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A Review of the Q9 Equivalent Cloud Method for Explosion Modelling

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Motivation & Background

Motivation & Background

- Probabilistic Explosion Risk Assessments (ERA) are used to characterise risks of accidental ignition of unintended release of flammable gases on/offshore
- ERA are a requirement of the NORSOK Z-013 [1] industry standard, with further guidance given by Lloyds Register [2]
- The primary outputs of these types of study are overpressure exceedance curves
- Used to inform design decisions relating to pressure loading on structures and safety critical plant

Motivation & Background

- Some concern over whether or not the modelling approaches used give sufficiently conservative results
- Also uncertainty over the extent of user-variability and how ‘expert judgment’ affects the ERA process
- Aim was to review the Q9 equivalent stoichiometric cloud approach to evaluate:
  - The scientific basis of the method
  - The extent to which it has been validated
  - How consistently the approach is applied by different users

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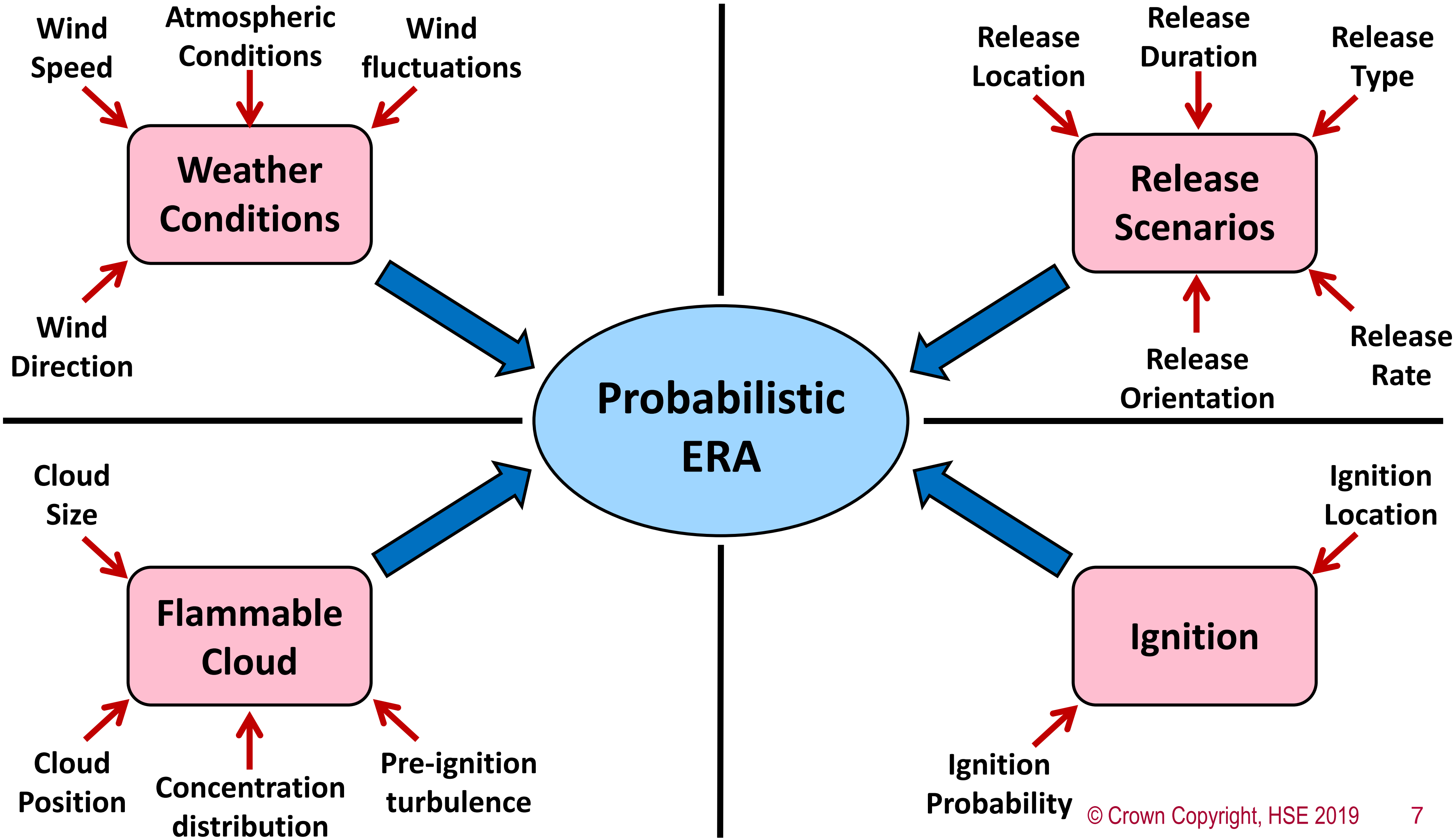
Probabilistic Explosion Risk Assessment (ERA) & the Equivalent Cloud Concept

