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

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Contents

HEALTH & SAFETY LABORATORY

- 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

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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"

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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

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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

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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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Contents

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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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- Scope
- Research Programme
  - Literature Review
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  - Modelling
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Fluids Classification

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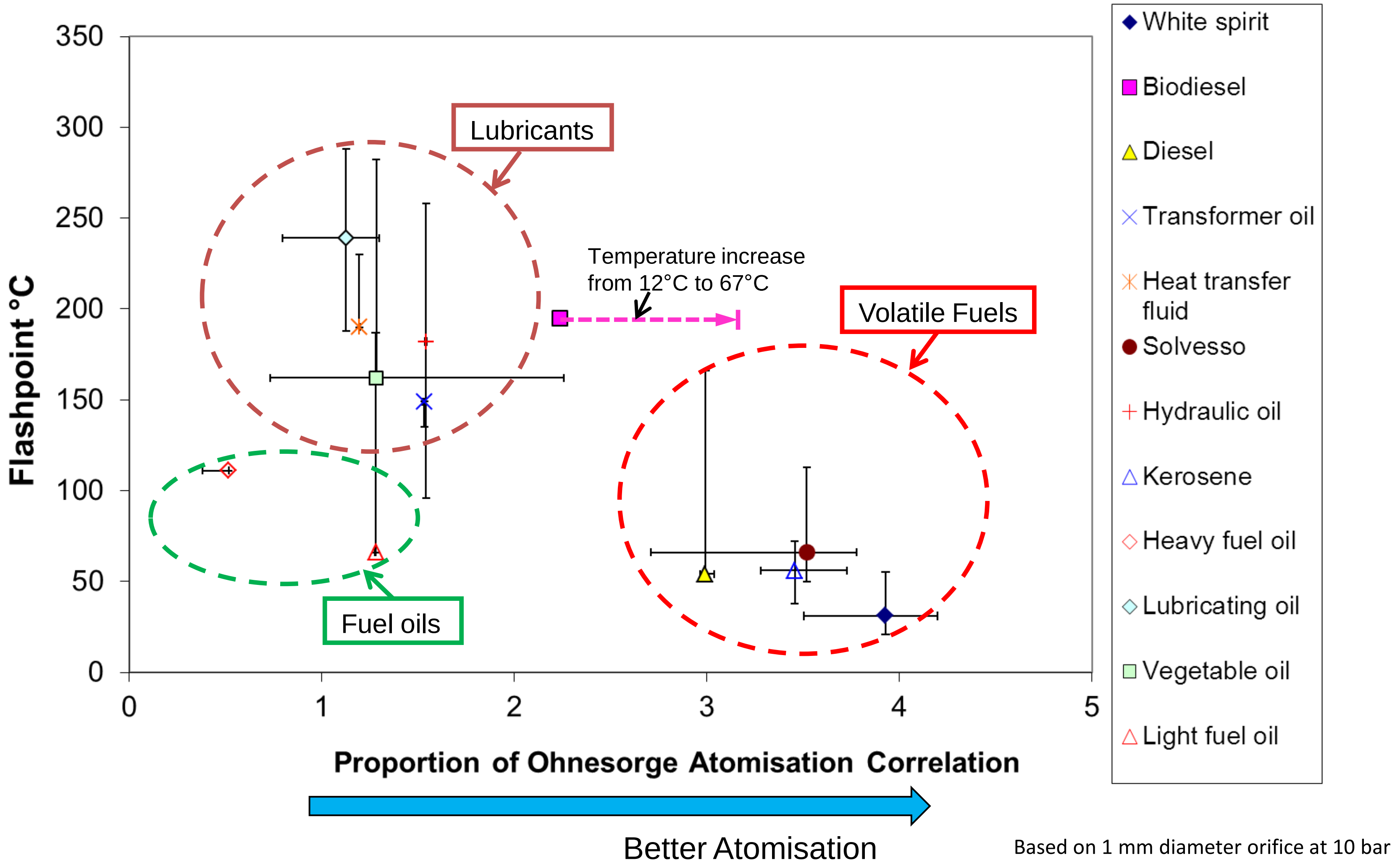
Fluids Classification



Based on 1 mm diameter orifice at 10 bar

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- Research Programme
  - Literature Review
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  - Modelling
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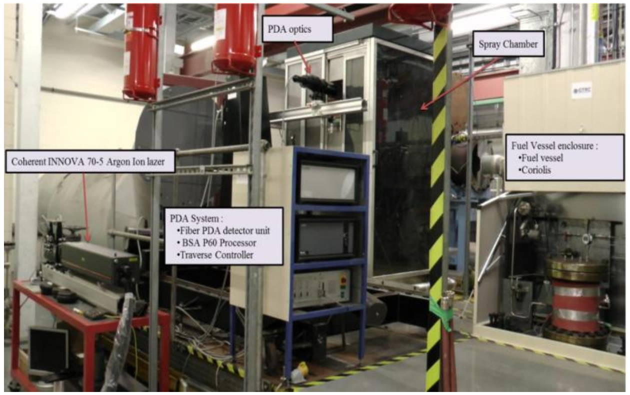
Experiments

- **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



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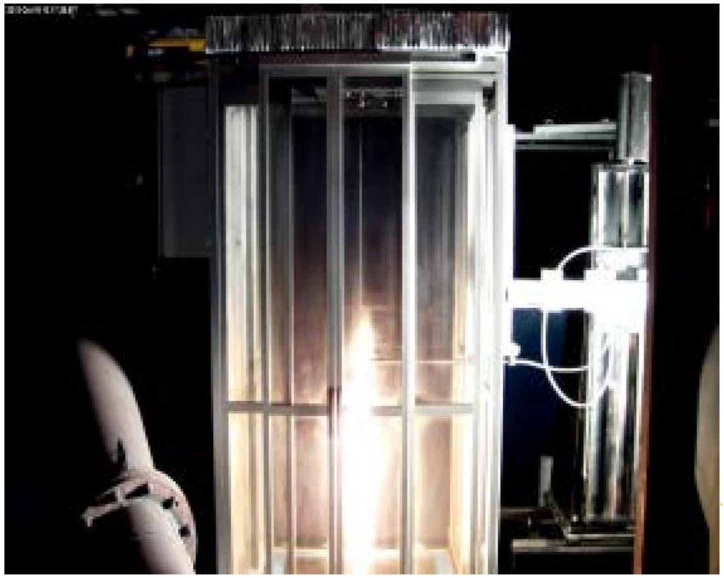
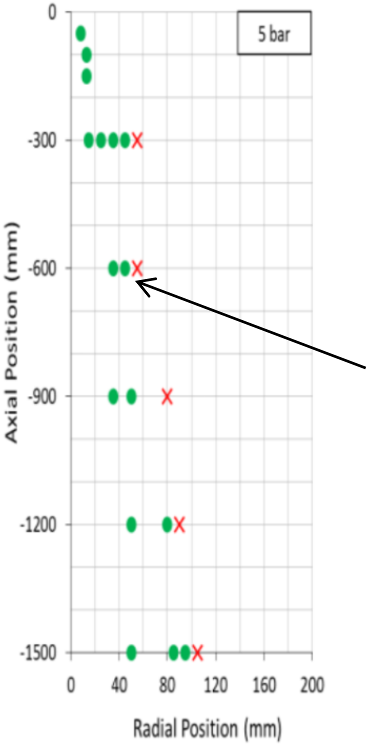
Experiments

