FABIG

FIRE AND BLAST INFORMATION GROUP

Lunchtime Webinar – 13 January 2021

The benefits of blind benchmarking of Probabilistic Explosion Risk Analysis (ERA) studies

abercus

rps MAKING COMPLEX EASY

Prankul Middha and Steve Howell (Abercus) and Tim Jones (RPS)

Agenda

Introduction – probabilistic ERA

Uncertainties in probabilistic ERA approach

Way forward

PROBABLAST JIP.

Agenda

Introduction – probabilistic ERA

Uncertainties in probabilistic ERA approach

Way forward

PROBABLAST JIP.

Introduction – probabilistic ERA

Explosion safety timeline

1970s – Need to understand explosions/simple models
- 1974: Flixborough explosion

1980s – Need to change safety standards/regulations
- 1988: Piper Alpha explosion and fire

1990s – Need to consider risk management/escalation

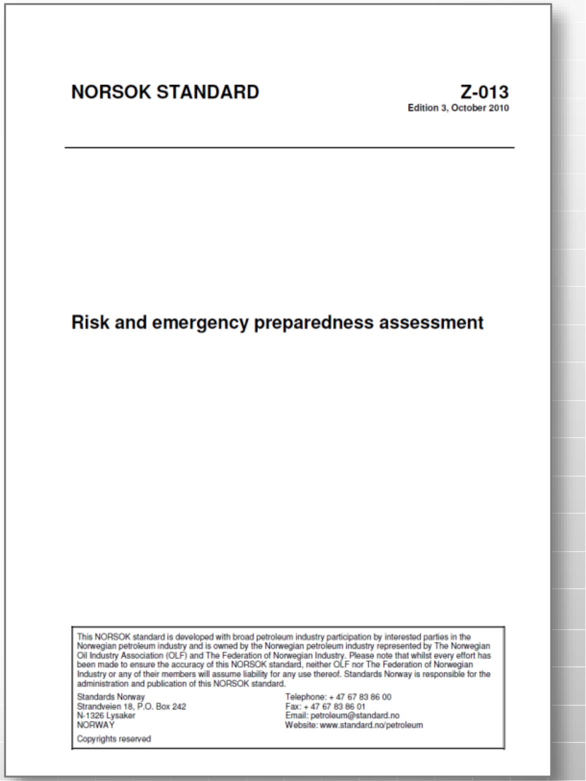
1990s – Explosion pressures higher than expected, explosion phenomena too complex for simple models, CFD required

2000s – Probabilistic ERA industry standard (NORSOK Z-013)

Introduction – probabilistic ERA

NORSOK Z-013

- The oil and gas industry has steadily moved towards a probabilistic approach for explosion risk assessment (ERA) since the conception of the NORSOK Z-013 standard [1] in the late 1990's and its first publication in 2001.



NORSOK STANDARD **Z-013**
Edition 3, October 2010

Risk and emergency preparedness assessment

This NORSOK standard is developed with broad petroleum industry participation by interested parties in the Norwegian petroleum industry and is owned by the Norwegian petroleum industry represented by The Norwegian Oil Industry Association (OLF) and The Federation of Norwegian Industry. Please note that whilst every effort has been made to ensure the accuracy of this NORSOK standard, neither OLF nor The Federation of Norwegian Industry or any of their members will assume liability for any use thereof. Standards Norway is responsible for the administration and publication of this NORSOK standard.

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[1] Risk and Emergency Preparedness Analysis, NORSOK standard Z-013 Annex F, Rev 3, 2010.

Introduction – probabilistic ERA

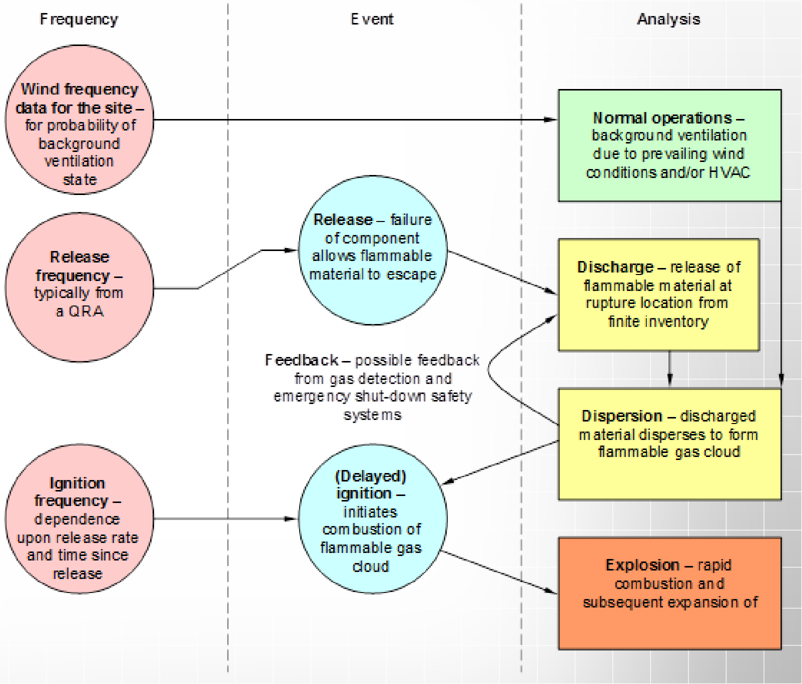
NORSOK Z-013 – typical methodology

- A probabilistic explosion risk assessment in line with NORSOK Z-013 involves three steps:
  - CFD simulations – use computational fluid dynamics (CFD) to simulate a large number of deterministic gas dispersion and explosion consequences to form a database of representative scenarios for pre and post (delayed) ignition behaviour following a loss of containment of flammable material.
  - Probabilistic analysis – consider frequencies and probabilities of release and ignition for each simulated scenario to construct exceedance data for blast loads.
  - Determine the blast loads – from the exceedance data, retrieve the blast load corresponding to the acceptability criterion (often 10^{-4}/yr or 10^{-5}/yr).

Introduction – probabilistic ERA

NORSOK Z-013 – typical methodology

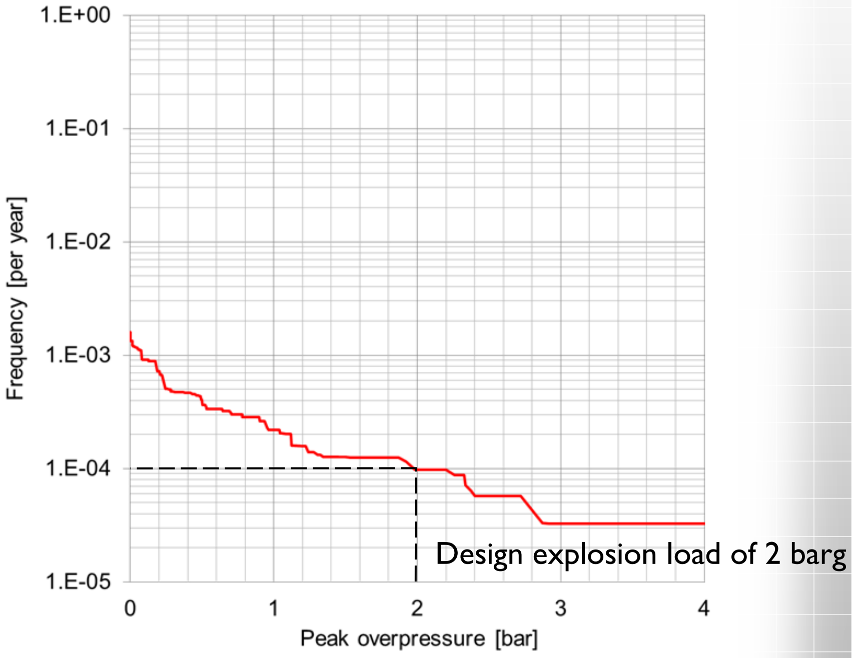
- Simulate a large number of deterministic representative scenarios
  - ventilation/dispersion/explosion.
- These stages are often decoupled so that each is a separate body of work connected only by frequency arguments relating to a single metric.
- With an understanding of the frequencies of occurrence at each stage, exceedance data for the explosion loads can be compiled.



Introduction – probabilistic ERA

NORSOK Z-013 – exceedance curves and the 10^{-4} criterion

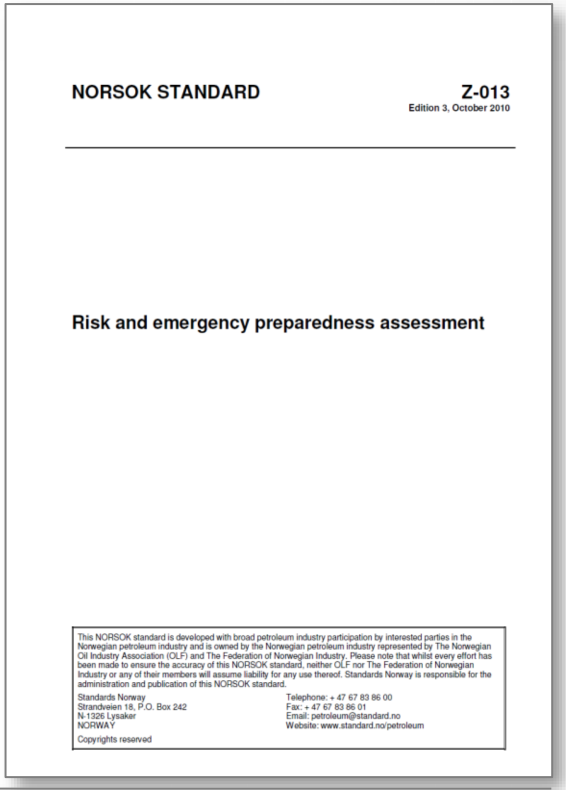
- The exceedance curves show the predicted frequency for explosion loading at a target of interest.
- For a specified allowable frequency, the design load is read from the curve and can be used as the basis of the structural design.



Introduction – probabilistic ERA

NORSOK Z-013 – potential for inconsistency

- NORSOK Z-013 is not prescriptive – there is room for interpretation
- The **devil is in the detail**, and each party undertaking probabilistic ERA in line with the standard is required to, develop its own approach
- Inevitably this can lead to inconsistency across the industry [2,3]
- This was recognised as early as the 1990s.



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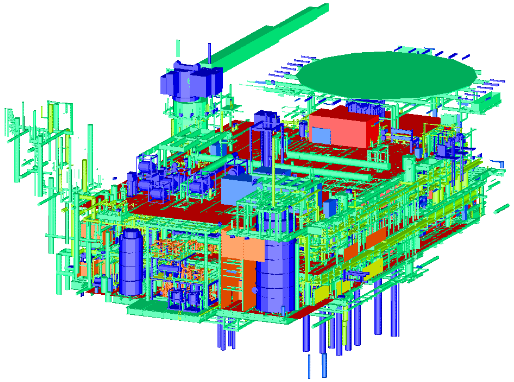
[2] *A review of the Q9 equivalent cloud method for explosion modelling*, Stewart J and Gant S (UK HSE), FABIG newsletter 75, 2019.

[3] *Quantifying risk and how it all goes wrong*, Miller K, Hazards 28, 2018.

Introduction – probabilistic ERA

NORSOK Z-013 – previous ERA blind comparison [4]

- In 1999, Statoil and Norsk Hydro arranged a blind comparison exercise to investigate the potential for inconsistency with the NORSOK Z-013 approach:
  - Five leading Norwegian consultancies performed nominally identical probabilistic ERA for the Huldra platform [4]
  - Exceedance curves for overpressure were compiled and presented anonymously (participants are identified only as A to E).



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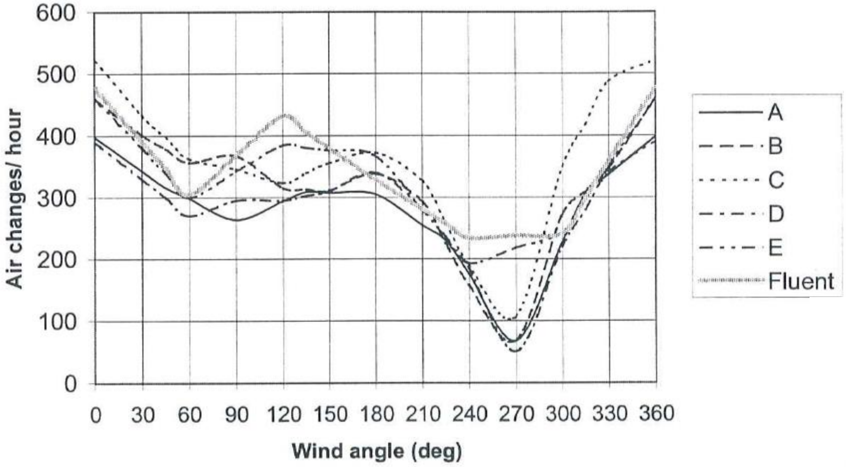
[4] *Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants*, Holen J, ERA Conference, London, 2001.

Introduction – probabilistic ERA

NORSOK Z-013 – previous ERA blind comparison [4]

- Four participants (A-D) used the FLACS CFD code and simulated transient dispersion.
- The fifth participant (E) used FLUENT for ventilation/ dispersion and FLACS for explosion, and simulated steady-state dispersion.