ERA & Equivalent Cloud Concept



ERA & Equivalent Cloud Concept

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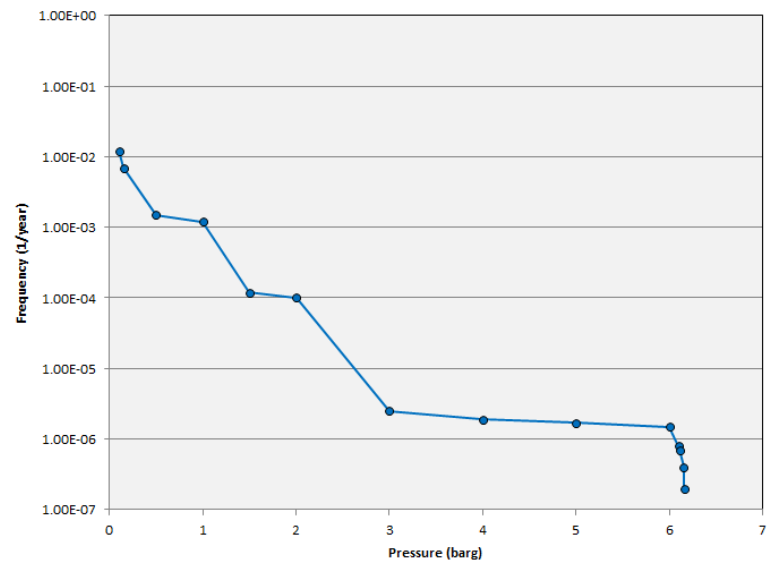
Wind Speed
Wind Direction
Release Scenario

Dispersion Simulations → **Translate to Equiv. Clouds** → **Explosion Simulations**

Pragmatic simplification

Cloud Size
Cloud Position
Ignition Probability
Ignition Location

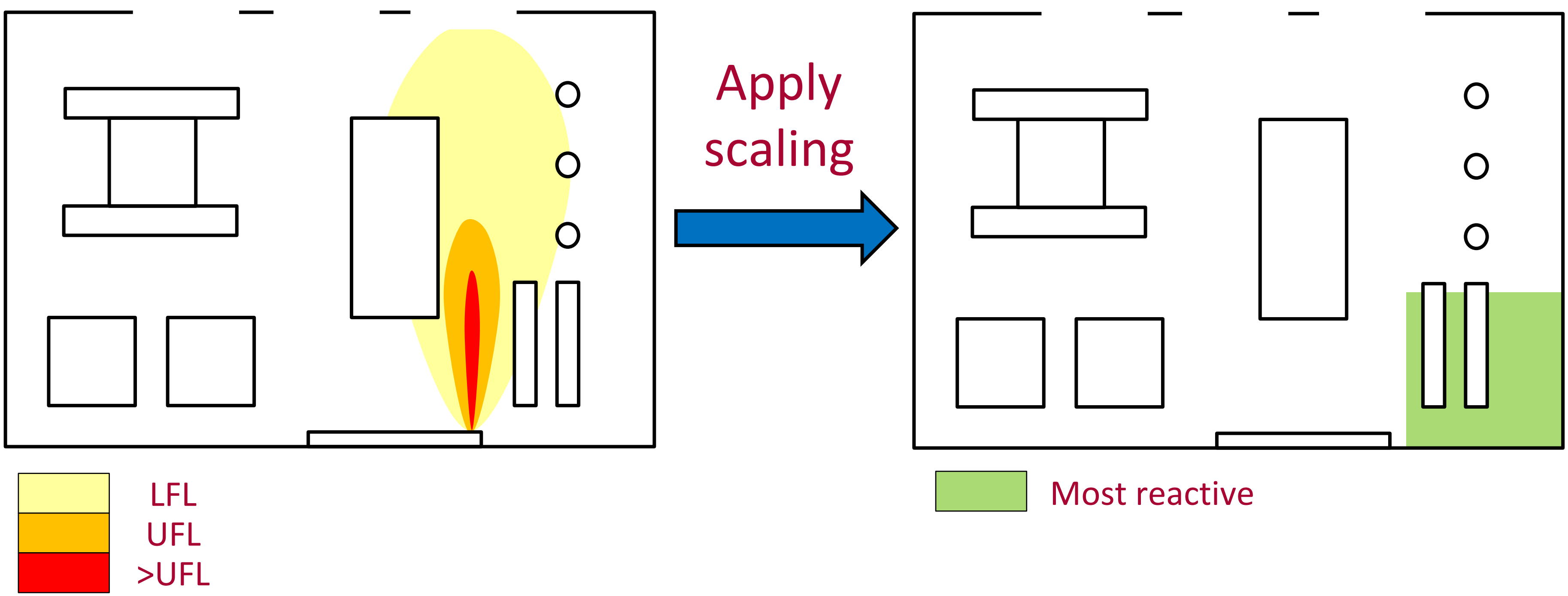
Results brought together to produce overpressure exceedance curves