- 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

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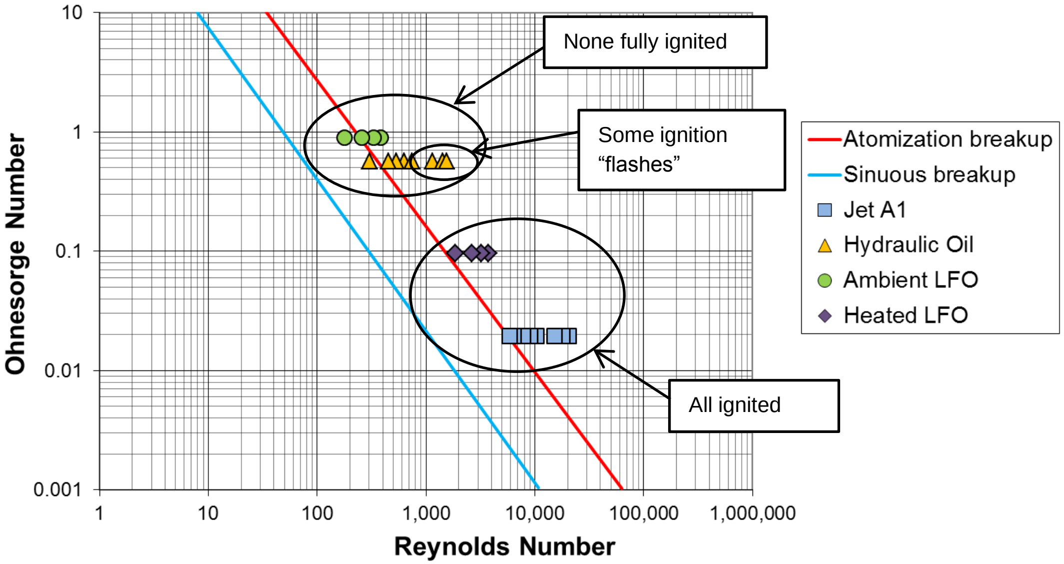
Experiments

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



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Contents

- Background and Motivation
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- Scope
- Research Programme
  - Literature Review
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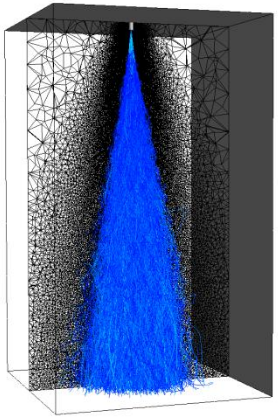
CFD Modelling

- **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



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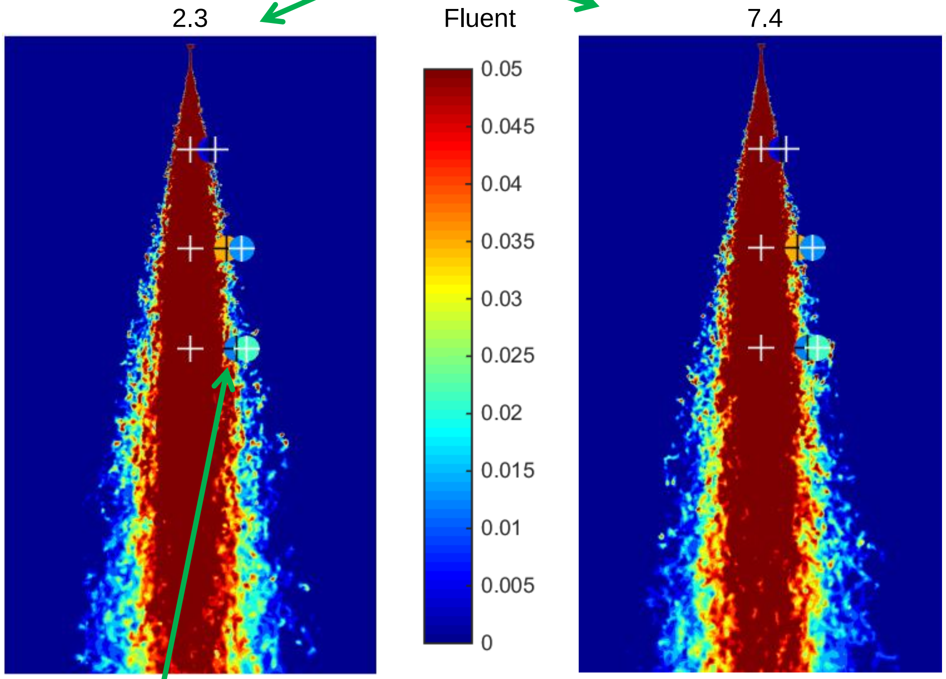
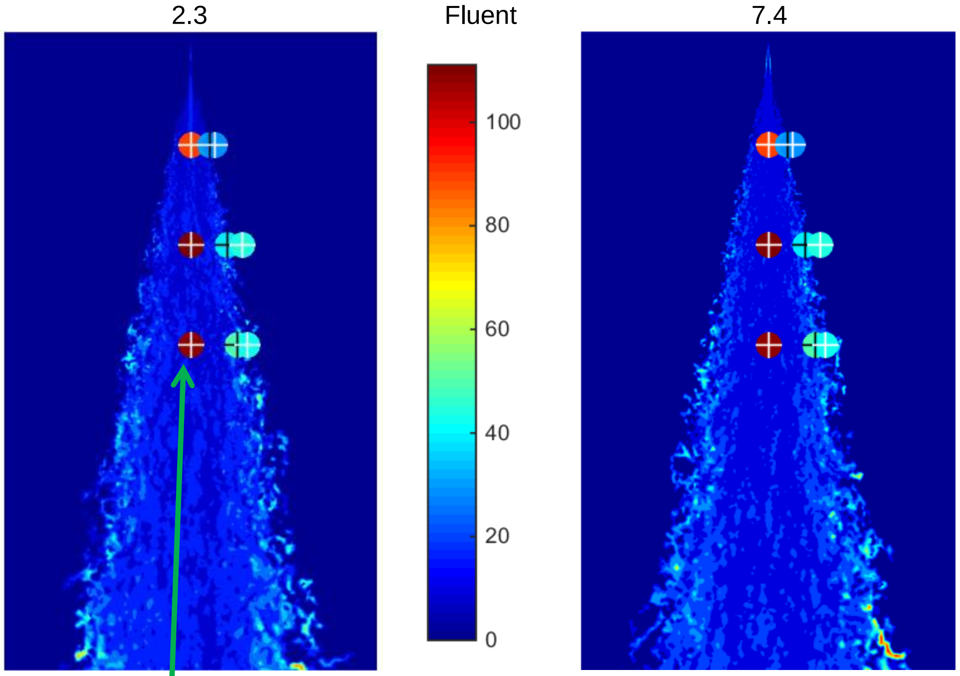
CFD Modelling: Effect of cone angle

Cone angle has little effect



Droplet concentration (g/m^3)



Droplet SMD (µm)

Good agreement with ignition locations

Poor agreement with droplet size on centreline

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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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- Research Programme
  - Literature Review
  - Fluids Classification
  - Experiments
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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