Air changes – 10 m/s wind



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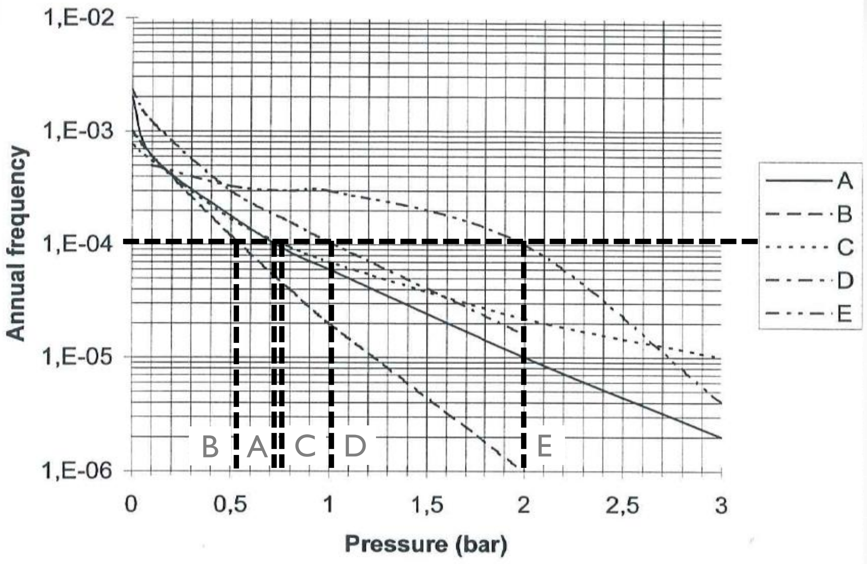
[4] *Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants*, Holen J, ERA Conference, London, 2001.

Introduction – probabilistic ERA

NORSOK Z-013 – previous ERA blind comparison [4]

- Participants A-D predicted a 10^{-4}/yr overpressure of 0.5-1.0 barg at the firewall
  - Predictions A and C were very close
- Participant E predicted 2 barg.
- As a consequence of this comparison, standard ERA procedures were agreed but unfortunately they have diverged again in recent years.

Exceedance curves for overpressure at the firewall



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[4] *Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants*, Holen J, ERA Conference, London, 2001.

Introduction – probabilistic ERA

NORSOK Z-013 – concerns with current methodology

- In recent years, several parties have expressed concerns relating to the consistency of the probabilistic approach:
  - NORSOK Z-013 is not prescriptive – there is room for interpretation.
  - There is no international standard detailing the methodology.
  - No similar benchmark as that carried out in Norway in the late 1990s has ever been performed in the UK or other regions around the world.
  - Abercus and RPS have reviewed several probabilistic studies and, depending upon the input assumptions, the design blast loads may vary significantly.

Introduction – probabilistic ERA

NORSOK Z-013 – concerns with current methodology

- In recent years, several parties have expressed concerns relating to the consistency of the probabilistic approach.
- Recent work from the UK HSE stated [2]:
  - *Clearer guidance on how probabilistic ERA should be undertaken is needed, along with more rigorous documentation of the assumptions, and associated uncertainties, made when performing an ERA to determine an overpressure exceedance curve. With the present system, it is extremely difficult to have proper oversight (either by the client or regulator) when the ERA is based on so many expert judgement decisions.* ***There is little value in undertaking ERA studies if the results cannot be trusted****.*

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[2] *A review of the Q9 equivalent cloud method for explosion modelling*, Stewart J and Gant S (UK HSE), FABIG newsletter 75, 2019.

Introduction – probabilistic ERA

NORSOK Z-013 – concerns with current methodology

- The NORSOK Z013 standard was first released in the late 1990s at a time when CFD was still a niche technology with relatively few practitioners – it has now been around for 20 years.
- During the same period there have been continual advances in both computer hardware and engineering simulation tools, and the use of simulation technologies continues to increase apace.
- There are now many more parties offering probabilistic ERA studies than there were 20 years ago and, as such, there is an urgent need to establish whether this work is done in a consistent manner across the industry − essentially an update to the previous Norwegian comparison exercise.

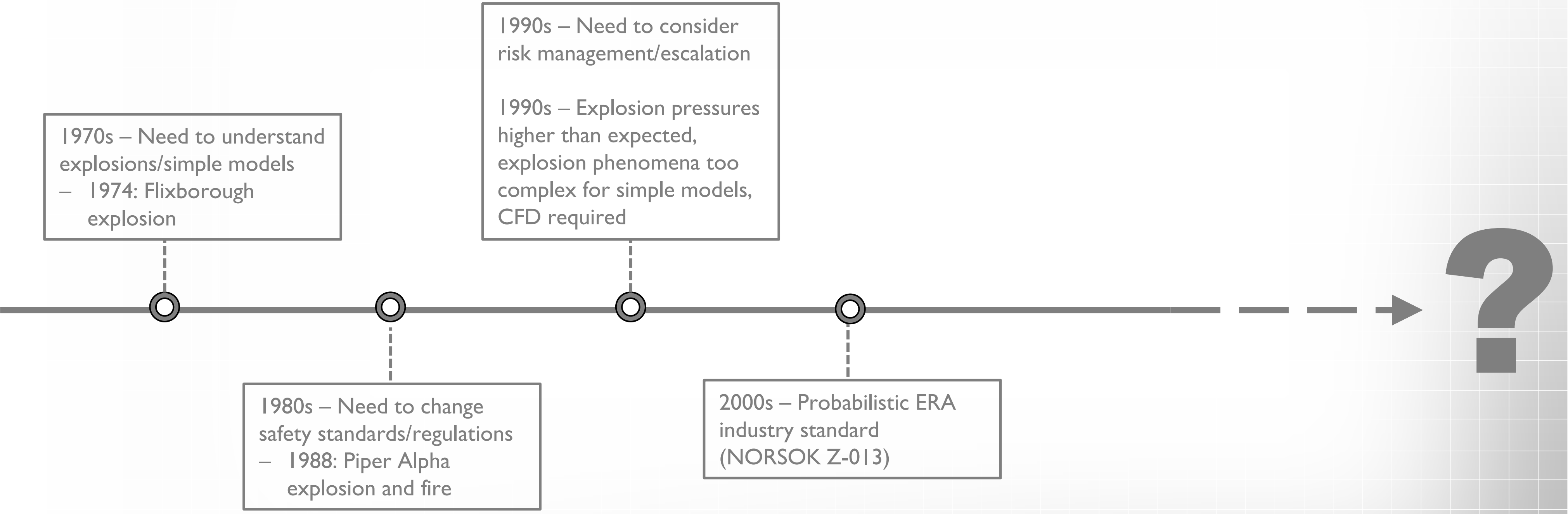
Introduction – probabilistic ERA

NORSOK Z-013 – concerns/potential implications

- Lack of guidance leads to lack of consistency.
- This can lead to over/under design of SCEs (for example, blast walls, decks and vessel supports).
  - Over design leads to unnecessary weight and cost and possibly protection against ‘wrong’ hazards
  - Under design leads to the risk to personnel being underestimated.
- Difficulty to ensure consistency of design process
  - Often, these studies are completed numerous times (different stages of the project lifecycle)
  - Unless the EPC company/operator uses the same ERA provider, the design loads may change significantly

Introduction – probabilistic ERA

Explosion safety timeline



1970s – Need to understand explosions/simple models
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1990s – Explosion pressures higher than expected, explosion phenomena too complex for simple models, CFD required

2000s – Probabilistic ERA industry standard (NORSOK Z-013)

Agenda

Introduction – probabilistic ERA

Uncertainties in probabilistic ERA approach

Way forward

PROBABLAST JIP.

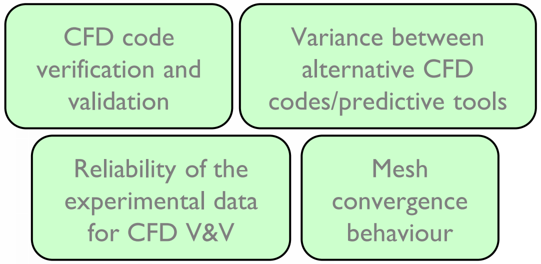
Uncertainties in probabilistic ERA approach

Areas of uncertainty

	Deterministic	**Probabilistic**
Tools/workflows/ procedures	Predictive tools CFD code verification and validation Variance between alternative CFD codes/predictive tools Reliability of the experimental data for CFD V&V Mesh convergence behaviour	Probabilistic methodology Coupling ventilation to dispersion DDT 3D risk assessment Coupling dispersion to explosion Coupling to structural response
Data inputs	Predictive tool inputs (Deterministic simulations) Congestion densities Mesh alignment, representation of obstacles Capturing detection and subsequent shutdown/blowdown Pre-ignition turbulence	Inputs to the probabilistic assessment Scenario selection and resolution (ventilation, dispersion and explosion) Transient leak profiles or steady state Release frequencies Ignition probabilities Frozen cloud

Uncertainties in probabilistic ERA approach

Areas of uncertainty – predictive tools


CFD code verification and validation

Variance between alternative CFD codes/predictive tools

Reliability of the experimental data for CFD V&V

Mesh convergence behaviour

- CFD code verification and validation
  - Are the physical models (for example, combustion and turbulence) robustly implemented within the CFD code
- Reliability of the experimental data used for V&V
  - How repeatable are the underlying explosion experiments (BFETS…)
- Variance between alternative CFD codes/predictive tools
  - How do the predictions for the alternative predictive tools compare?
- Mesh convergence behaviour
  - Can the code converge to a consistent solution upon repeated refinement of the mesh?

Uncertainties in probabilistic ERA approach

Areas of uncertainty – predictive tool inputs (deterministic)

Congestion densities

Mesh alignment, representation of obstacles

Capturing detection and subsequent shutdown/blowdown

Pre-ignition turbulence

- Congestion densities
  - Ventilation and dispersion are affected by congestion
  - Explosion dynamics are strongly affected by congestion
  - How well is congestion density really understood?
- Mesh alignment, representation of obstacles
  - Aligning objects to the mesh can have a significant impact on the predictions from CFD codes employing the porosity distributed resistance (PDR) approach and similar approaches
  - The representation of obstacles, both small-scale (for example, I-beams) and large (for example, a turret) can have a significant effect upon the CFD predictions
- Capturing detection and subsequent shutdown/blowdown
  - Should depressurization start as the release is initiated?
  - Should detection be determined during the course of a simulation by placing detectors within the CFD domain?
- Pre-ignition turbulence
  - Should this be included?
  - Near the jet or everywhere in the cloud?

Uncertainties in probabilistic ERA approach

Areas of uncertainty – probabilistic methodology

Coupling ventilation to dispersion

DDT

3D risk assessment

Coupling dispersion to explosion

Coupling to structural response

- Coupling ventilation to dispersion
  - Coupled by characteristic velocity only?
- Coupling dispersion to explosion
  - Mapping of dispersion predictions to explosion simulations (Q9 / FLAM / LFL+ / real clouds)
- Deflagration-detonation transition
  - What is the likelihood of DDT? Is it considered using the DPDX criterion?
- 3D risk assessment
  - There is no guidance on how to undertake 3D risk assessment, so is the process consistent?
- Coupling to structural response
  - Is it possible to identify a representative event within the simulated explosion scenarios to use for structural design?

Uncertainties in probabilistic ERA approach

Areas of uncertainty – inputs to the probabilistic assessment

Scenario selection and resolution (ventilation, dispersion and explosion)

Transient leak profiles or steady state

Release frequencies

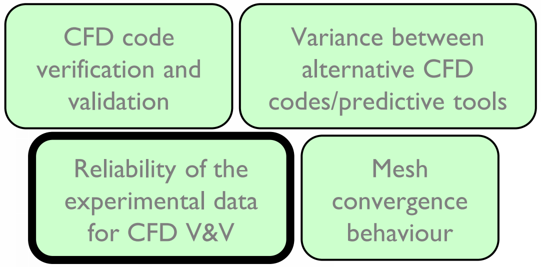
Ignition probabilities

Frozen cloud

- Scenario selection and resolution
  - Ventilation – how many wind speeds/directions should be simulated? Assume low wind speed (conservative) or median or other (may be optimistic)?
  - Dispersion – how many release rates? (Z-013 requires 9!) If fewer, how should intermediate rates be interpolated? Frozen cloud? How many release directions and locations? Should transient dispersion be considered or is steady-state OK?
  - Explosion – how many gas clouds should be considered? What locations/cloud sizes/shapes should be considered?
- Release frequencies
  - How reliable is the available release frequency data?
- Ignition probabilities
  - Which ignition model should be used? (UKOOA, TDIIM, MISOF…)

Uncertainties in probabilistic ERA approach

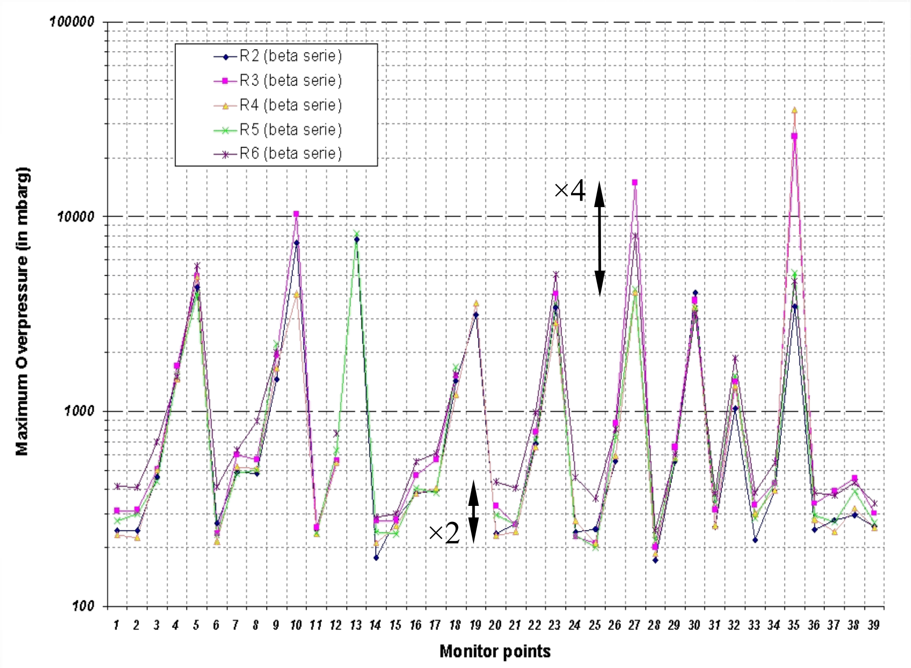
Reliability of the experimental data used for V&V


CFD code verification and validation

Variance between alternative CFD codes/predictive tools

Reliability of the experimental data for CFD V&V

Mesh convergence behaviour



- Experiments used for validation of explosion models have their own uncertainty
- Repeatability is often not studied and when it is, the results may not be ‘satisfactory’ [5]

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[5] *Gas explosions in large scale offshore module geometries: overpressures, mitigation and repeatability*, Al-Hassan T and Johnson DM, OMAE conference, Lisbon, 1998.