ERA & Equivalent Cloud Concept

Inhomogeneous cloud from realistic release

Equivalent stoichiometric gas volume



ERA & Equivalent Cloud Concept

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- Equivalent cloud metrics in FLACS [3]:
  - ERFAC (kg)
  - FLAM (m^3) [equivalent to ΔFL below]
  - Q5 (m^3)
  - Q9 (m^3) **most commonly used**
  - Q8 (m^3)
- Other options also used [4]:
  - >LFL (m^3) **conservative**
  - ΔFL (m^3) [equivalent to FLAM]
- Ratio of volumes between ΔFL:Q8:Q9 is approx. 3:2:1

EQUIVALENT CLOUD METRIC	EQUATION
ERFAC (kg) [7]	$M_{ERFAC} = \frac{1}{S_{max}} \sum_{i=1}^{n} (fuel_{mass} \times S)_i$
Q5 (m³) [7]	$V_{Q5} = \frac{1}{S_{max} E_{max}} \sum_{i=1}^{n} (fuel_{vol} \times S \times E)_i$
Q9 (m³) [7]	$V_{Q9} = \frac{1}{(SE)_{max}} \sum_{i=1}^{n} (fuel_{vol} \times S \times E)_i$
Q8 (m³) [7]	$V_{Q8} = \frac{1}{E_{max}} \sum_{i=1}^{n} (fuel_{vol} \times E)_i$ where $LFL \leq C \leq UFL$
$>LFL$ (m³) [1]	$V_{>LFL} = \sum_{i=1}^{n} (fuel_{vol})_i$ where $C \geq LFL$
ΔFL (m³) [1]	$V_{\Delta FL} = \sum_{i=1}^{n} (fuel_{vol})_i$ where $LFL \leq C \leq UFL$

ERA & Equivalent Cloud Concept

1995

Gexcon introduce first equivalent cloud metric with parameter **ERFAC**

1999

Q5 proposed to include gas expansion effects – aim was to eliminate **ERFAC** bias towards fuel-rich clouds

2005

Introduction of **Q8** & **Q9** to account for fuels where max. flame speed and expansion occur at different equivalence ratios

No change to methods & limited changes to modelling guidance

2019

What now & next?

ERA & Equivalent Cloud Concept

- Methods are designed to give a reasonable approximation of expected overpressures in the context of a probabilistic assessment
- Based on two key assumptions:
  - Explosion models (and modellers!) accurately predict overpressures in uniform clouds
  - Scaling gives a uniform cloud generating a similar overpressure to the corresponding inhomogeneous cloud

Validation of the Q9 Approach

Validation of Q9 Approach

- Two main (publically-available) evaluations of Q9
  - Tam et al. (2008) [4]
  - Hansen et al. (2013) [5]
- Both works compare model predictions to data from the BFETS Phase 3B experiments
  - Natural gas
  - Full-scale offshore module (28 x 12 x 8 m)
  - Full and partial fill tests with near-stoichiometric concentration
  - Ignited jet release tests (~33/43 mm orifice)

Validation of Q9 Approach

- Tam et al. [4] compared FLACS-predicted overpressures to data from the BFETS Phase 3B tests using Q9, >LFL and ΔFL equivalent clouds
- The equivalent cloud volumes used were estimated from the gas concentration measurements made during the BFETS tests
- This approach separates out the dispersion and explosion elements of the study in an attempt to quantify the performance of the equivalent cloud metrics used
- The cloud position and ignition location were varied in an approach consistent with that used in a probabilistic ERA

Validation of Q9 Approach

- Tam et al.[4] showed that for measured overpressures > 0.1 bar FLACS under-predicted by more than a factor of two (on average) using Q9 clouds
- Using the other two equivalent cloud metrics, FLACS gave conservative predictions of the overpressure in the BFETS tests
- The Tam et al. results showed that using Q9 gave the largest scatter in predictions, and therefore least consistent performance
- Tam et al. concluded:

"This study does not support the use of Q9."