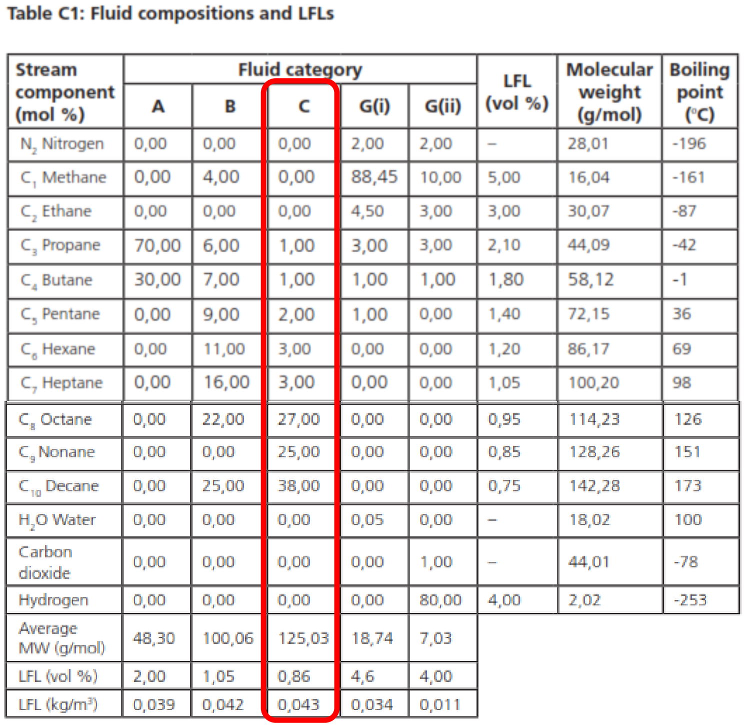

Table C1: Fluid compositions and LFLs

Stream component (mol %)	Fluid category					LFL (vol %)	Molecular weight (g/mol)	Boiling point (°C)
	A	B	C	G(i)	G(ii)			
N_2 Nitrogen	0,00	0,00	0,00	2,00	2,00	–	28,01	-196
C_1 Methane	0,00	4,00	0,00	88,45	10,00	5,00	16,04	-161
C_2 Ethane	0,00	0,00	0,00	4,50	3,00	3,00	30,07	-87
C_3 Propane	70,00	6,00	1,00	3,00	3,00	2,10	44,09	-42
C_4 Butane	30,00	7,00	1,00	1,00	1,00	1,80	58,12	-1
C_5 Pentane	0,00	9,00	2,00	1,00	0,00	1,40	72,15	36
C_6 Hexane	0,00	11,00	3,00	0,00	0,00	1,20	86,17	69
C_7 Heptane	0,00	16,00	3,00	0,00	0,00	1,05	100,20	98
C_8 Octane	0,00	22,00	27,00	0,00	0,00	0,95	114,23	126
C_9 Nonane	0,00	0,00	25,00	0,00	0,00	0,85	128,26	151
C_{10} Decane	0,00	25,00	38,00	0,00	0,00	0,75	142,28	173
H_2O Water	0,00	0,00	0,00	0,05	0,00	–	18,02	100
Carbon dioxide	0,00	0,00	0,00	0,00	1,00	–	44,01	-78
Hydrogen	0,00	0,00	0,00	0,00	80,00	4,00	2,02	-253
Average MW (g/mol)	48,30	100,06	125,03	18,74	7,03			
LFL (vol %)	2,00	1,05	0,86	4,6	4,00			
LFL (kg/m³)	0,039	0,042	0,043	0,034	0,011			

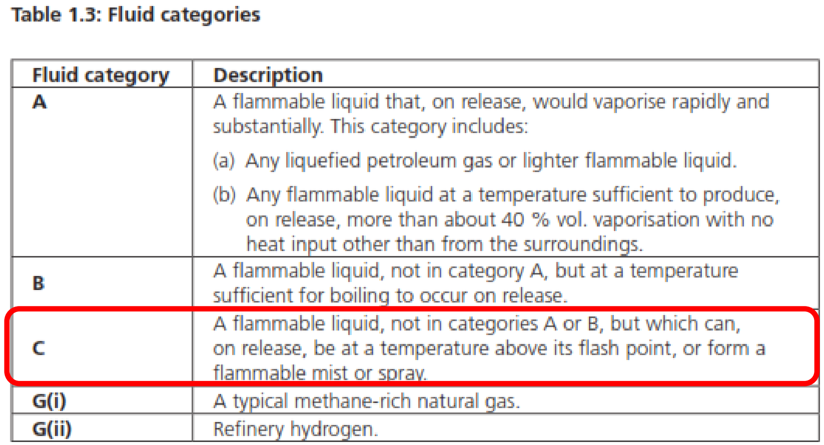

Table 1.3: Fluid categories

Fluid category	Description
A	A flammable liquid that, on release, would vaporise 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. vaporisation with no heat input other than from the surroundings.
B	A flammable liquid, not in category A, but at a temperature sufficient for boiling to occur on release.
C	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.
G(i)	A typical methane-rich natural gas.
G(ii)	Refinery hydrogen.

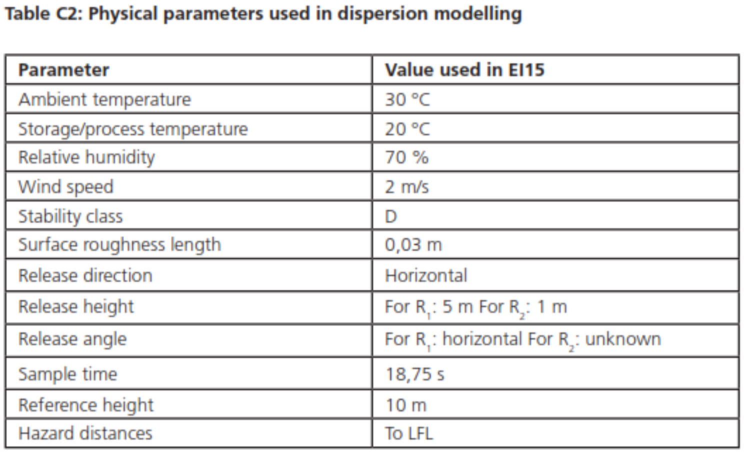

Table C2: Physical parameters used in dispersion modelling

Parameter	Value used in EI15
Ambient temperature	30 °C
Storage/process temperature	20 °C
Relative humidity	70 %
Wind speed	2 m/s
Stability class	D
Surface roughness length	0,03 m
Release direction	Horizontal
Release height	For R_1: 5 m For R_2: 1 m
Release angle	For R_1: horizontal For R_2: unknown
Sample time	18,75 s
Reference height	10 m
Hazard distances	To LFL

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EI15 Code of Safe Practice

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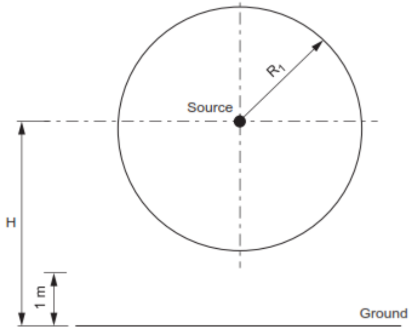
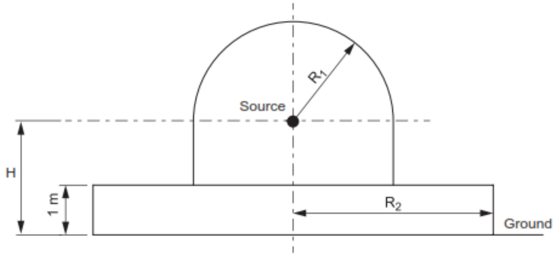
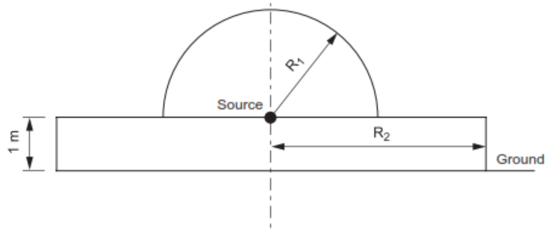