Uncertainties in probabilistic ERA approach

Mesh convergence behaviour

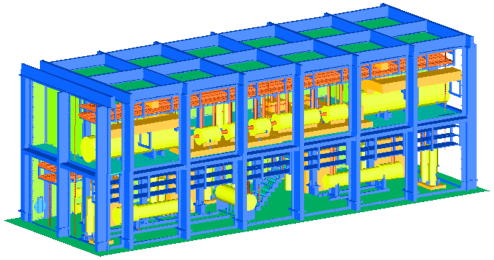
CFD code verification and validation

Variance between alternative CFD codes/predictive tools

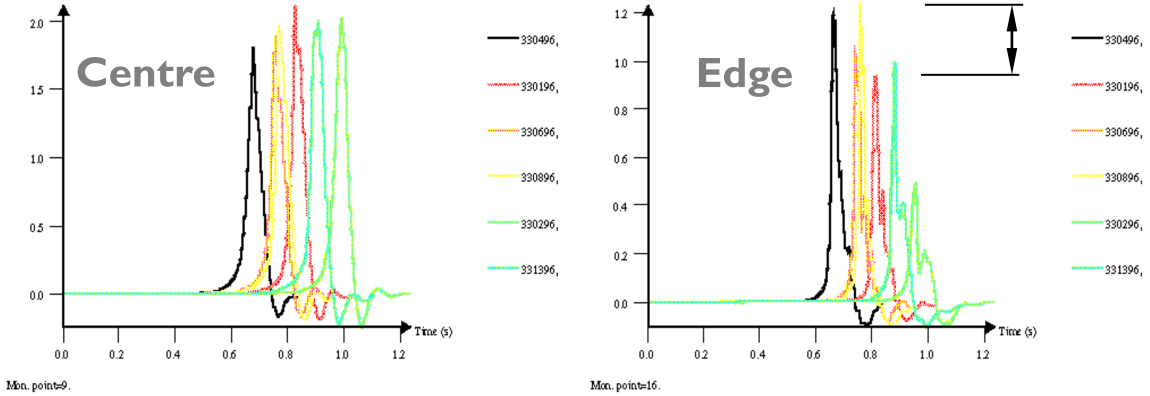
Reliability of the experimental data for CFD V&V

Mesh convergence behaviour

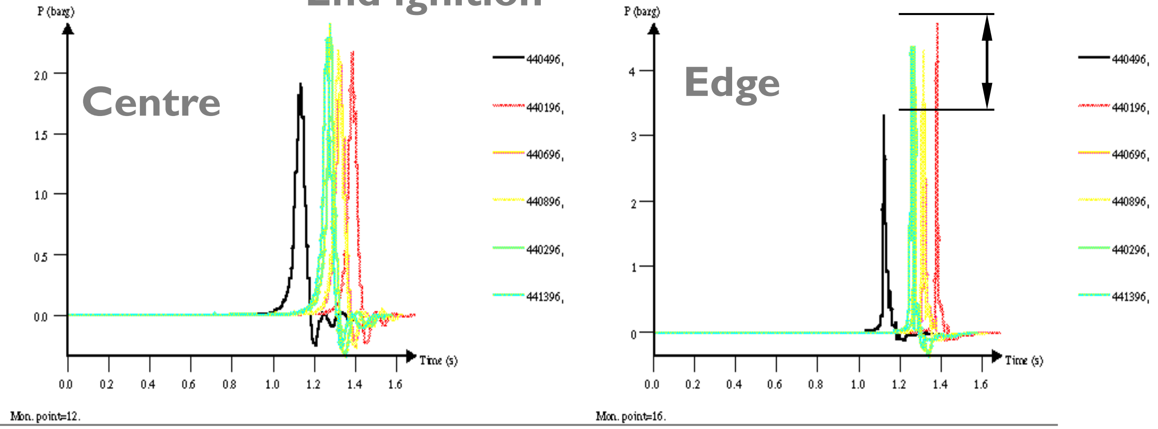
- BFETS full scale geometry
- 6 grid resolutions
  - 0.4 m, 0.66 m, 0.8 m, 1.0 m, 1.3 m, 2.0 m



Central ignition



End ignition



* Credit Gexcon

Uncertainties in probabilistic ERA approach

Variance between alternative CFD tools

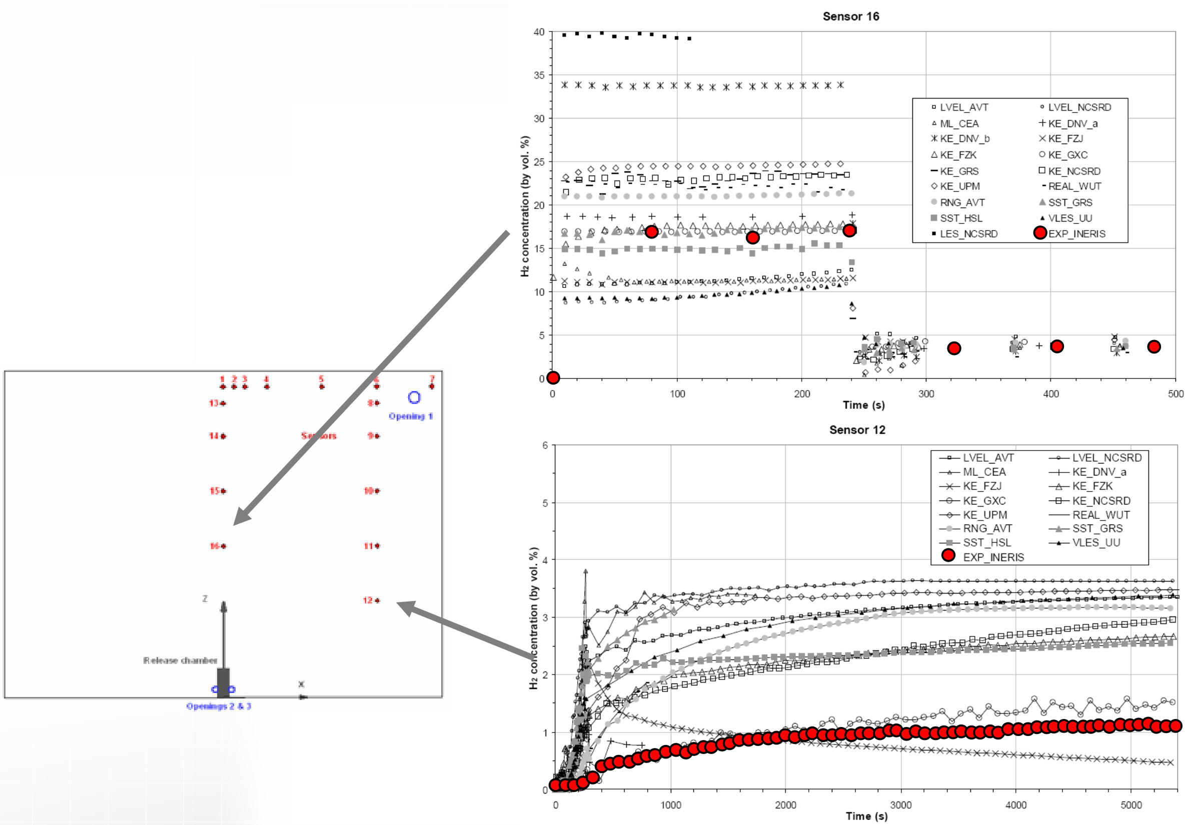
CFD code verification and validation

Variance between alternative CFD codes/predictive tools

Reliability of the experimental data for CFD V&V

Mesh convergence behaviour

- INERIS Garage release experiments [6]
- Hydrogen release, 1 g/s (4 minutes) in a 80 m^3 room



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[6] *An inter-comparison exercise on the capabilities of CFD models to predict the short and long term distribution and mixing of hydrogen in a garage*, Venetsanos AG et al, Intl J Hyd Ener, 34(14), 5912-23, 2009.

Uncertainties in probabilistic ERA approach

Mesh alignment with obstacles

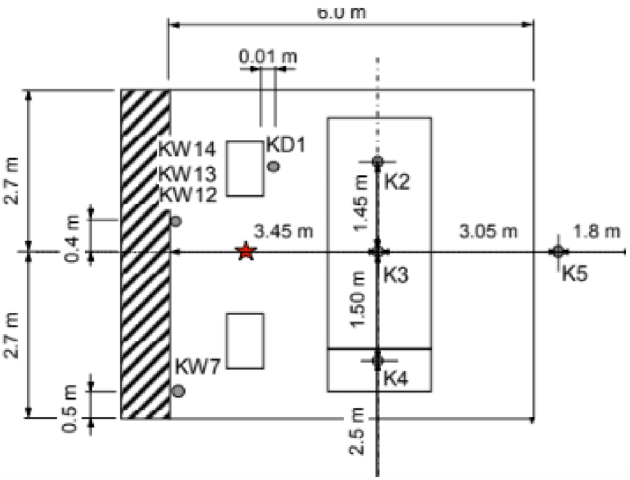
Congestion densities

Mesh alignment, representation of obstacles

Capturing detection and subsequent shutdown/blowdown

Pre-ignition turbulence

- Refueling station experiments [7]
- Hydrogen explosion in a stoichiometric cloud (70 m³)



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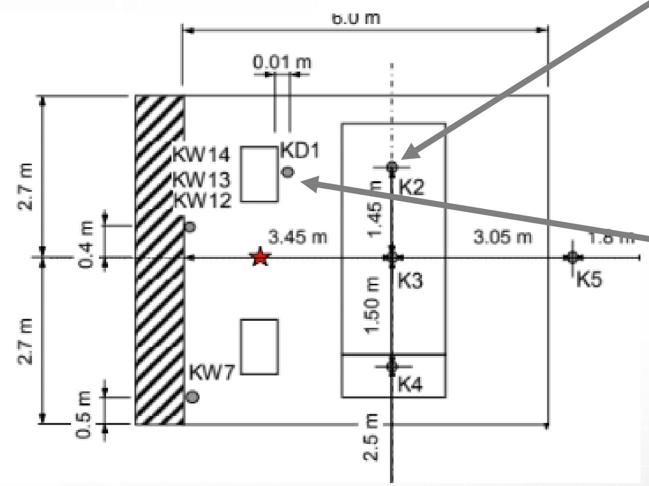
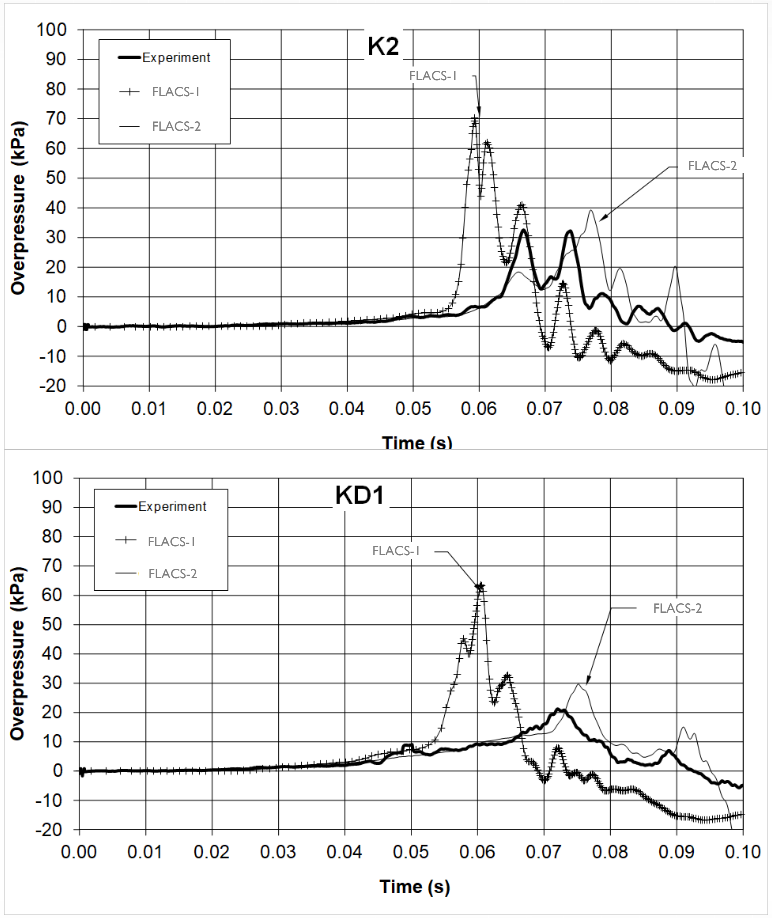
[7] *An inter-comparison exercise on CFD model capabilities to predict a hydrogen explosion in a simulated vehicle refuelling environment,* Makarov D et al, Intl J Hyd Ener, 34(6), 2800-14, 2009.