Validation of Q9 Approach

- The Hansen et al. [5] study first examined the performance of the FLACS dispersion model for predicting Q9 cloud size
- The authors compared predicted Q9 cloud size to values estimated from BFETS Phase 3B concentration measurements
- Large uncertainty in experimental values due to sparse array of gas sensors used in the tests – approx. one every 60 m^3 on average
- Predicted Q9 volumes were calculated in two ways:
  - From predicted concentrations at experimental sensor locations
  - From FLACs internal calculation of Q9 (over all mesh cells)
- Some large deviations between prediction/experiment and between two methods used to determine predicted cloud size

Validation of Q9 Approach

- Hansen et al. then used equivalent stoichiometric clouds with sizes ranging from 2% to 100% fill of the BFETS module in an explosion modelling study
- Cloud position and ignition location was varied and results were presented both with/without pre-ignition turbulence
- The results showed FLACS gave comparable overpressures to the measurements without pre-ignition turbulence and slightly conservative results with pre-ignition turbulence included in the model

Validation of Q9 Approach

	Tam et al. (2008)	Hansen et al. (2013)
Q9 size from dispersion simulation results?	✗	?
Most reactive gas concentration used?	✓	✓
Cloud position & ignition location varied?	✓	✓
Conclusion	Significant under-prediction	Agreement within a factor of 2

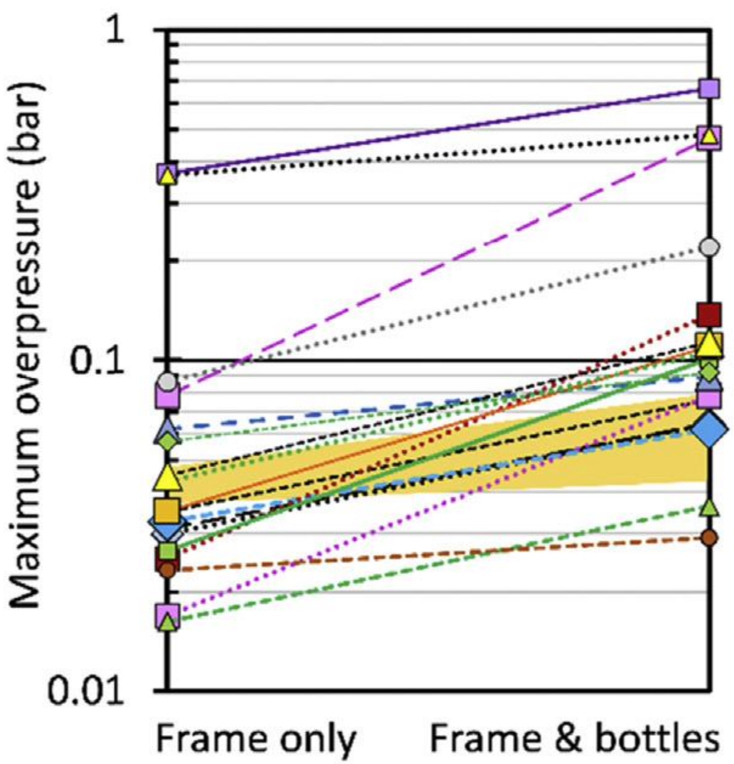
Validation of Q9 Approach

- Tam et al. (2008) and Hansen et al. (2013) studies lead to opposing conclusions on suitability of Q9
- Highlights the importance of having clear guidance on how equivalent clouds should be used in ERA
- Ongoing JIP AIRRE looking at ways of updating and improving equivalent cloud approaches
- ***"better guidelines are required to avoid arbitrary results depending on the settings defined by individual users of the CFD software",*** Skjold et al. [6]

Key Issues Associated with use of Equivalent Clouds

Model Sensitivity & User Variability

- Significant model and user-induced variability for predictions of overpressure for ignited homogeneous clouds