(a) Releases where H > R_1 + 1 m



(b) Releases where 1 m < H < R_1 + 1 m



(c) Releases where H < 1 m

Figure 3.6: Shape factors for pressurised releases

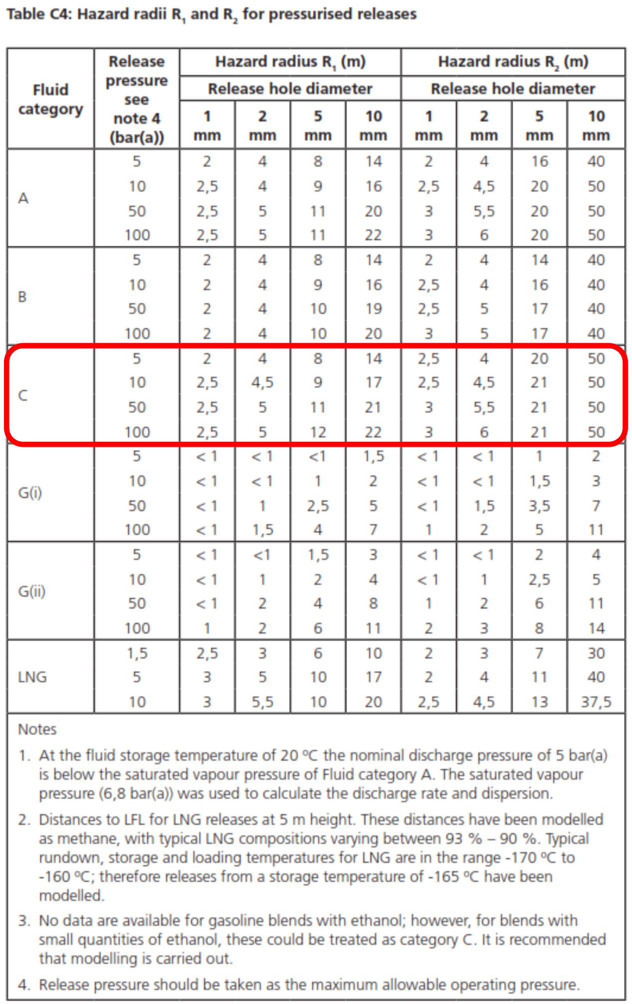


Table C4: Hazard radii R_1 and R_2 for pressurised releases

Fluid category	Release pressure see note 4 (bar(a))	Hazard radius R_1 (m)				Hazard radius R_2 (m)			
		Release hole diameter				Release hole diameter			
		1 mm	2 mm	5 mm	10 mm	1 mm	2 mm	5 mm	10 mm
A	5	2	4	8	14	2	4	16	40
	10	2,5	4	9	16	2,5	4,5	20	50
	50	2,5	5	11	20	3	5,5	20	50
	100	2,5	5	11	22	3	6	20	50
B	5	2	4	8	14	2	4	14	40
	10	2	4	9	16	2,5	4	16	40
	50	2	4	10	19	2,5	5	17	40
	100	2	4	10	20	3	5	17	40
C	5	2	4	8	14	2,5	4	20	50
	10	2,5	4,5	9	17	2,5	4,5	21	50
	50	2,5	5	11	21	3	5,5	21	50
	100	2,5	5	12	22	3	6	21	50
G(i)	5	< 1	< 1	<1	1,5	< 1	< 1	1	2
	10	< 1	< 1	1	2	< 1	< 1	1,5	3
	50	< 1	1	2,5	5	< 1	1,5	3,5	7
	100	< 1	1,5	4	7	1	2	5	11
G(ii)	5	< 1	<1	1,5	3	< 1	< 1	2	4
	10	< 1	1	2	4	< 1	1	2,5	5
	50	< 1	2	4	8	1	2	6	11
	100	1	2	6	11	2	3	8	14
LNG	1,5	2,5	3	6	10	2	3	7	30
	5	3	5	10	17	2	4	11	40
	10	3	5,5	10	20	2,5	4,5	13	37,5

Notes

1. At the fluid storage temperature of 20 ºC 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 LFL 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 ºC to -160 ºC; therefore releases from a storage temperature of -165 ºC 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.

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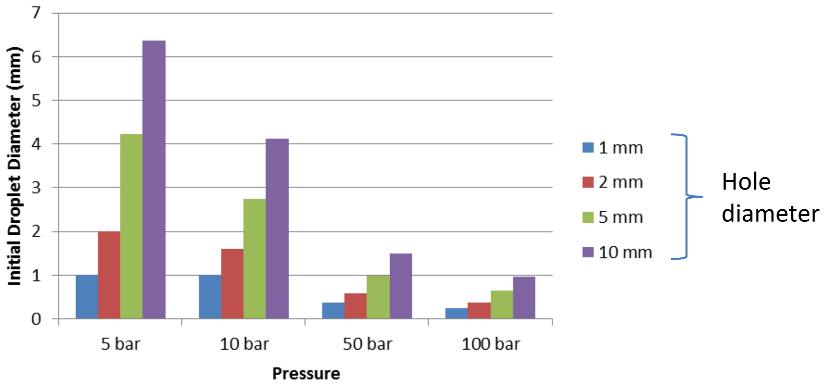
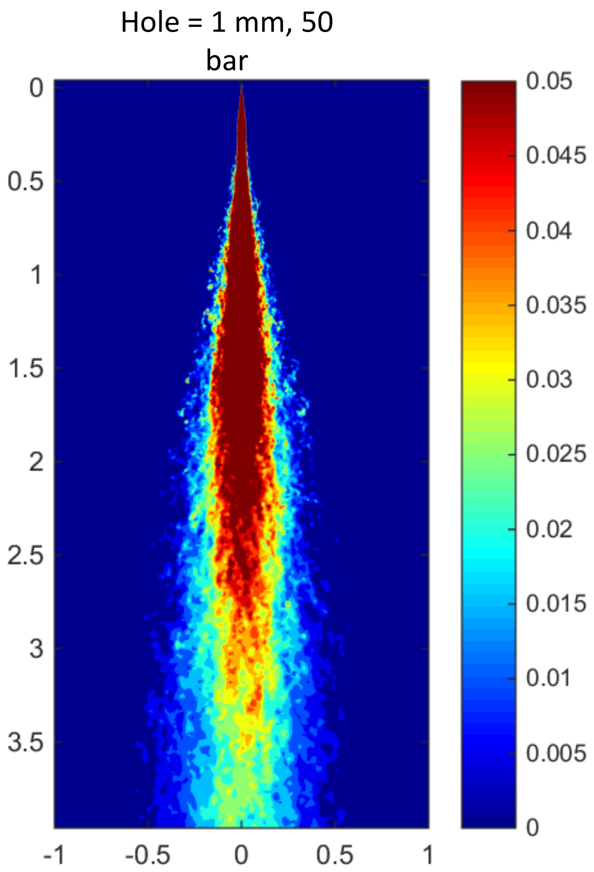
CFD Modelling of EI15 Conditions

- 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





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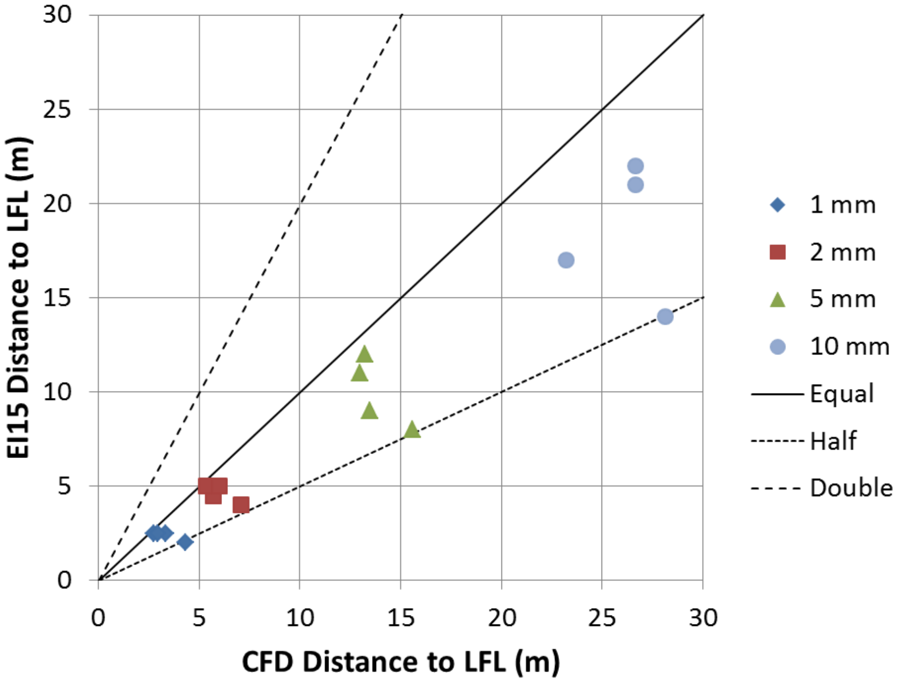
CFD compared to EI15