Uncertainties in probabilistic ERA approach

Mesh alignment with obstacles

- Congestion densities
- **Mesh alignment, representation of obstacles**
- Capturing detection and subsequent shutdown/blowdown
- Pre-ignition turbulence





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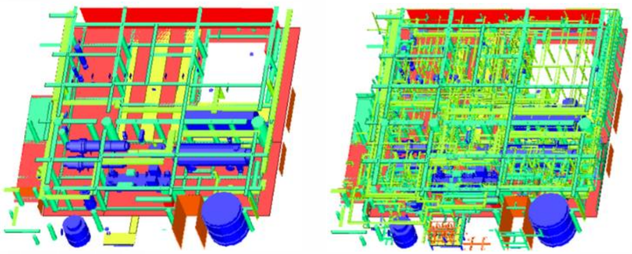

- The effect of congestion upon the explosion overpressures in industrial facilities was first recognized in the early 1980's.
- In our experience, congestion factors have been increasing over the past 15 years, not because facilities are becoming more congested, but because CAD models are including more data.
- It is possible that congestion factors may have been under-estimated in the past.
- There are two sources of congestion information in the public domain known to us [8/9 and 10]

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[8] *A CFD based approach to the correlation of maximum explosion overpressure to process plant parameters*, Huser A, Foyn T and Skottene M, J Loss Prev Proc Ind, 22, 324-331, 2009.

[9] *Turbulence rules – anticipated small pieces modelling*, Huser A, FLACS user group meeting, London, November 2011.

[10] *Development of advanced CFD tools for the enhanced prediction of explosion pressure development and deflagration risk on drilling and production facilities*, RPSEA report 12121-6403-01.Final, 30 September 2016.

Uncertainties in probabilistic ERA approach

Congestion density

Huser and coworkers [8,9]

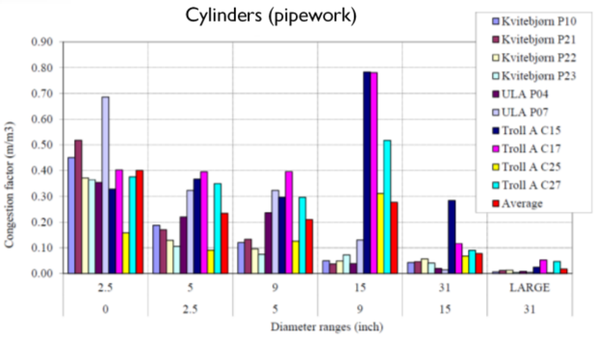
Congestion densities

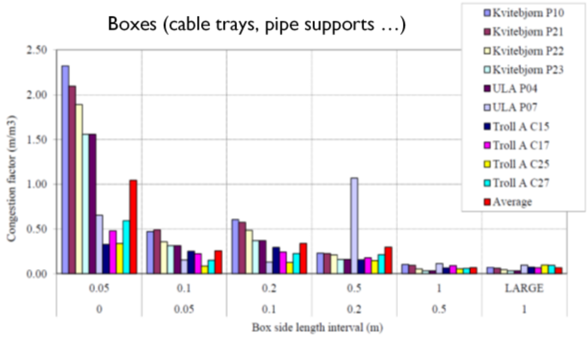
Mesh alignment, representation of obstacles

Capturing detection and subsequent shutdown/blowdown

Pre-ignition turbulence

- Huser and coworkers [8,9] have reported congestion densities for the Kvitebjorn, Ula and Troll A platforms in the Norwegian sector of the North Sea





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Uncertainties in probabilistic ERA approach

Congestion density

Congestion densities

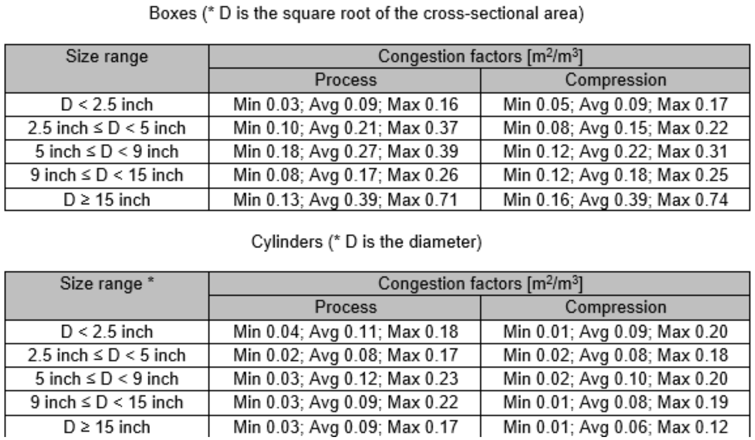
Mesh alignment, representation of obstacles

Capturing detection and subsequent shutdown/blowdown

Pre-ignition turbulence

- The RPSEA report presented a summary of historical congestion data for 15 offshore installations in the Arctic and the Gulf of Mexico
- The minimum, average and maximum congestion densities are presented for process and compression modules.

RPSEA data, m^2/m^3 [10]



Boxes (* D is the square root of the cross-sectional area)

Size range	Congestion factors [m^2/m^3]	
	Process	Compression
D < 2.5 inch	Min 0.03; Avg 0.09; Max 0.16	Min 0.05; Avg 0.09; Max 0.17
2.5 inch ≤ D < 5 inch	Min 0.10; Avg 0.21; Max 0.37	Min 0.08; Avg 0.15; Max 0.22
5 inch ≤ D < 9 inch	Min 0.18; Avg 0.27; Max 0.39	Min 0.12; Avg 0.22; Max 0.31
9 inch ≤ D < 15 inch	Min 0.08; Avg 0.17; Max 0.26	Min 0.12; Avg 0.18; Max 0.25
D ≥ 15 inch	Min 0.13; Avg 0.39; Max 0.71	Min 0.16; Avg 0.39; Max 0.74

Cylinders (* D is the diameter)

Size range *	Congestion factors [m^2/m^3]	
	Process	Compression
D < 2.5 inch	Min 0.04; Avg 0.11; Max 0.18	Min 0.01; Avg 0.09; Max 0.20
2.5 inch ≤ D < 5 inch	Min 0.02; Avg 0.08; Max 0.17	Min 0.02; Avg 0.08; Max 0.18
5 inch ≤ D < 9 inch	Min 0.03; Avg 0.12; Max 0.23	Min 0.02; Avg 0.10; Max 0.20
9 inch ≤ D < 15 inch	Min 0.03; Avg 0.09; Max 0.22	Min 0.01; Avg 0.08; Max 0.19
D ≥ 15 inch	Min 0.03; Avg 0.09; Max 0.17	Min 0.01; Avg 0.06; Max 0.12

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[10] *Development of advanced CFD tools for the enhanced prediction of explosion pressure development and deflagration risk on drilling and production facilities*, RPSEA report 12121-6403-01.Final, 30 September 2016.

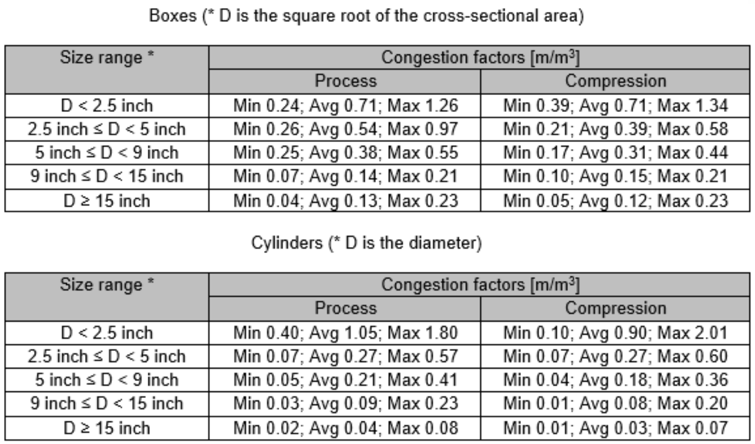
Uncertainties in probabilistic ERA approach

Congestion density

Congestion densities
Mesh alignment, representation of obstacles
Capturing detection and subsequent shutdown/blowdown
Pre-ignition turbulence

- Converting RPSEA data into a length basis for comparison with data from Huser and coworkers (in units [m/m^3]) (converted assuming the mid size for each size range) leads to the right table.
- There is good agreement between the two data sets (Abercus conversion).

RPSEA data, m/m^3 [10]



Boxes (* D is the square root of the cross-sectional area)

Size range *	Congestion factors [m/m^3]	
	Process	Compression
D < 2.5 inch	Min 0.24; Avg 0.71; Max 1.26	Min 0.39; Avg 0.71; Max 1.34
2.5 inch ≤ D < 5 inch	Min 0.26; Avg 0.54; Max 0.97	Min 0.21; Avg 0.39; Max 0.58
5 inch ≤ D < 9 inch	Min 0.25; Avg 0.38; Max 0.55	Min 0.17; Avg 0.31; Max 0.44
9 inch ≤ D < 15 inch	Min 0.07; Avg 0.14; Max 0.21	Min 0.10; Avg 0.15; Max 0.21
D ≥ 15 inch	Min 0.04; Avg 0.13; Max 0.23	Min 0.05; Avg 0.12; Max 0.23

Cylinders (* D is the diameter)

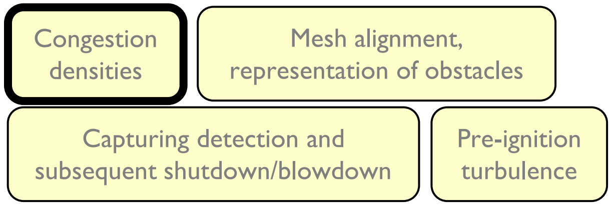
Size range *	Congestion factors [m/m^3]	
	Process	Compression
D < 2.5 inch	Min 0.40; Avg 1.05; Max 1.80	Min 0.10; Avg 0.90; Max 2.01
2.5 inch ≤ D < 5 inch	Min 0.07; Avg 0.27; Max 0.57	Min 0.07; Avg 0.27; Max 0.60
5 inch ≤ D < 9 inch	Min 0.05; Avg 0.21; Max 0.41	Min 0.04; Avg 0.18; Max 0.36
9 inch ≤ D < 15 inch	Min 0.03; Avg 0.09; Max 0.23	Min 0.01; Avg 0.08; Max 0.20
D ≥ 15 inch	Min 0.02; Avg 0.04; Max 0.08	Min 0.01; Avg 0.03; Max 0.07

---

[10] *Development of advanced CFD tools for the enhanced prediction of explosion pressure development and deflagration risk on drilling and production facilities*, RPSEA report 12121-6403-01.Final, 30 September 2016.

Uncertainties in probabilistic ERA approach

Congestion density



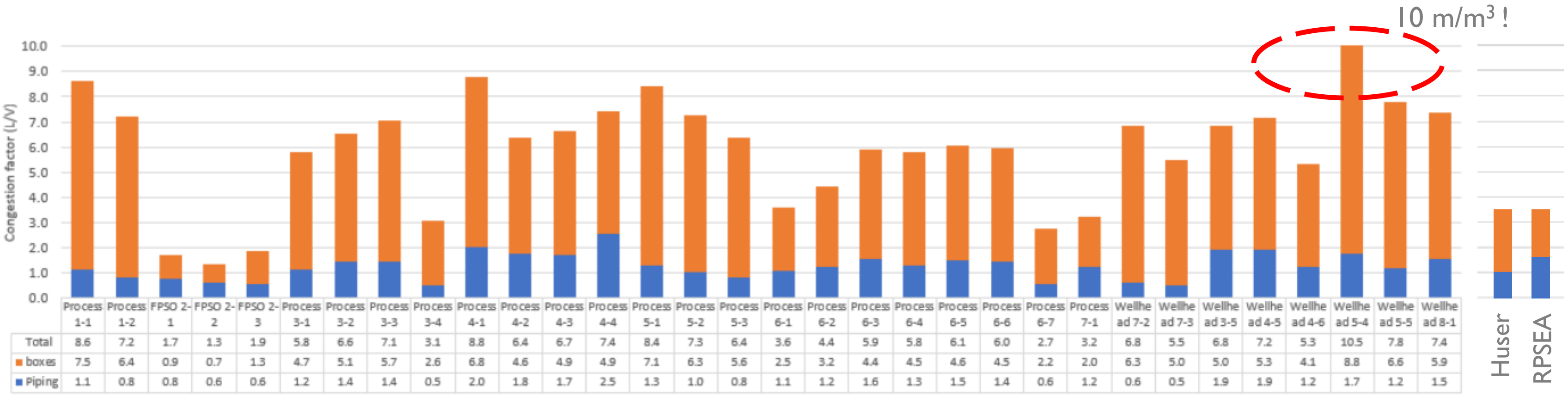
Congestion densities

Mesh alignment, representation of obstacles

Capturing detection and subsequent shutdown/blowdown

Pre-ignition turbulence

- Recently, the RISP/RISP-Ex JIP has presented some new congestion data [11]
- This is based on several as-built geometries in the Norwegian sector
- There seems to be a large increase in the congestion density compared to previous datasets.



10 m/m^3 !