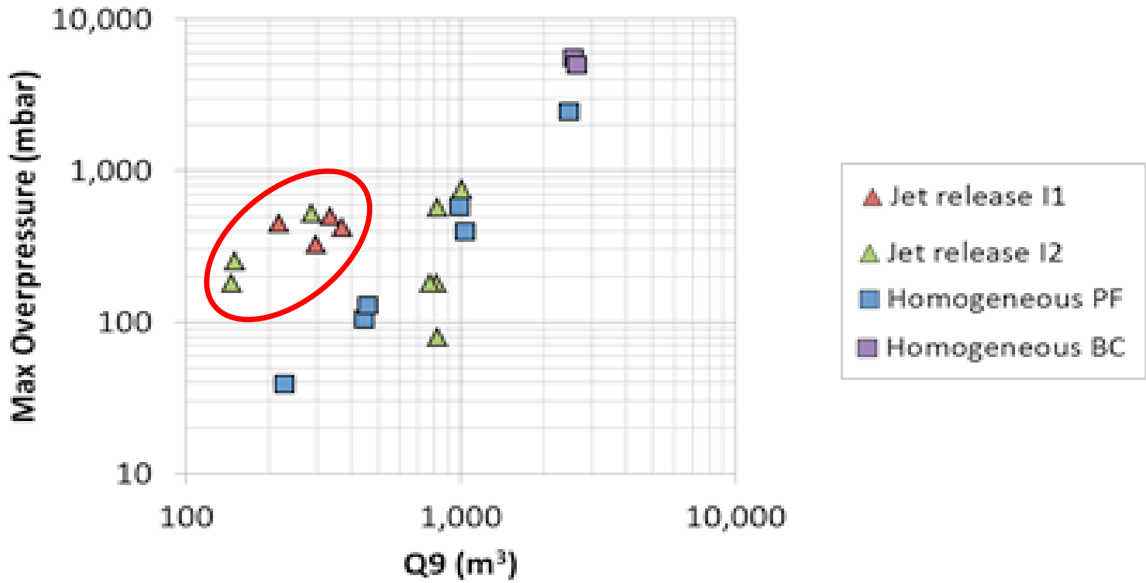
- Factor of 23 variation in predictions across all models/users for vented H_2 deflagrations
- Model sensitivity for natural gas simulations has been shown to be much smaller [7]
- Blind-prediction study for full-scale NG explosions in congested modules needed to assess user effect

Pre-Ignition Turbulence

- Pre-ignition turbulence can significantly affect overpressures generated in gas explosions
- For highly congested scenarios, the effect is modest in comparison to the turbulence generated by obstacles during the explosion [6]
- For moderate levels of congestion, e.g. BFETS, it is important that turbulence generated by the release is accounted for in any explosion model
- A consistent methodology and/or clearer guidance on how to include the effects of pre-ignition turbulence in an ERA is needed

Pre-Ignition Turbulence

- BFETS Phase 3B data
  - Significant scatter for ignited jet release scenarios
  - Trend for increase in overpressure with increasing homogeneous gas cloud volume
  - **Jet release cases give higher overpressure than homogeneous stoichiometric cases with similar Q9 volume**



Pre-Ignition Turbulence

- Hansen et al.[5] study illustrates that including pre-ignition turbulence gives more conservative results when using Q9
- Tolias et al.[8] showed that FLACS-predicted overpressure in uniform H_2 clouds varied by a factor of 2.5 as a result of changes (within the user guidelines for the model!) to initial turbulence length scale
- The FLACS User Manual [3], Hansen et al.[5] paper, NORSOK Z-013 [1] and Lloyds Register [2] guidance all suggest including pre-ignition turbulence in an ERA study
- None of these documents says how, yet it is clear that it can have a significant impact on model predictions

Conclusions of Q9 Review

Conclusions

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- The Q9 method is an engineering approach designed for use within the framework of a probabilistic ERA
- Use of equivalent cloud methods are based on assumptions that:
  - The explosion model used can accurately predict overpressure in homogeneous stoichiometric clouds
  - The scaling between inhomogeneous and equivalent stoichiometric clouds gives volumes generating similar overpressures
- Neither assumption is valid consistently, with evidence for and against each

Conclusions

- Published research demonstrates that inconsistent results can be produced by different experts undertaking ERA
- There is a strong reliance upon expert judgment in the process with detailed modelling choices made regarding:
  - Choice of equivalent cloud method
  - Pre-ignition turbulence
  - Choice of cloud size categories and locations
  - Choice of ignition locations
  - Ignition probability modelling
  - CFD model set up – e.g. grid resolution
- Improved guidance is needed to reduce the inconsistency across studies

Next Steps & Potential Future Work

Potential Future Work

- Aims of future work on the topic should focus on:
  - Characterising the level of uncertainty in probabilistic ERA studies
  - Reducing model sensitivity and user variability
  - Developing clearer guidance and good practice guidelines for undertaking probabilistic ERA
  - Working towards providing greater transparency in the ERA process to harmonize approaches/results
- A possible way forward would be a JIP involving consultants, model developers and regulators to undertake an ERA inter-comparison exercise
- A similar exercise was performed nearly 20 years ago [9] in the Norwegian sector

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Questions?