- 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

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Tentative Area Classification Guidelines

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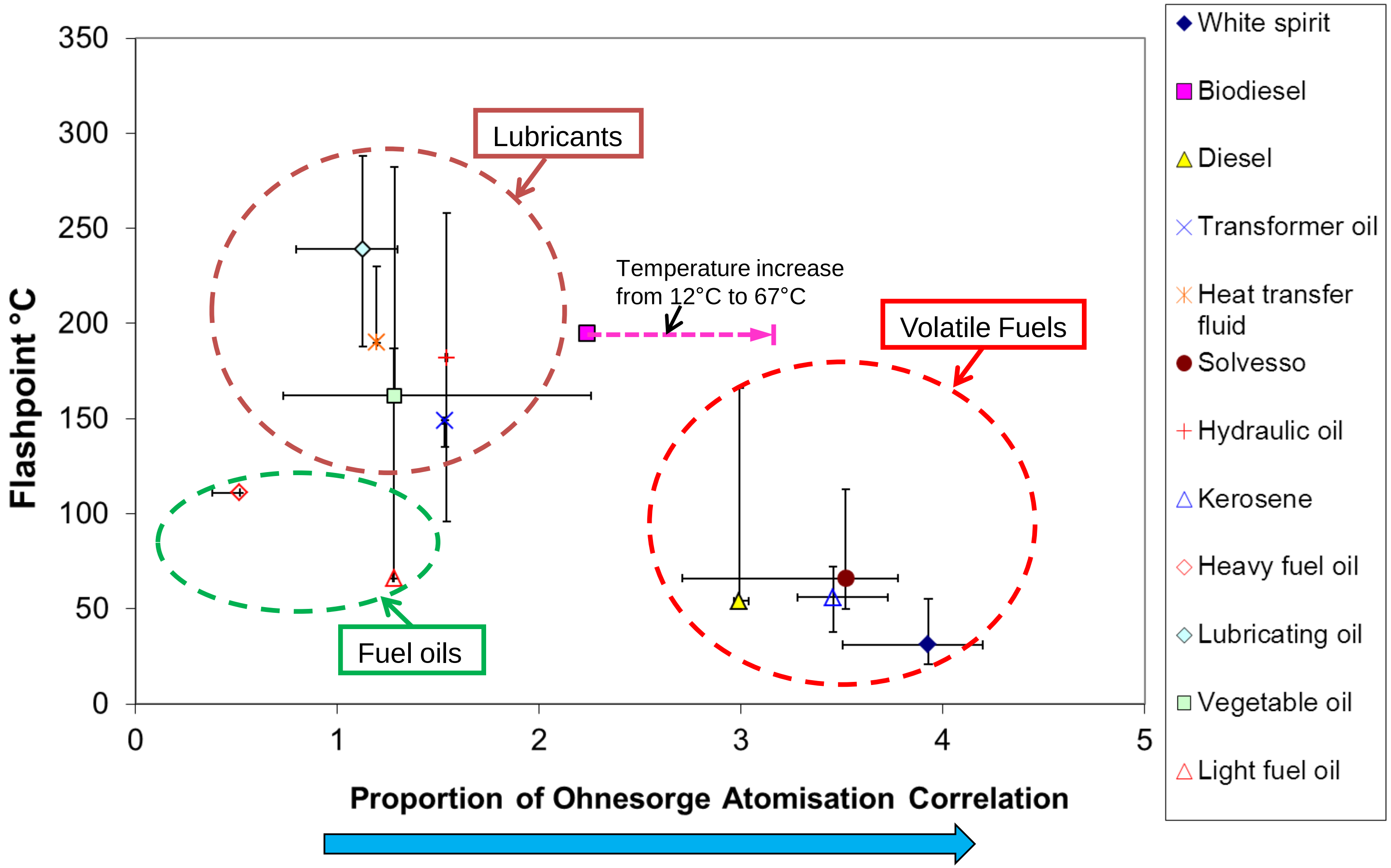

Based on 1 mm diameter orifice at 10 bar

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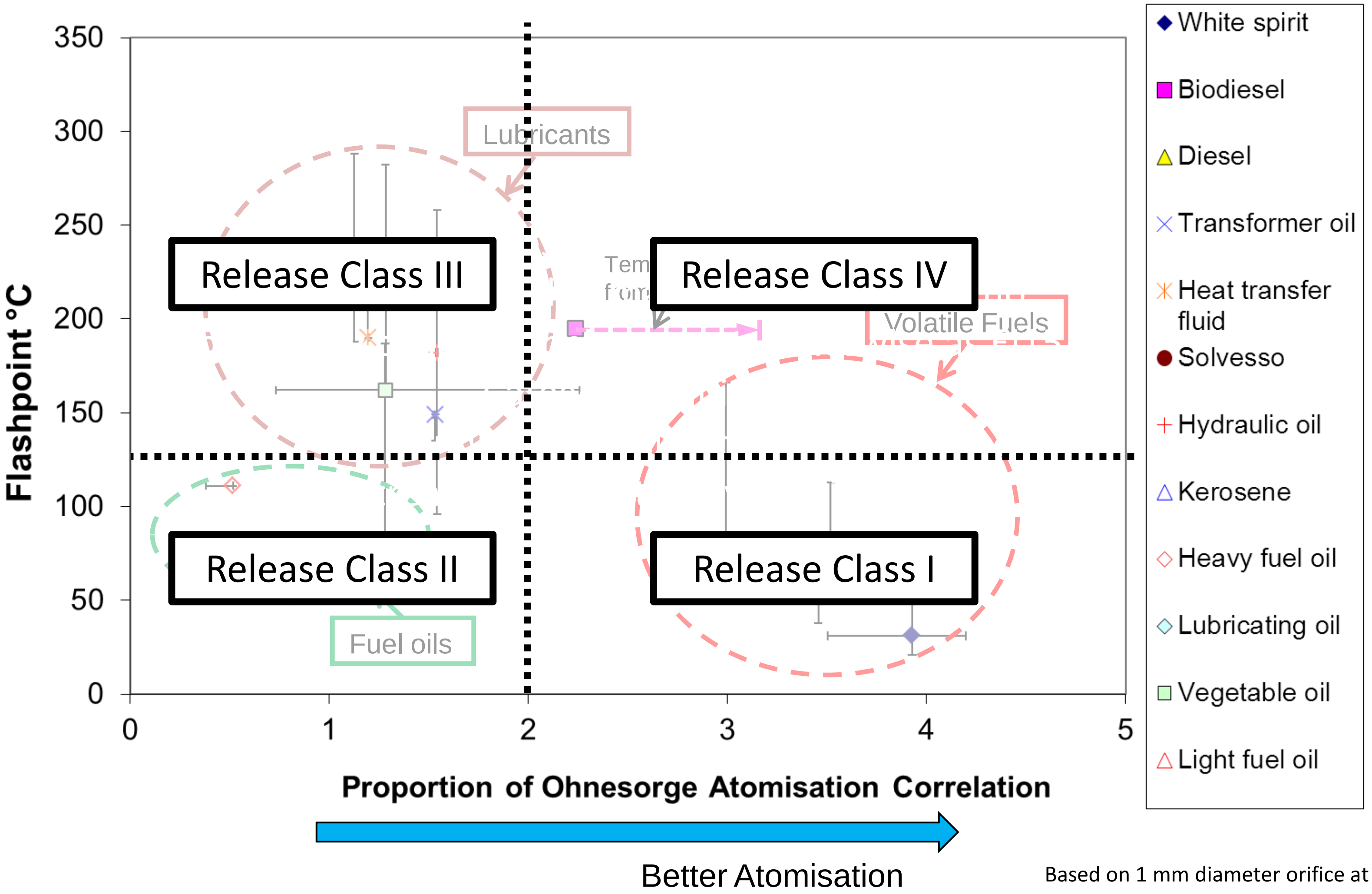
Tentative Area Classification Guidelines