	Process 1-1	Process 1-2	FPSO 2-1	FPSO 2-2	FPSO 2-3	Process 3-1	Process 3-2	Process 3-3	Process 3-4	Process 4-1	Process 4-2	Process 4-3	Process 4-4	Process 5-1	Process 5-2	Process 5-3
Total	8.6	7.2	1.7	1.3	1.9	5.8	6.6	7.1	3.1	8.8	6.4	6.7	7.4	8.4	7.3	6.4
🟧 boxes	7.5	6.4	0.9	0.7	1.3	4.7	5.1	5.7	2.6	6.8	4.6	4.9	4.9	7.1	6.3	5.6
🟦 Piping	1.1	0.8	0.8	0.6	0.6	1.2	1.4	1.4	0.5	2.0	1.8	1.7	2.5	1.3	1.0	0.8

	Process 6-1	Process 6-2	Process 6-3	Process 6-4	Process 6-5	Process 6-6	Process 6-7	Process 7-1	Wellhead 7-2	Wellhead 7-3	Wellhead 3-5	Wellhead 4-5	Wellhead 4-6	Wellhead 5-4	Wellhead 5-5	Wellhead 8-1
Total	3.6	4.4	5.9	5.8	6.1	6.0	2.7	3.2	6.8	5.5	6.8	7.2	5.3	10.5	7.8	7.4
🟧 boxes	2.5	3.2	4.4	4.5	4.6	4.5	2.2	2.0	6.3	5.0	5.0	5.3	4.1	8.8	6.6	5.9
🟦 Piping	1.1	1.2	1.6	1.3	1.5	1.4	0.6	1.2	0.6	0.5	1.9	1.9	1.2	1.7	1.2	1.5

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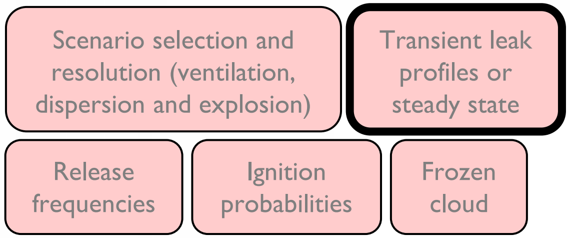
[11] *RispEx – decision support for explosion design* loads, Garstad JJ, DNVGL report 2020-0628, August 2020.

Uncertainties in probabilistic ERA approach

Representation of leak profile



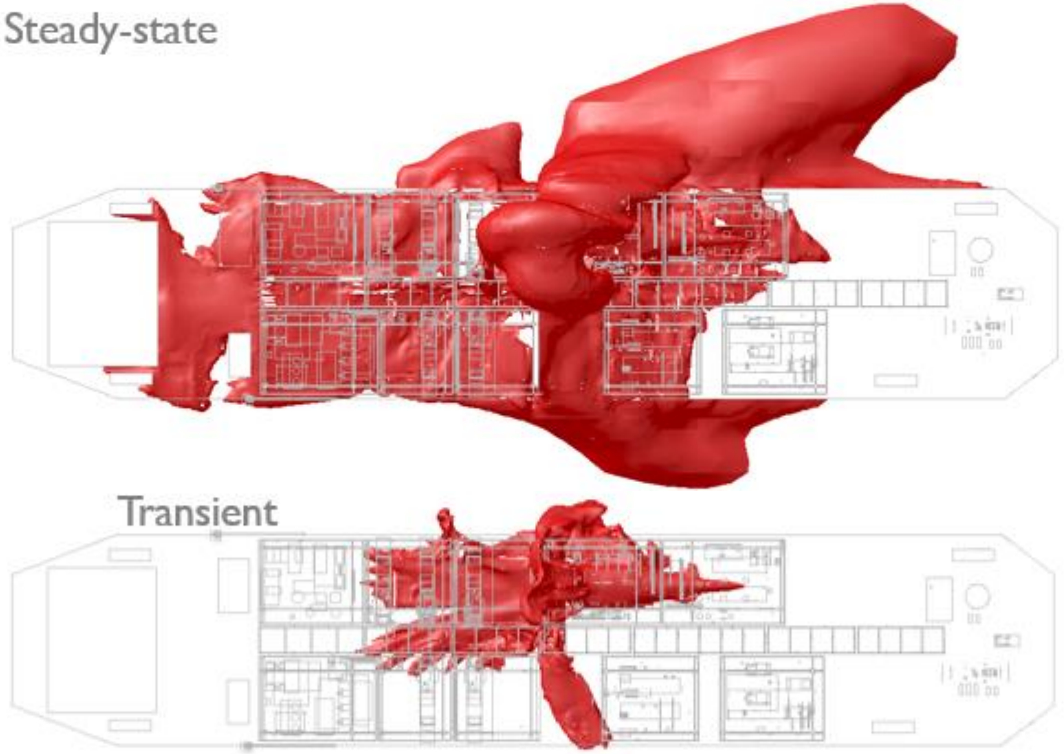
Scenario selection and resolution (ventilation, dispersion and explosion)

Transient leak profiles or steady state

Release frequencies

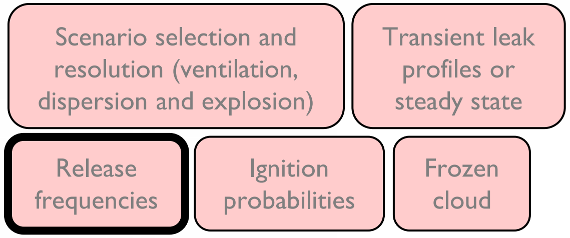
Ignition probabilities

Frozen cloud



Uncertainties in probabilistic ERA approach

Release frequency



Scenario selection and resolution (ventilation, dispersion and explosion)

Transient leak profiles or steady state

Release frequencies

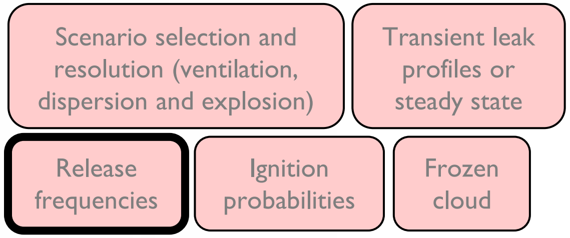
Ignition probabilities

Frozen cloud

- In a recent project review, Abercus had an immediate concern that the 10^{-4} /yr blast overpressures predicted at the key target of interest seemed rather low.
- After a review of the CFD model and associated congestion factors, which all looked sensible, focus was turned to the release frequencies assumed for the analysis.

Uncertainties in probabilistic ERA approach

Release frequency


Scenario selection and resolution (ventilation, dispersion and explosion)
Transient leak profiles or steady state
Release frequencies
Ignition probabilities
Frozen cloud

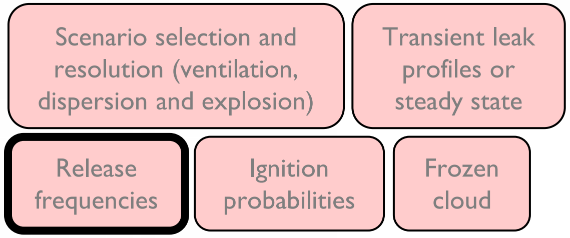
- The actual numbers presented in this table have been modified from the project report in order to protect the anonymity of the project. They do, however, remain in proportion to those presented in the project report.

Hole size [mm]	< 19	19-50	50-75	75-100	100-150	>150	Total
Source 1	1.35×10^{-2}	4.33×10^{-3}	3.49×10^{-3}	4.59×10^{-5}	9.17×10^{-5}	2.76×10^{-4}	2.18×10^{-2}
Source 2	1.62×10^{-2}	1.08×10^{-2}	9.13×10^{-4}	9.13×10^{-4}	1.82×10^{-3}	2.14×10^{-3}	3.29×10^{-2}
Source 3	5.40×10^{-2}	1.15×10^{-2}	3.08×10^{-3}	1.10×10^{-3}	1.78×10^{-3}	5.33×10^{-3}	7.68×10^{-2}
Source 4	1.92×10^{-2}	9.69×10^{-3}	7.81×10^{-4}	7.81×10^{-4}	1.17×10^{-4}	3.49×10^{-4}	3.09×10^{-2}

- Source 1 is the release frequency data assumed for the original assessment.
- Source 2 is equivalent data independently retrieved by Abercus as part of the review.
  - **Note that both Source 1 and Source 2 ultimately derive from the same source data, the HCR database.**
- Source 3 and Source 4 is data retrieved from two previous Abercus projects for comparison.

Uncertainties in probabilistic ERA approach

Release frequency



Scenario selection and resolution (ventilation, dispersion and explosion)

Transient leak profiles or steady state

Release frequencies

Ignition probabilities

Frozen cloud

- Both Source 1 and Source 2 ultimately derive from the same source data, the HCR database, however there are clear differences in the data compiled for this project.
- Most significantly, the data for Source 1 is around one order of magnitude lower than that for Source 2 for releases with a hole size of 75 mm or greater – as highlighted by the red values in the table on the previous slide.
- Exceedance curves for blast overpressure at a principal target of interest are presented for the four sources of release frequency data on the next slide.

Uncertainties in probabilistic ERA approach

Release frequency

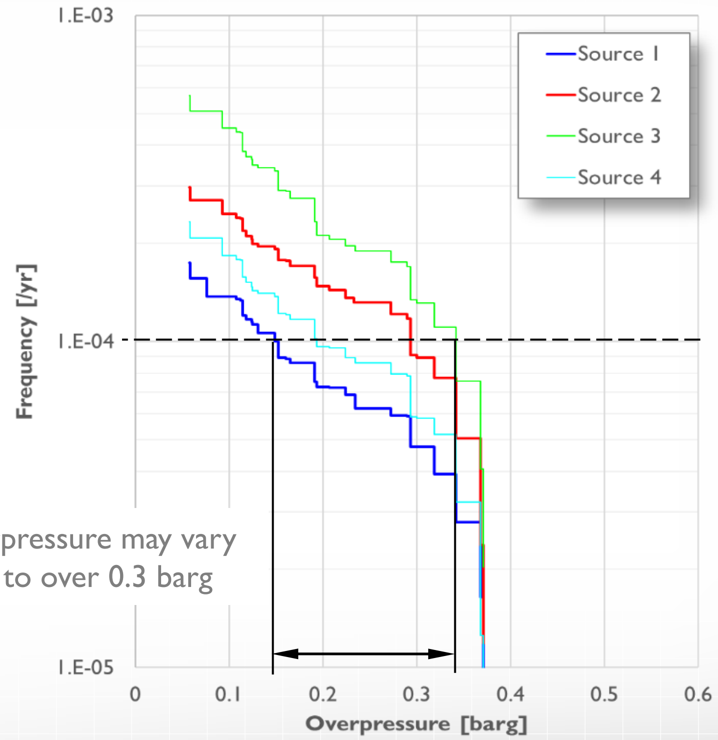
Scenario selection and resolution (ventilation, dispersion and explosion)

Transient leak profiles or steady state

Release frequencies

Ignition probabilities

Frozen cloud

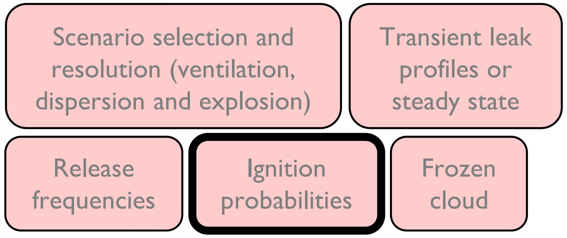


The 10^{-4} /yr overpressure may vary from 0.15 barg to over 0.3 barg

Exceedance curves for peak overpressure for four alternative sources of release frequency data

Uncertainties in probabilistic ERA approach

Ignition probability



Scenario selection and resolution (ventilation, dispersion and explosion)

Transient leak profiles or steady state

Release frequencies

Ignition probabilities

Frozen cloud

Ignition methodology	Probability of ignition	Probability of explosion given ignition	Time dependence
A	UKOOA 25	Fixed at 20%	UKOOA
B	UKOOA 25	Cox, Lees and Ang	UKOOA
C	UKOOA 25	Ignored	UKOOA
D	UKOOA 25	Fixed at 20%	Ignored
E	UKOOA 25	Cox, Lees and Ang	Ignored
F	UKOOA 25	Ignored	Ignored

- In the UK sector, the input ignition frequencies are often derived from the UKOOA ignition model [13].
- However, within this model there is scope to interpret aspects of the model differently.
- Exceedance curves at a principal target of interest for a previous Abercus assessment is presented for six alternative formulations for ignition frequency, each of which is permissible according to the UKOOA model.

