storage temperature of -165 °C have been modelled.
3. No data are available for gasoline blends with ethanol; however, for blends with small quantities of ethanol, these could be treated as category C. It is recommended that modelling is carried out.
4. Release pressure should be taken as the maximum allowable operating pressure.
CFD Modelling of EI15 Conditions

- Downward directed jet
  - Not horizontal jet assumed in EI15

- Substance: Jet A1

- Assumed LFL = 0.043 g/m$^3$
  - Same as EI15, but uncertain...

- Droplet size: DNV Phase III JIP RR model
  - Max limit on droplet size of orifice diameter

![Graph showing initial droplet diameter versus pressure](image)
CFD compared to EI15

- Gravitational effects are different
  - Horizontal releases in EI15
  - Vertically-downward releases in CFD

- Overall conclusion:
  - Results broadly consistent
  - Could increase hazard range in EI15 for vertical direction, beneath release, for lower pressures
Tentative Area Classification Guidelines

Temperature increase from 12°C to 67°C

Based on 1 mm diameter orifice at 10 bar
Based on 1 mm diameter orifice at 10 bar

- a. For hole sizes of 1 mm or above and pressure below 20 bar: No flammable zone if there is no possibility of spray impingement, otherwise as EI15 Category C fluids.
- b. For conditions outside this range: Unknown – treat as EI15 Category C fluids.

Tentative Area Classification Guidelines

Flashpoint °C

Proportion of Ohnesorge Atomisation Correlation

Release Class I

Release Class II

Release Class III

Release Class IV

Volatile Fuels

Lubricants

Fuel oils

Tentative Area Classification Guidelines

Better Atomisation
Better Atomisation

Volatile Fuels

Fuel oils

Lubricants

Temperature increase from 12°C to 67°C

a. For hole sizes of 1 mm or above and pressure below 20 bar: No flammable zone if there is no possibility of spray impingement, otherwise as EI15 Category C fluids.

b. For conditions outside this range: Unknown – treat as EI15 Category C fluids.

Tentative Area Classification Guidelines

Treat as EI15 Category C fluids for pressures <5 bar, treat as 5 bar. Conservatism strongly recommended. Perhaps assume >1 barg as hazardous.

Release Class III
Hole ≥ 1 mm and pressure ≤ 20 bar: No flammable zone
For conditions outside this range: Treat as EI15 Category C fluids

Release Class II
Hole ≥ 1 mm and pressure ≤ 20 bar: No flammable zone if no impingement otherwise as EI15 Category C fluids.
For conditions outside this range: Treat as EI15 Category C fluids

Release Class IV
Treat as EI15 Category C fluids
Tentative Area Classification Guidelines

- Tentative guidelines are based on the findings of the JIP experiments and modelling
- For more complex spray release situations, e.g. impingement on hot surfaces, the assessment will need to take other factors into account
- Guidelines should be reviewed as more information on flammable mists becomes available.
- Only suitably ignition protected equipment should be installed within hazardous zone
- No current standard against which equipment may be certified as safe in a flammable mist
  - Ingress Protection (IP) of 5 (or higher) against liquid ingress
  - Surface temperature rating below the auto-ignition temperature
  - Other protection concepts, e.g. intrinsic safety, encapsulation, or pressurisation
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Possible Future Work?

- Ignition limits
  - LEL criteria for mists
  - Vertical extent of ignitable cloud
  - Influence of ignition energy

- Better characterisation of low quality sprays

- Characterisation of impinging jet/flammability

- Influence of orifice - size, slots, orifice length/diameter, etc.

- Improved models → engineering guidance tools

- (Flange guards and mist detectors)
Acknowledgement

- **Sponsors:** HSE, ONR, RIVM, GE, Siemens, EDF/British Energy, RWE, Maersk Oil, Statoil, BP, ConocoPhilips, Nexen, Syngenta, Aero Engine Controls, Atkins, Frazer Nash, Energy Institute

- **Project team:**
  - Richard Bettis, Simon Coldrick, Graham Burrell, Roger Santon, Brian Fullam, Roger Brentnall and Bronwen Ley (HSE)
  - Kyriakos Mouzakitis, Anthony Giles, Steven Morris and Philip Bowen (Cardiff University)
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Hazards 26

In association with the Mary Kay O’Connor Process Safety Center

24–26 May 2016, Edinburgh, UK

Stand 39

simon.gant@hsl.gsi.gov.uk
Overall assessment of model performance

- Which combination of CFD sub-models fits the experiments best?
  - Difficult to assess all 38 simulations for Jet A1 at 20 bar

- Solution: Statistical Performance Measures (SPMs)
  - Indicate model’s ability to predict the mean
    (i.e. whether it under- or over-predicts on average)
  - Indicate degree of scatter in predictions
    (i.e. the deviation from the average)
Statistical Performance Measures (SPMs)

- **Mean relative bias**
  - Ability to predict on average
  \[
  MRB = \left( \frac{C_o - C_p}{(C_p + C_o)/2} \right)
  \]

- **Mean relative square error**
  - The level of scatter
  \[
  MRSE = \left( \frac{(C_o - C_p)^2}{[(C_p + C_o)/2]^2} \right)
  \]

\[C_o = \text{observed} \quad C_p = \text{predicted}\]
SPMs for Concentration

"Perfect" model: MRB=MRSE=0

Factor-of-two level of agreement:
(MRB = 0.66; MRSE = 0.44)

Key:
- On the centreline
- At the ignition locations
- At the non-ignitions locations
SPMs for Sauter Mean Diameter

PRR = DNV Phase III JIP Rosin-Rammler
MI = Miesse

within factor-of-two for both concentration and SMD on centreline of spray
Do the SPM results make sense?

- DNV Phase III JIP model

![Graph showing measured and predicted droplet concentrations.

- Cross indicates ignited.
- Number indicates measured droplet count.
- No droplets predicted at this location.
- Axial location (m) and Radial location (m).]
Do the SPM results make sense?

- Fluent model

Concentrations well predicted
Droplet size significantly under-predicted