Based on 1 mm diameter orifice at 10 bar

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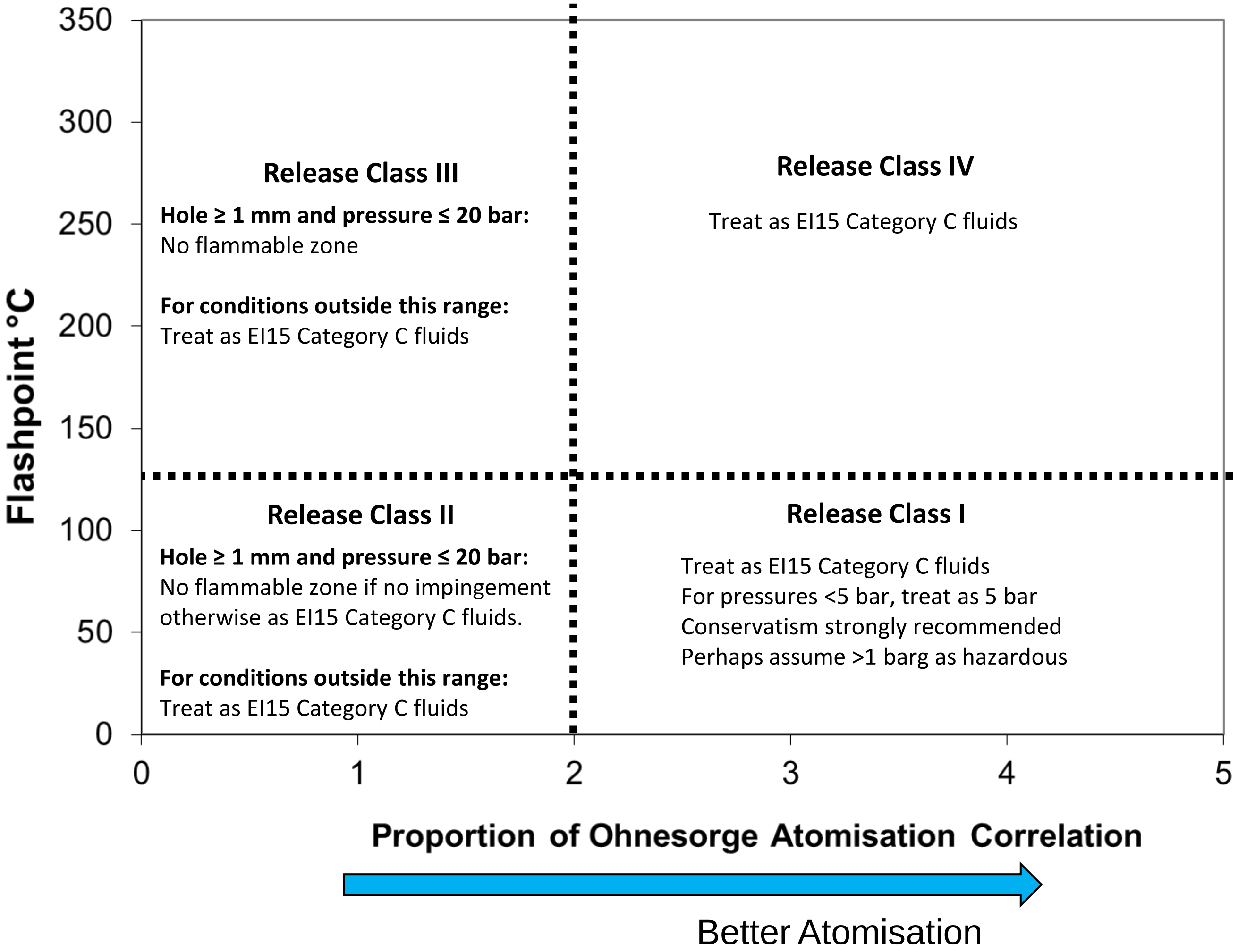
Tentative Area Classification Guidelines



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 IV

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 I

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

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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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Contents

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  - Literature Review
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  - Experiments
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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)

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Acknowledgement

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- 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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24 –26 May 2016, Edinburgh, UK

Stand 39

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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)

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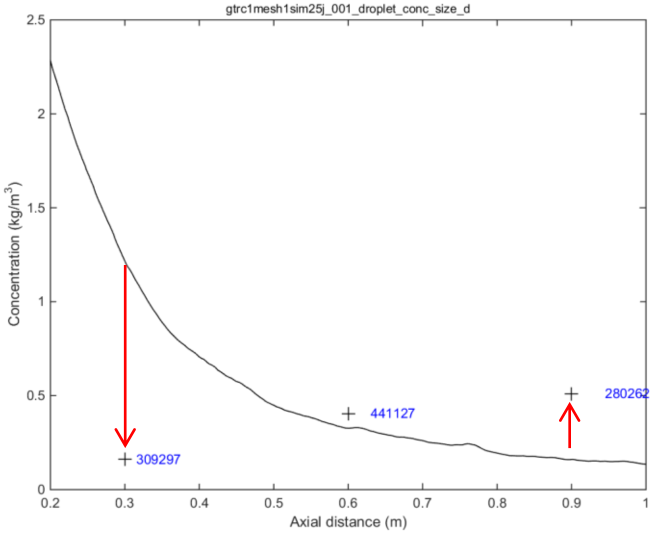
Statistical Performance Measures (SPMs)