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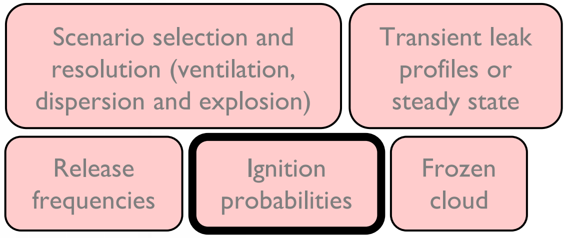
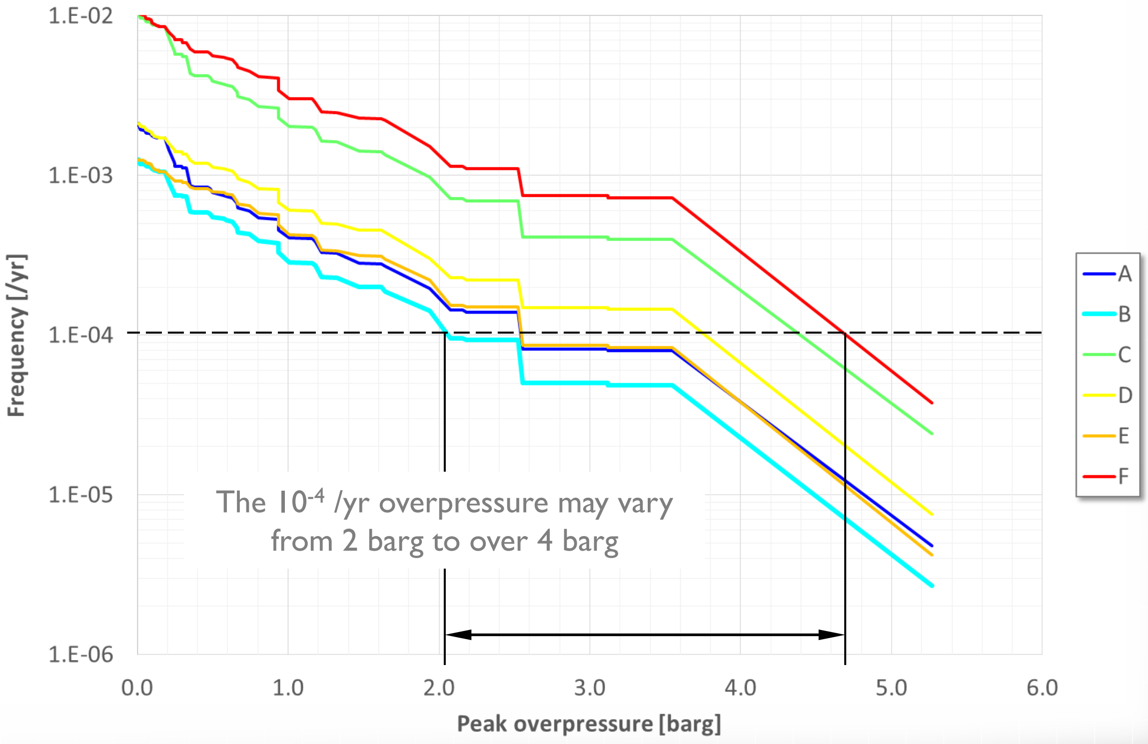
[13] IP Research Report, Ignition probability review, model development and look up correlations, Energy Institute, 2006.

Uncertainties in probabilistic ERA approach

Ignition probability



Ignition methodology	Probability of ignition	Probability of explosion given ignition	Time dependence
A	UKOOA 25	Fixed at 20%	UKOOA
B	UKOOA 25	Cox, Lees and Ang	UKOOA
C	UKOOA 25	Ignored	UKOOA
D	UKOOA 25	Fixed at 20%	Ignored
E	UKOOA 25	Cox, Lees and Ang	Ignored
F	UKOOA 25	Ignored	Ignored



The 10^{-4} /yr overpressure may vary from 2 barg to over 4 barg

Exceedance curves for peak overpressure for six alternative ignition frequency methods

Uncertainties in probabilistic ERA approach

Flammable volume methodology

Coupling ventilation to dispersion

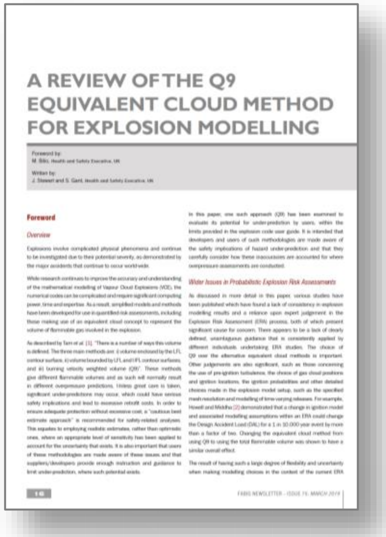
DDT

3D risk assessment

Coupling dispersion to explosion

Coupling to structural response

- Is the equivalent stoichiometric volume (Q9) the appropriate measure for cloud volume?

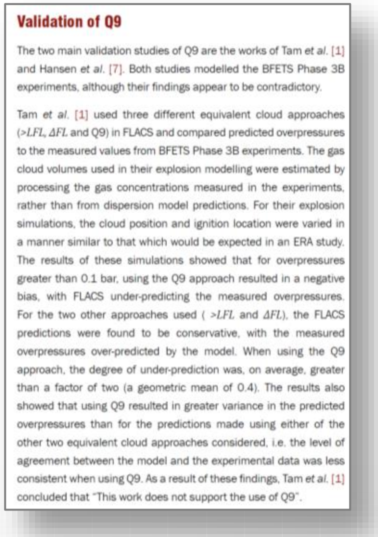


A REVIEW OF THE Q9 EQUIVALENT CLOUD METHOD FOR EXPLOSION MODELLING

Foreword

Overview

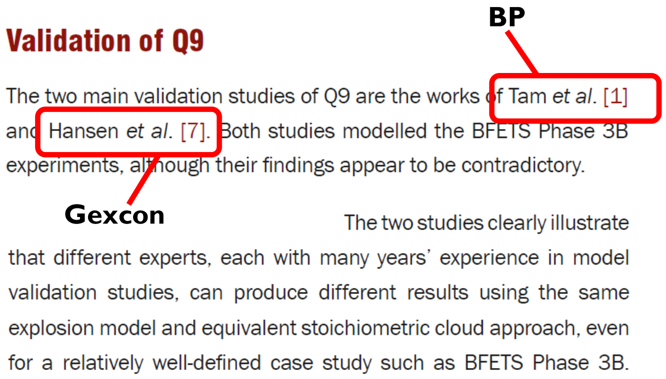
Wider Issues in Probabilistic Explosion Risk Assessments



Validation of Q9

The two main validation studies of Q9 are the works of Tam *et al.* [1] and Hansen *et al.* [7]. Both studies modelled the BFETS Phase 3B experiments, although their findings appear to be contradictory.

Tam *et al.* [1] used three different equivalent cloud approaches (>*LFL*, *ΔFL* and Q9) in FLACS and compared predicted overpressures to the measured values from BFETS Phase 3B experiments. The gas cloud volumes used in their explosion modelling were estimated by processing the gas concentrations measured in the experiments, rather than from dispersion model predictions. For their explosion simulations, the cloud position and ignition location were varied in a manner similar to that which would be expected in an ERA study. The results of these simulations showed that for overpressures greater than 0.1 bar, using the Q9 approach resulted in a negative bias, with FLACS under-predicting the measured overpressures. For the two other approaches used (>*LFL* and *ΔFL*), the FLACS predictions were found to be conservative, with the measured overpressures over-predicted by the model. When using the Q9 approach, the degree of under-prediction was, on average, greater than a factor of two (a geometric mean of 0.4). The results also showed that using Q9 resulted in greater variance in the predicted overpressures than for the predictions made using either of the other two equivalent cloud approaches considered, i.e. the level of agreement between the model and the experimental data was less consistent when using Q9. As a result of these findings, Tam *et al.* [1] concluded that "This work does not support the use of Q9".



Validation of Q9

BP

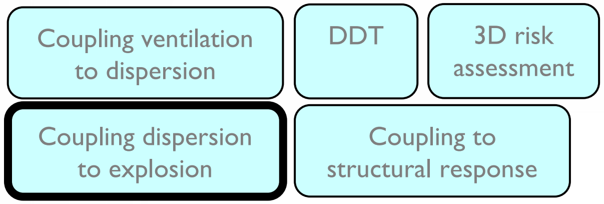
The two main validation studies of Q9 are the works of Tam *et al.* [1] and Hansen *et al.* [7]. Both studies modelled the BFETS Phase 3B experiments, although their findings appear to be contradictory.

Gexcon

The two studies clearly illustrate that different experts, each with many years' experience in model validation studies, can produce different results using the same explosion model and equivalent stoichiometric cloud approach, even for a relatively well-defined case study such as BFETS Phase 3B.

Uncertainties in probabilistic ERA approach

Flammable volume methodology



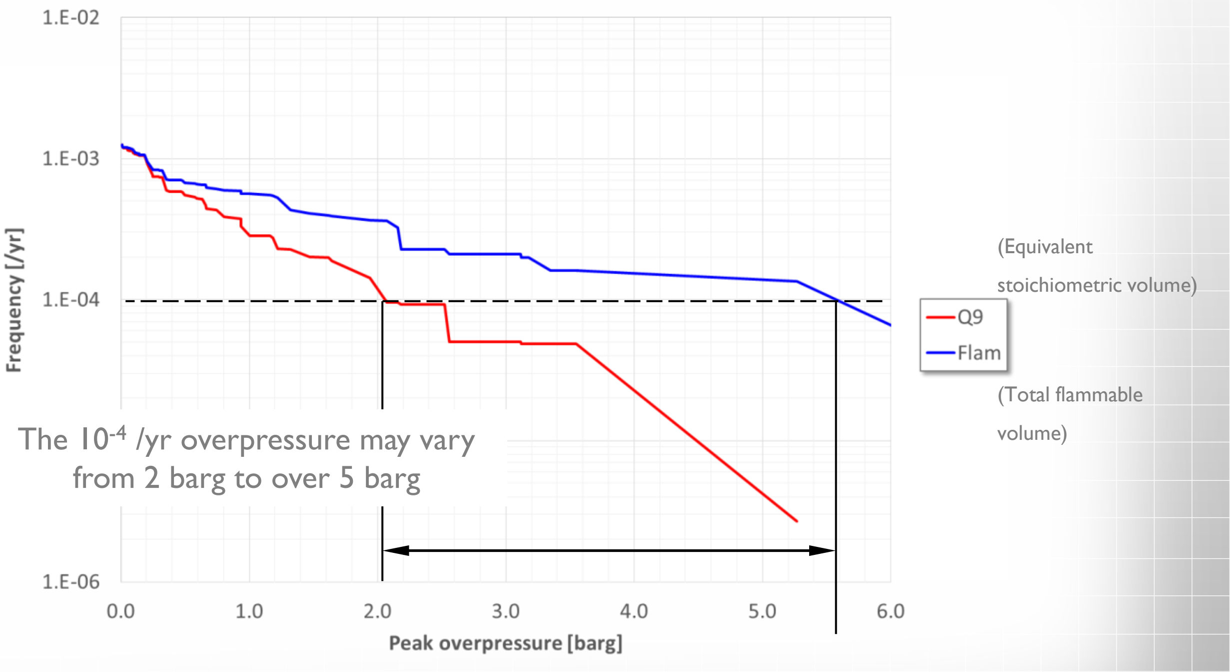
Coupling ventilation to dispersion

DDT

3D risk assessment

Coupling dispersion to explosion

Coupling to structural response

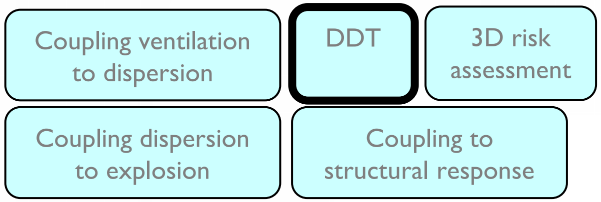


The 10^{-4} /yr overpressure may vary from 2 barg to over 5 barg

Exceedance curves for peak overpressure for two alternative flammable volume methodologies

Uncertainties in probabilistic ERA approach

Deflagration to detonation transition



Coupling ventilation to dispersion

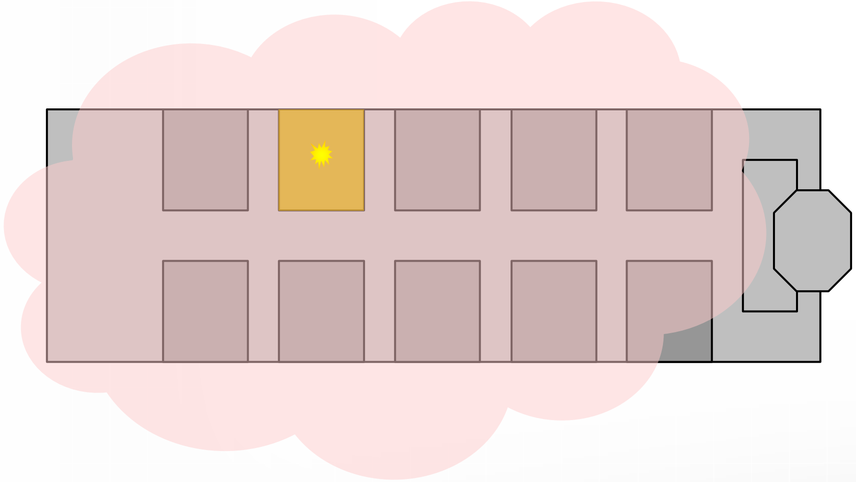
DDT

3D risk assessment

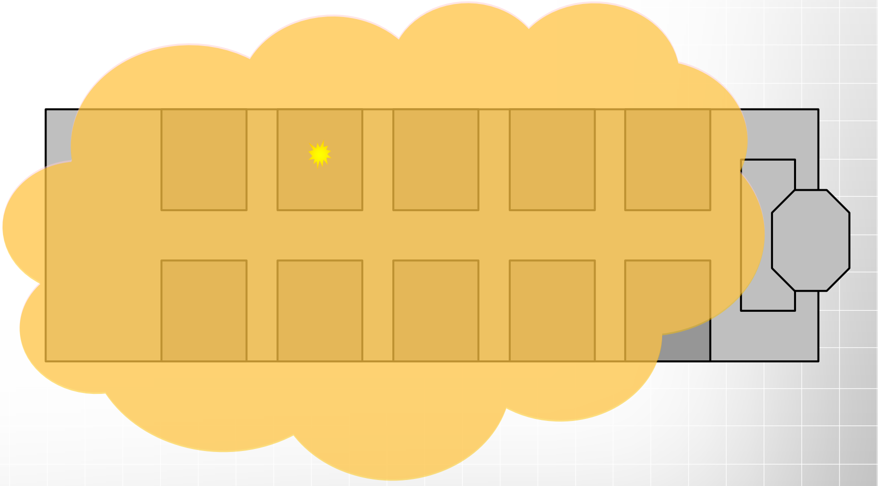
Coupling dispersion to explosion

Coupling to structural response

- There is a growing body of evidence that it may be possible for a deflagration to transition to a detonation on offshore facilities (FABIG, March 2019). This possibility has been largely ignored by our industry to date.



For a deflagration, the explosion overpressure can be mitigated by safety gaps.

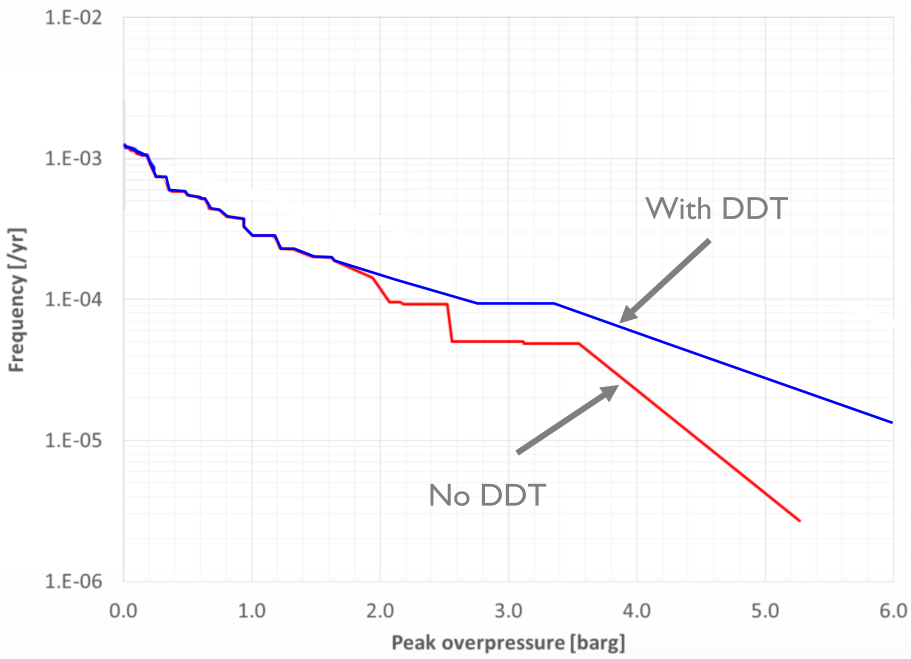


If DDT occurs, the safety gaps may not be effective.

Uncertainties in probabilistic ERA approach

Deflagration to detonation transition

- Coupling ventilation to dispersion
- **DDT**
- 3D risk assessment
- Coupling dispersion to explosion
- Coupling to structural response



Exceedance curves for peak overpressure
with and without consideration of detonation

Uncertainties in probabilistic ERA approach

Sensitivity to assumptions

- When exceedance data is presented, however, it is usually only a single set of exceedance data that is provided.
  - Sensitivities are usually not presented, or may not have been considered.
  - Abercus has previously argued that these sensitivities should be transparent and properly understood [12].
- We have recently independently reviewed several ERA studies and, depending upon the assumptions, the design blast load may vary significantly – from several barg to zero!!!
- With this level of sensitivity to the underlying input assumptions, this information should be included as a minimum in any ERA.

---

[12] New paradigms for determining structural design loads for blast, Steve Howell and Prankul Middha, Hazards 28, 2018.

Agenda

Introduction – probabilistic ERA

Uncertainties in probabilistic ERA approach

Way forward

PROBABLAST JIP.

Way forward

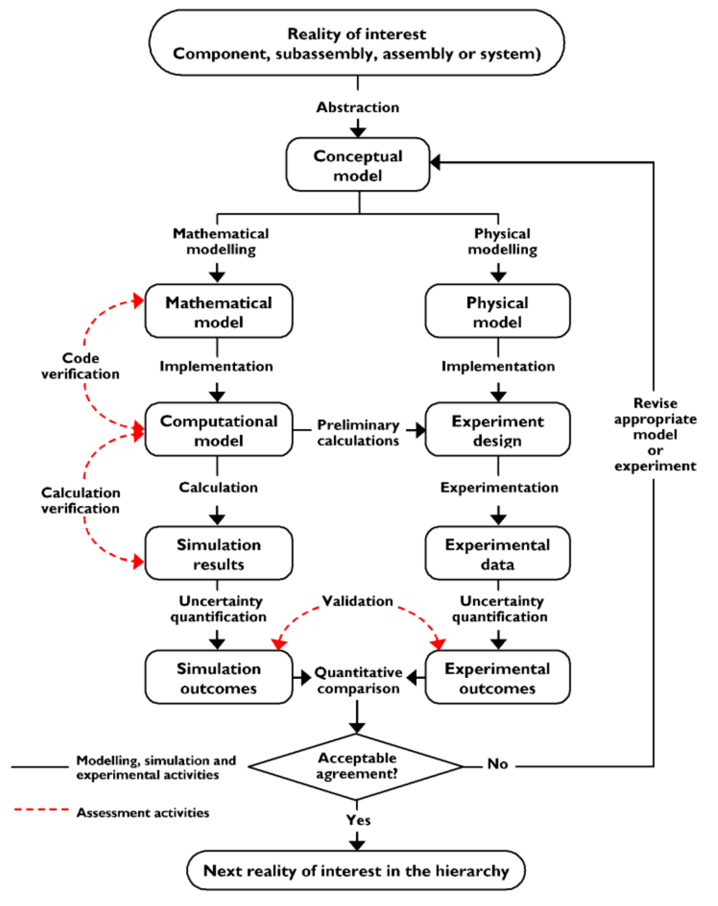
Thoughts…

- Verification and validation
- Absolute or relative assessment criteria
- RISP/RISP-Ex.

Way forward

Verification and validation

- NAFEMS/ASME V&V 10 diagram [13]
  - Verification – are the equations solved correctly (mathematics)
  - Validation – are the correct equations being solved (physics)
  - Verification activities all lie within a particular branch (code and calculation verification lie within the left hand branch)
  - Validation requires a quantitative comparison of the modelling and experimental branches.


Reality of interest
Component, subassembly, assembly or system)
Abstraction
Conceptual model
Mathematical modelling
Physical modelling
Mathematical model
Physical model
Code verification
Implementation
Implementation
Computational model
Preliminary calculations
Experiment design
Revise appropriate model or experiment
Calculation
Experimentation
Calculation verification
Simulation results
Experimental data
Uncertainty quantification
Validation
Uncertainty quantification
Simulation outcomes
Quantitative comparison
Experimental outcomes
Modelling, simulation and experimental activities
Acceptable agreement?
No
Assessment activities
Yes
Next reality of interest in the hierarchy

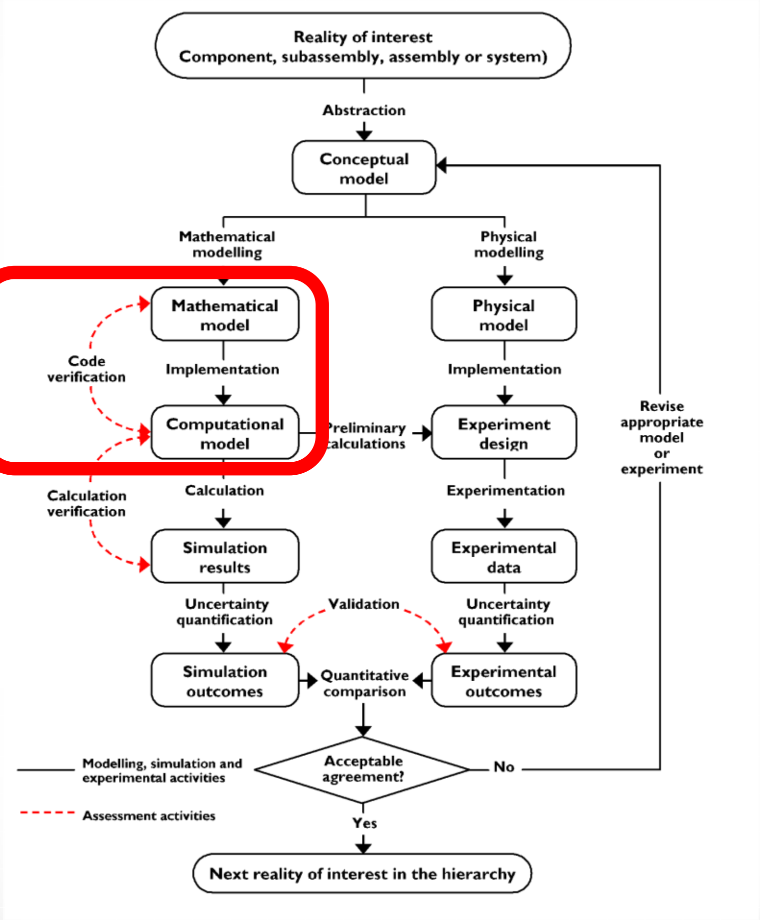
---

[13] *What is: verification and validation?*, NAFEMS document WT09, 2014.

Way forward

Verification and validation

- Code verification
  - Deterministic (CFD/FEA) – need a highly accurate reference solution, often an analytical solution for a simplified scenario (laminar flow in a pipe – parabolic flow profile) to verify the code [14]
  - Probabilistic – no such analogous reference solution yet exists, even for a simplified scenario, so how can anyone demonstrate that their probabilistic procedures are verified?



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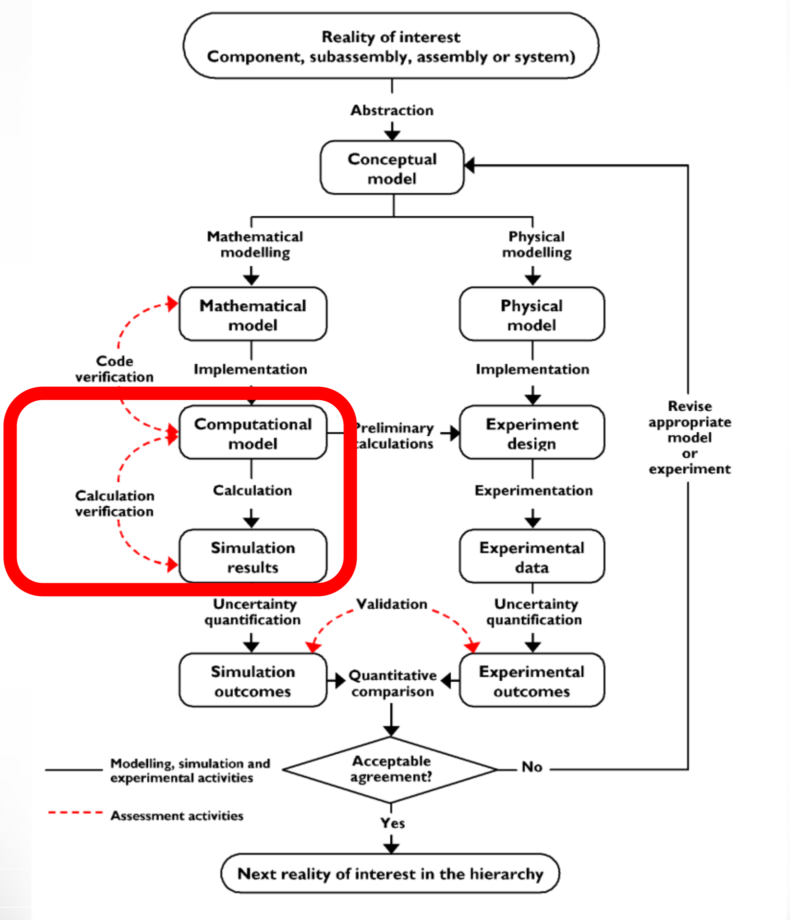
[14] *Software quality assurance and code verification in computational simulation*, Oberkampf W and Howell S, NAFEMS, 23 November 2020.

Way forward

Verification and validation

- Calculation verification
  - Deterministic (CFD/FEA) – this means, for example, checking iterative convergence and that the discretization (mesh and time-step) is sufficiently refined [14]
  - Probabilistic – how many simulations (ventilation/dispersion/explosion) are required to sufficiently discretize the probabilistic space? Does it depend upon the approach (discrete allocation vs response-surface)?