- Mean relative bias
  - Ability to predict on average

$$MRB = \left\langle \frac{(C_o - C_p)}{(C_p + C_o)/2} \right\rangle$$



- Mean relative square error
  - The level of scatter

$$MRSE = \left\langle \frac{(C_o - C_p)^2}{[(C_p + C_o)/2]^2} \right\rangle$$

C_o = observed C_p = predicted

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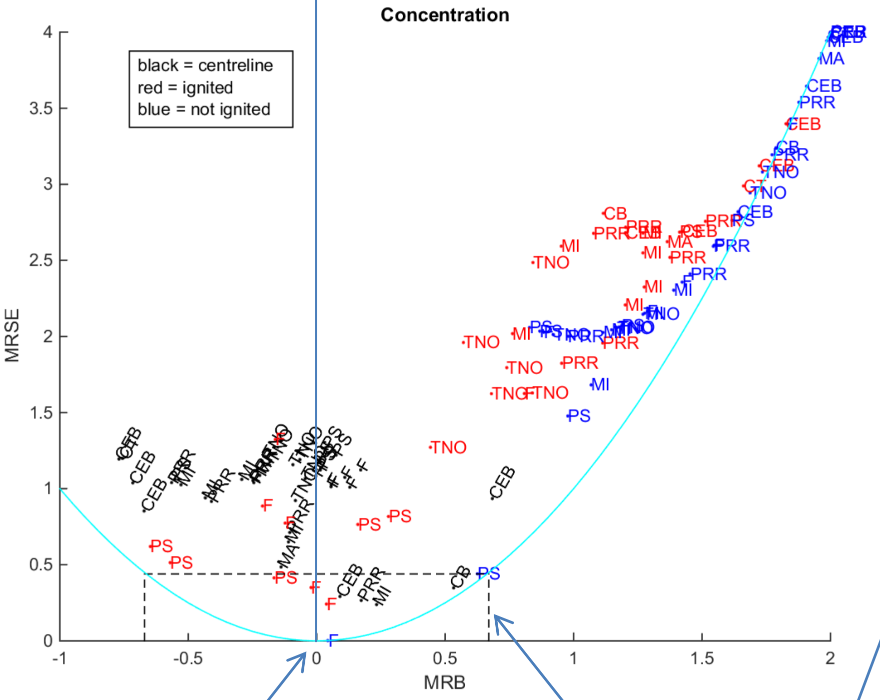
SPMs for Concentration

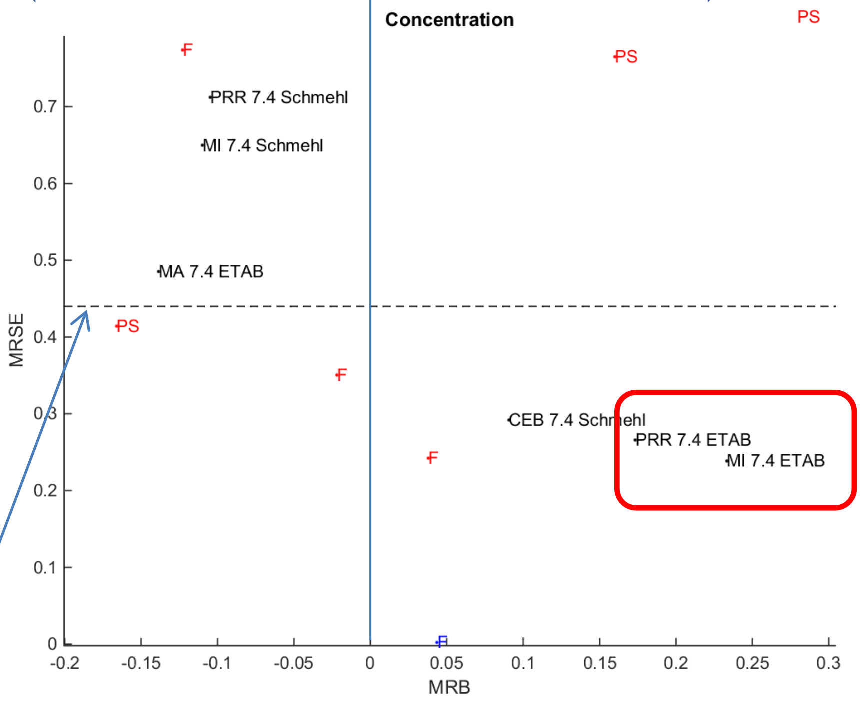
Model over-predicts

Model under-predicts



Model over-predicts

Model under-predicts



"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

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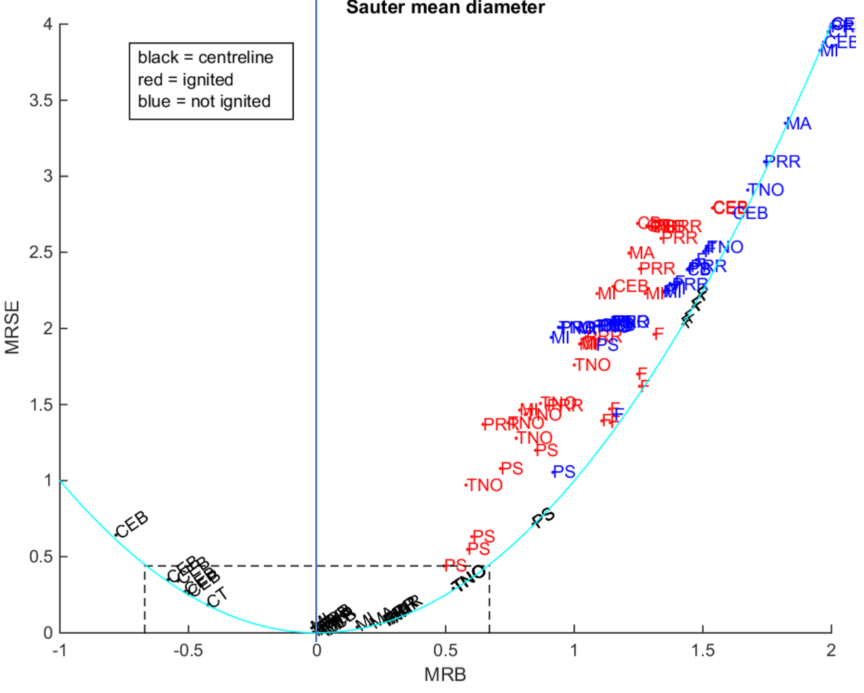
SPMs for Sauter Mean Diameter

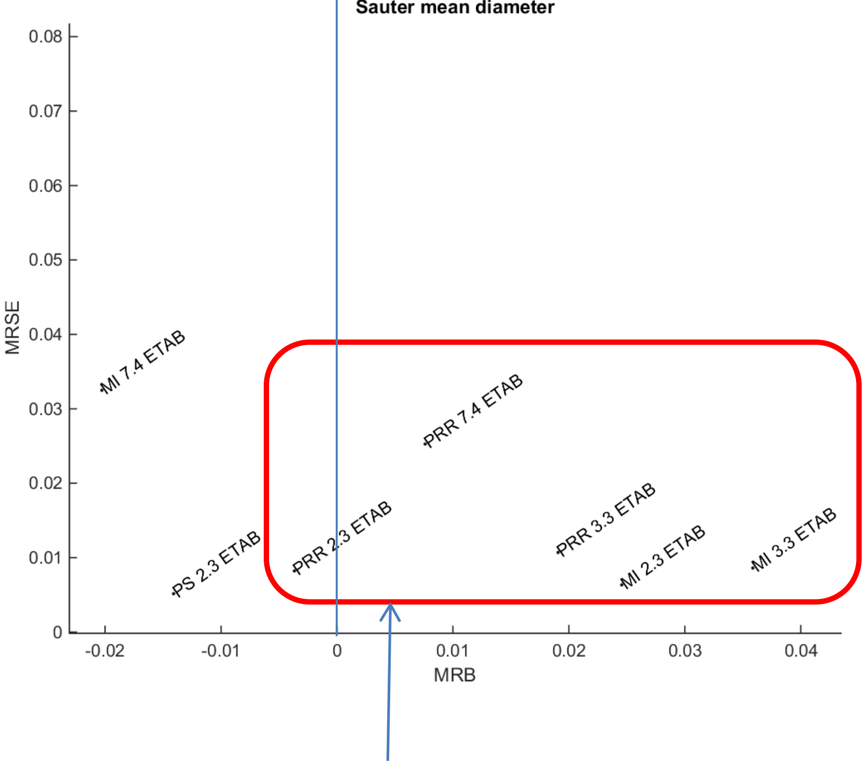
Model over-predicts

Model under-predicts



Model over-predicts

Model under-predicts



PRR = DNV Phase III JIP Rosin-Rammler

MI = Miesse

within factor-of-two for both concentration and SMD on centreline of spray

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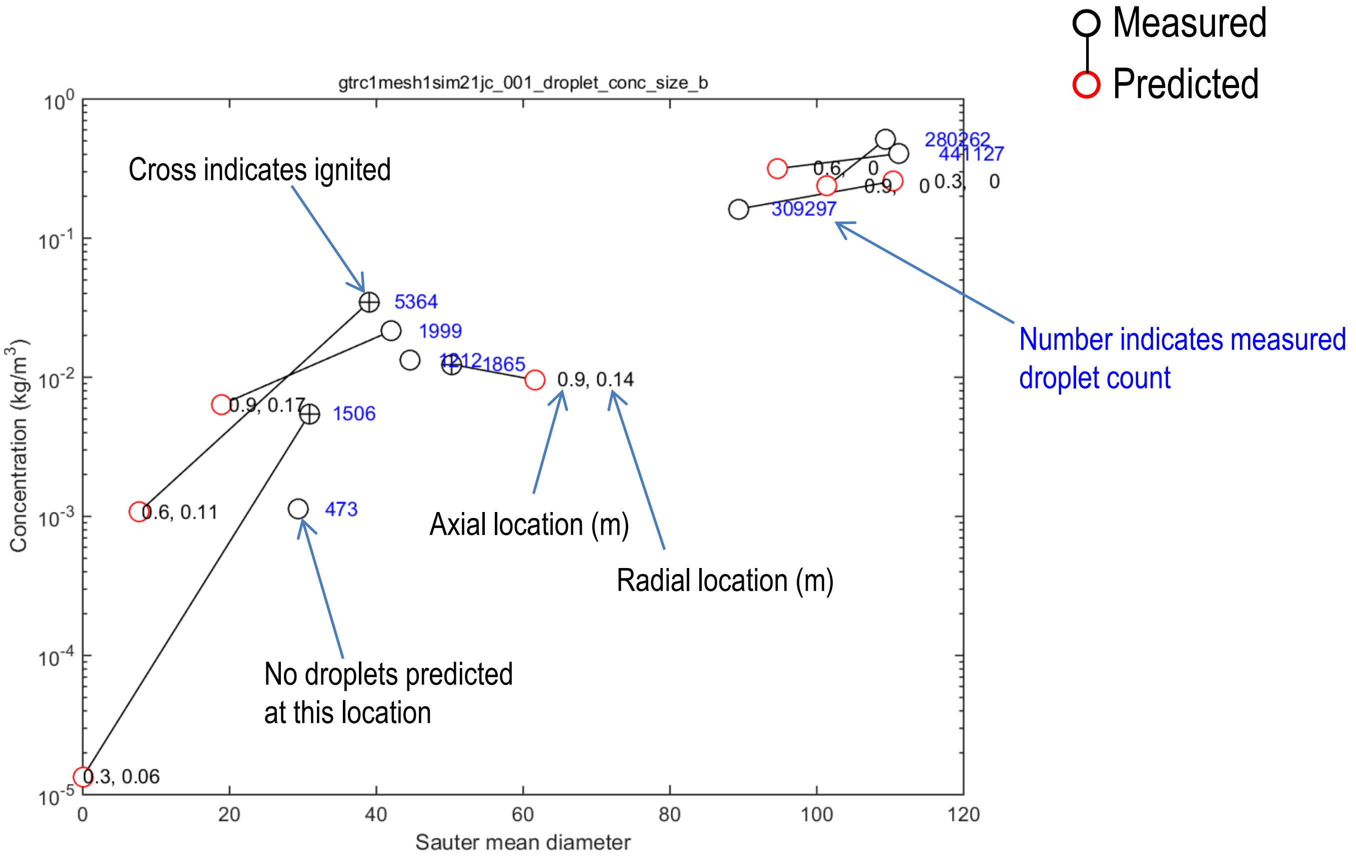
Do the SPM results make sense?

- DNV Phase III JIP model



Cross indicates ignited

Number indicates measured droplet count

Axial location (m)

Radial location (m)

No droplets predicted at this location

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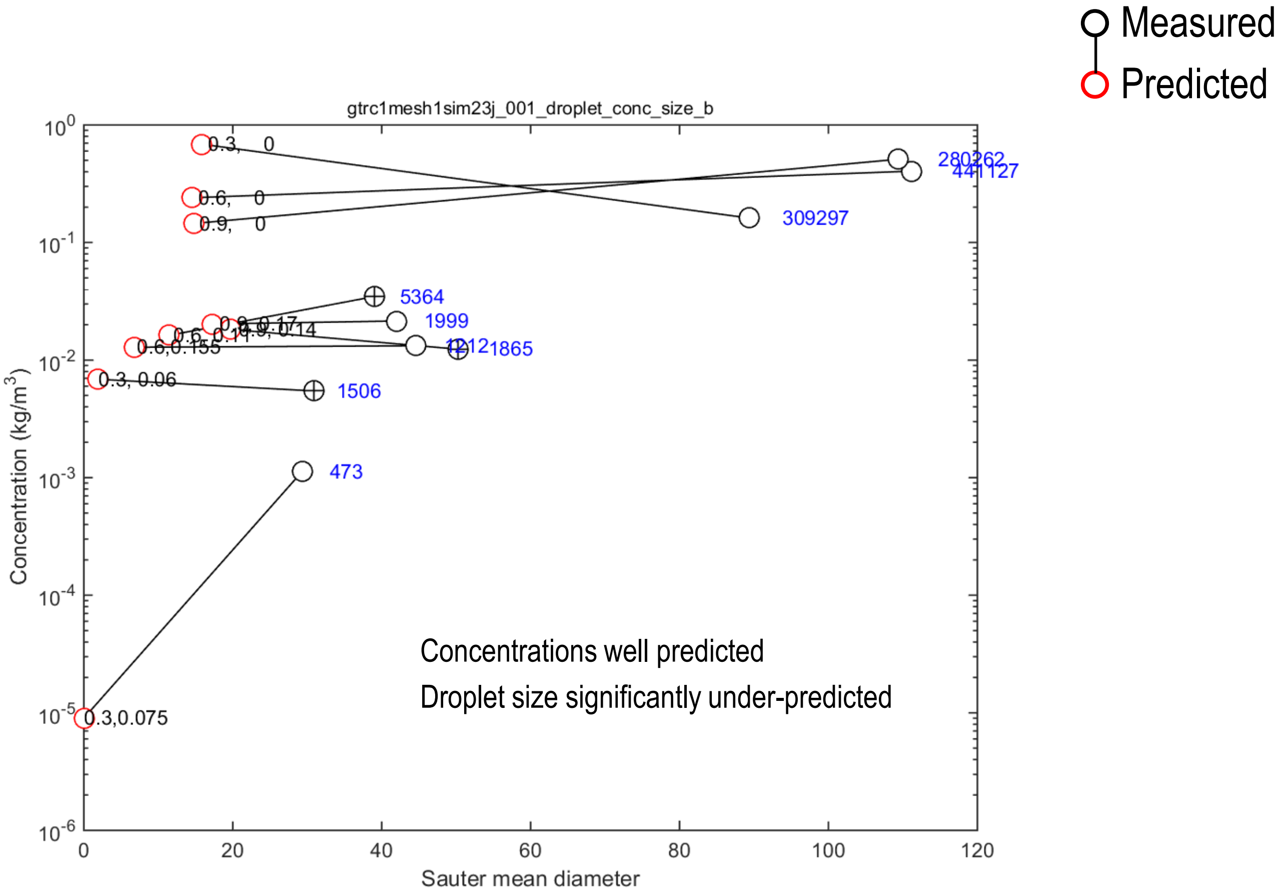
Do the SPM results make sense?

- Fluent model



Concentrations well predicted

Droplet size significantly under-predicted

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