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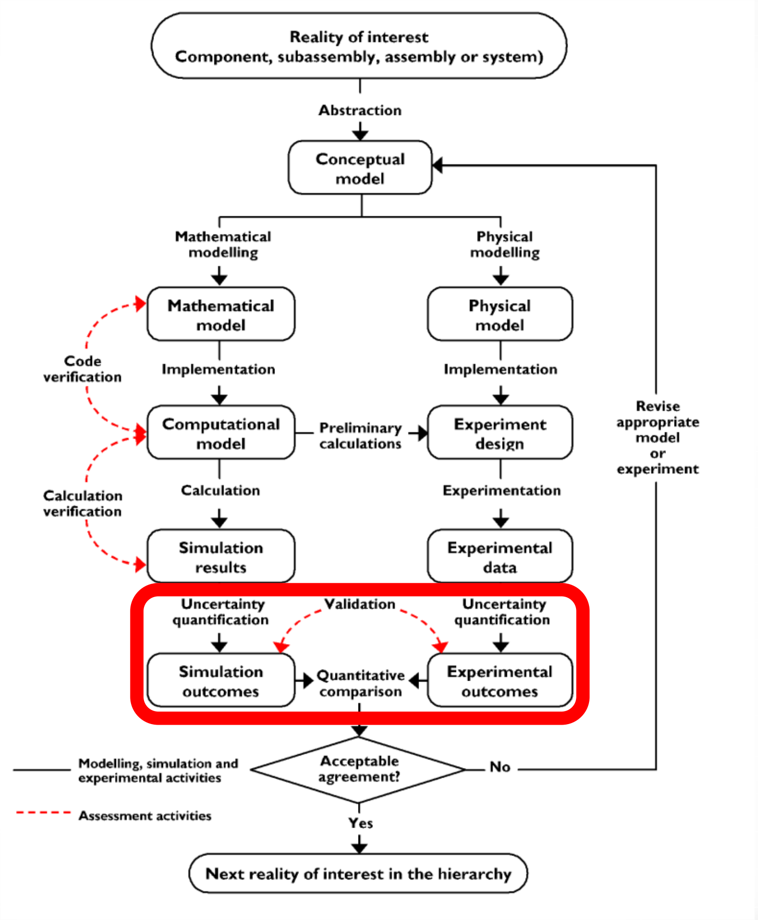
[14] *Software quality assurance and code verification in computational simulation*, Oberkampf W and Howell S, NAFEMS, 23 November 2020.

Way forward

Verification and validation

- Validation
  - Deterministic (CFD/FEA) – requires a quantitative comparison of numerical predictions with real experimental data (BFETS/HSE/new FABIG database).
  - Probabilistic – does experimental data exist? If not, can the probabilistic methodology be validated or is it purely a mathematical verification exercise?



Reality of interest
Component, subassembly, assembly or system)

Abstraction

Conceptual model

Mathematical modelling

Physical modelling

Mathematical model

Physical model

Code verification

Implementation

Implementation

Computational model

Preliminary calculations

Experiment design

Revise appropriate model or experiment

Calculation verification

Calculation

Experimentation

Simulation results

Experimental data

Uncertainty quantification

Validation

Uncertainty quantification

Simulation outcomes

Quantitative comparison

Experimental outcomes

Modelling, simulation and experimental activities

Assessment activities

Acceptable agreement?

No

Yes

Next reality of interest in the hierarchy

Way forward

Absolute or relative acceptance criteria

- There might be an opportunity to learn from another industry with respect to assessment criteria where there is uncertainty and multiple simulation tools [15]:
  - The assessment process involves creating a model of the real asset, and the software then automatically creating a similar notional asset
  - The performance of the notional asset is used to determine a relative assessment criterion for the real asset
- This approach has the **significant benefit** that any uncertainties associated with the input assumptions will be inherent in both models, so that when they are compared any error will, to a large degree, cancel out.

---

[15] *On the 10^{-4}/yr criterion for blast overpressure – an alternative comparative approach for safer design*, Howell S and Middha P, Hazards 30, 2020.

Way forward

RISP/RISP-Ex

- Concerns with the current status quo have been recognized in the Norwegian sector and positive action has been taken to address this:
  - A JIP has recently been carried out – Risk Informed decision Support in development Projects (RISP) [16].
  - This approach reduces the emphasis on simulating a large number of scenarios with CFD and therefore mitigates the possibility of user inconsistency, specifically for the CFD aspects.
  - Using knowledge gained over the past 40 years, a software tool RISP-Ex [11] is developed to provide DALs that are used in the decision making process with respect to explosion hazards – using a look-up approach.

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[11] *RispEx – decision support for explosion design* loads, Garstad JJ, DNVGL report 2020-0628, August 2020.

[16] JIP – Risk informed decision support in development projects (RISP), Report LaC-P0647-R-0125, September 2019.

Way forward

RISP/RISP-Ex

- It is recognized that RISP-Ex is a simplified methodology, but it is a consistent approach so that the DAL predictions returned by RISP-Ex should be independent of the party that has undertaken the work.
- RISP-Ex could, in future, offer an alternative methodology to CFD-based probabilistic ERA with respect to determination of DALs, especially where *standard* design is being pursued
- For novel designs, and while RISP-Ex is becoming established, CFD-based probabilistic ERA is still likely to be needed.

Agenda

Introduction – probabilistic ERA

Uncertainties in probabilistic ERA approach

Way forward

PROBABLAST JIP.

PROBABLAST JIP

Introduction

1970s – Need to understand explosions/simple models
- 1974: Flixborough explosion

1980s – Need to change safety standards/regulations
- 1988: Piper Alpha explosion and fire

1990s – Need to consider risk management/escalation

1990s – Explosion pressures higher than expected, explosion phenomena too complex for simple models, CFD required

2000s – Probabilistic ERA industry standard (NORSOK Z-013)

2010s – New initiatives…
- RISP/RISP-Ex
- 3D Risk Assessment

2020s – JIP PROBABLAST

PROBABLAST JIP

Introduction

- Despite other recent initiatives, CFD-based probabilistic ERA (based on standards such as NORSOK Z-013) is still likely to be needed in the future.
- The result of having such a large degree of flexibility and uncertainty when making modelling choices in the context of the current ERA process leads to inconsistency.
- One alternative is for regulators to unilaterally adopt a more prescriptive approach to the ERA methodology, but the scale of the uncertainty has not currently been quantified and hence is not understood.

PROBABLAST JIP

Introduction

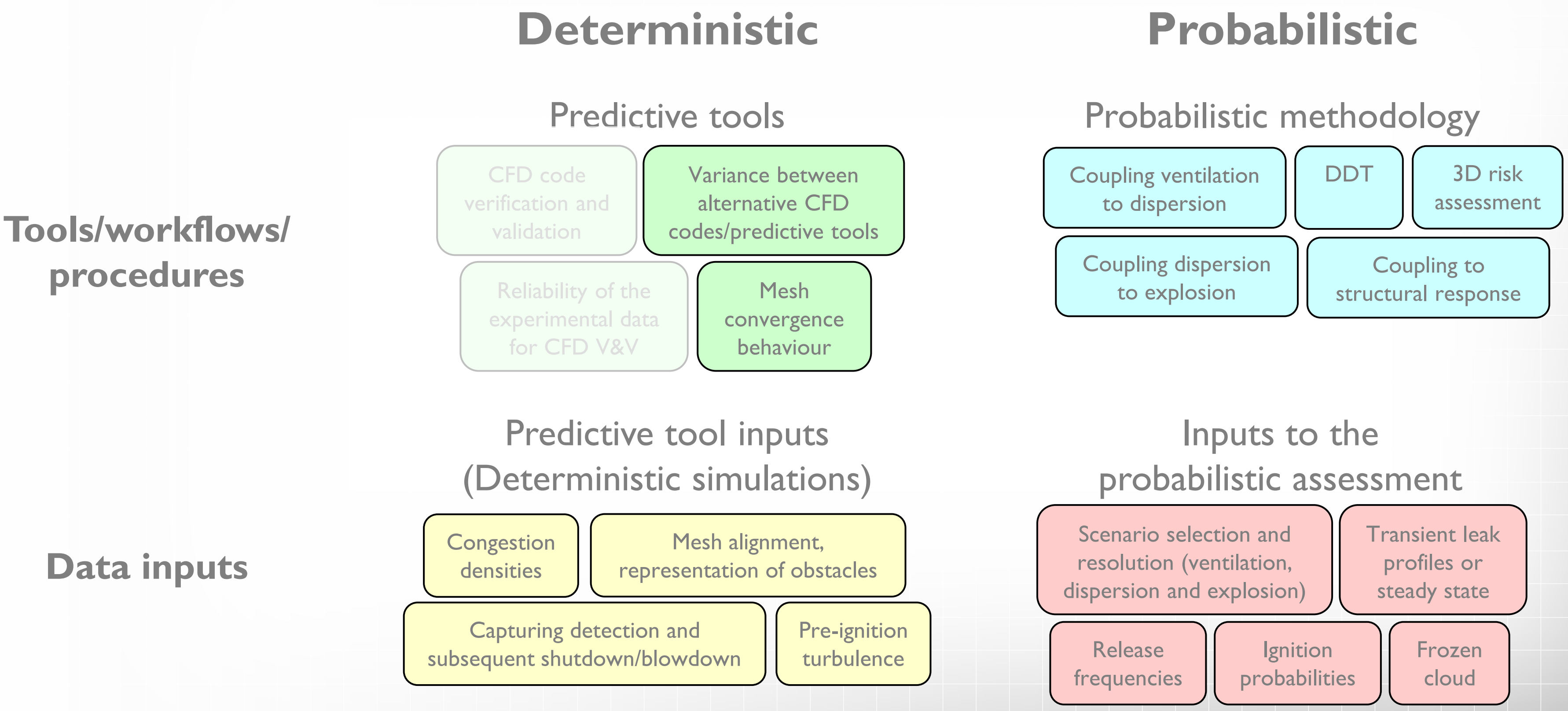
- A joint industry project, PROBABLAST JIP, is established to carry out a blind probabilistic ERA inter-comparison exercise
- The project work is divided into three phases:

Phase	Objective
A	Identify whether there is an issue regarding inconsistency in approach across the industry
B	Share experience and learnings in the public domain
C	Help develop good practice guidelines (eventual goal)

- Many of the leading safety consultancies have already expressed interest to participate in the blind study.

PROBABLAST JIP

Provisional scope



Deterministic

Probabilistic

Tools/workflows/ procedures

Predictive tools

- CFD code verification and validation
- Variance between alternative CFD codes/predictive tools
- Reliability of the experimental data for CFD V&V
- Mesh convergence behaviour

Probabilistic methodology

- Coupling ventilation to dispersion
- DDT
- 3D risk assessment
- Coupling dispersion to explosion
- Coupling to structural response

Data inputs

Predictive tool inputs (Deterministic simulations)

- Congestion densities
- Mesh alignment, representation of obstacles
- Capturing detection and subsequent shutdown/blowdown
- Pre-ignition turbulence

Inputs to the probabilistic assessment

- Scenario selection and resolution (ventilation, dispersion and explosion)
- Transient leak profiles or steady state
- Release frequencies
- Ignition probabilities
- Frozen cloud

PROBABLAST JIP

Provisional scope

- Participants to provide anonymous exceedance curves
  - Each participant can identify their own curve only – they can see how they compare to all the other participants.
- The JIP should reflect the current state of the industry
  - It is important that participants use their current procedures to get a fair representative snapshot of the industry.
- Predictions from the RISP-Ex tool will be included alongside the anonymous contributions from the other participants of the JIP.

PROBABLAST JIP

Phase A – identify if there is an issue regarding consistency

- Provisionally, there are four stages identified within Phase A.
  - A1 – post processing only.
    - No CFD analysis, no scenario selection.
  - A2 – scenario selection
    - Scenarios selected by participants but simulated by single nominated member.
  - A3 – agreed set of scenarios selected but simulated by users
    - Participants can use their predictive tool of choice
  - A4 – full probabilistic study for representative geometry
    - Participants to decide upon anticipated congestion
- It is expected that A1 and A2 will be self funded by participants.
- Depending upon the outcome of A1 and A2, it may be appropriate to seek funding to explore stages A3 and A4.

PROBABLAST JIP

Phase B – dissemination of results

- It is anticipated that the outcomes of the JIP will be disseminated through a wide selection of channels, including but not limited to:
  - FABIG meetings/newsletters
  - UKELG meetings
  - Conferences, for example, Hazards, NAFEMS and LPS
  - Peer-reviewed journal articles.
- All contributors to the JIP will be acknowledged appropriately.

PROBABLAST JIP

Phase C – develop good practice guidelines

- Following Phases A and B, the JIP participants will have a better understanding of the degree of inconsistency that exists and will be in a position to agree whether there is a need to establish best practice guidance for carrying out a probabilistic ERA.
- This work will be carried out in collaboration with the UK HSE and potentially other regulatory bodies such as the Norwegian PSA.

PROBABLAST JIP

Potential participants

abercus

rps MAKING COMPLEX EASY

arc Abbott Risk Consulting Ltd

ATKINS Member of the SNC-Lavalin Group

BriteFlow

ESR Technology Engineering, Safety & Risk

iresc Integrated Risk, Environmental & Safety Consultants

MMI Thornton Tomasetti

TÜVRheinland® Risktec

SAFETEC

SBM OFFSHORE

Vysus Group

NAFEMS

TOTAL

HSE Health & Safety Executive

* A further three parties have also already expressed an interest in participating.

PROBABLAST JIP

Potential participants

- NAFEMS, the international association for the engineering modelling, analysis and simulation community, will receive data from participants and make sure it is anonymized before sharing it further.
- The UK Health and Safety Executive (HSE) will provide an independent auditor/reviewer and will:
  - Provide a review of the work and deliverables
  - Undertake a brief analysis of the benchmark exercise results to enable us to produce some independent conclusions
  - Contribute to the development of best practice guidelines at the end of the project.

PROBABLAST JIP

Joining the JIP

- Kick-off is planned for mid-February 2021.
- Interested parties with relevant experience of CFD-based probabilistic ERA are encouraged to join this effort
  - Both consultancies who conduct the analysis but also parties who use the results should consider to join
- Please register your interest at the PROBABLAST JIP LinkedIn page: https://www.linkedin.com/groups/8980032/ and/or email prankul.middha@abercus.com.
- The scope of the PROBABLAST JIP remains provisional at this time. The precise scope will be agreed by the JIP following kick-off and, therefore, may be subject to some changes.

PROBABLAST JIP

Potential participants

abercus

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