European Research Community On Flow, Turbulence And Combustion

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Determining structural design loads by using CFD to simulate explosions within a probabilistic framework – current best practice and future trends

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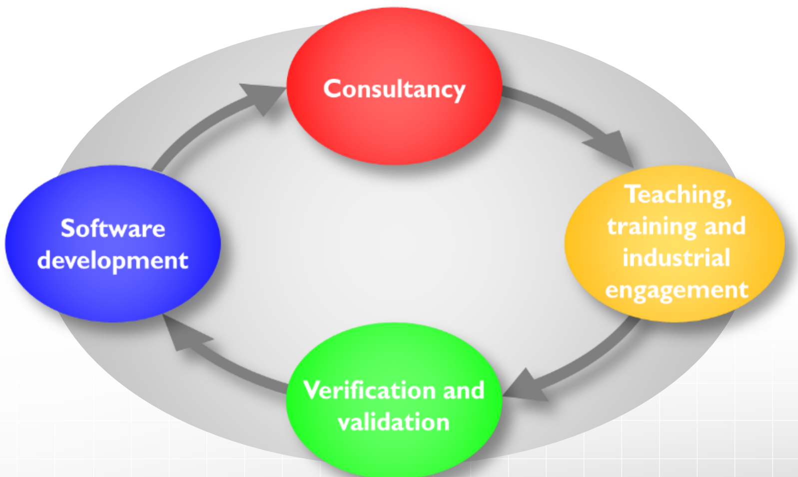
Abercus

Abercus is an independent, privately-owned consultancy specialising in advanced engineering simulation within the energy sector – computational fluid dynamics (CFD), finite element analysis (FEA), the development of bespoke software tools and teaching/training.



Agenda

- Introduction
- Using CFD to simulate explosions
- Probabilistic explosion assessment
- Current trends
- Future trends
- Discussion
- Summary.

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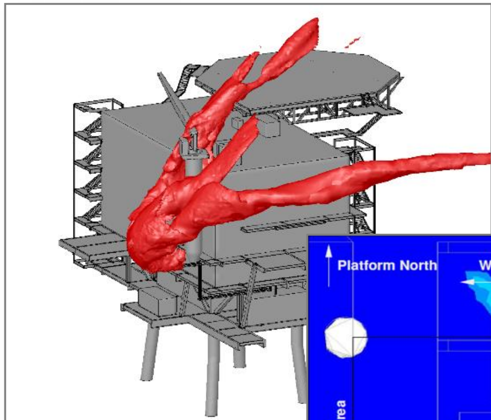
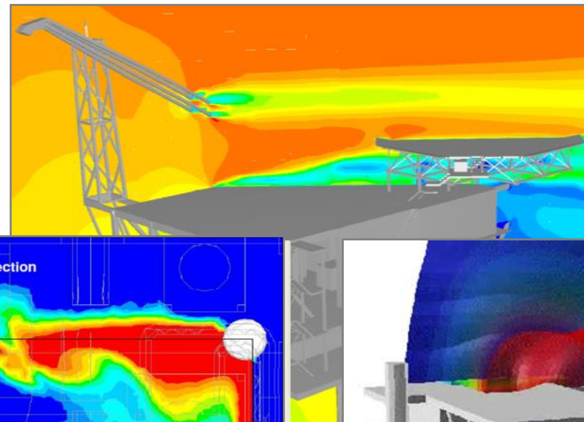
Introduction

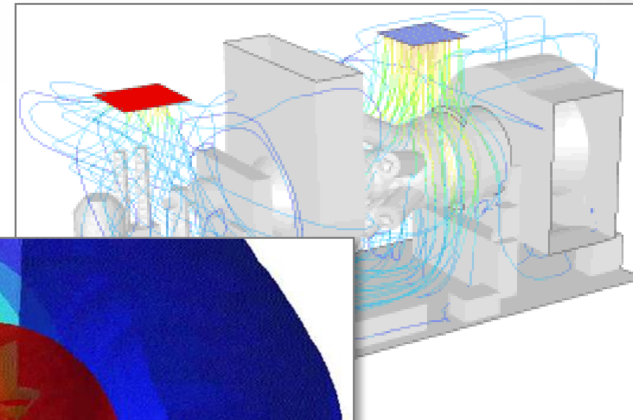
- CFD is widely used for technical safety applications:



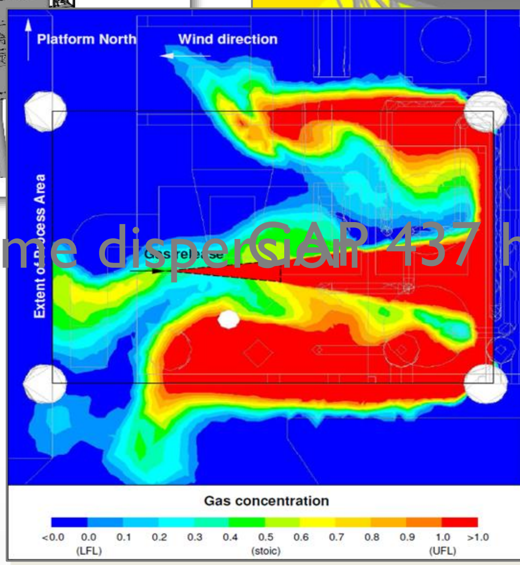
Exhaust plume dispersion



CAP 437 helideck assessment



ISO 15138 assessment of ventilation efficiency



Gas dispersion in the event of a loss of containment

Explosions

Introduction

- When designing for blast it is necessary to quantify the magnitude of the design accidental loads (DAL)
- CFD is often used to simulate a large number (hundreds or thousands) of individual dispersion and explosion scenarios within a probabilistic framework for this purpose
- The success of this approach relies on three aspects:
  - Retaining a fit-for-purpose LPC (low performance computing) approach when creating individual simulation cases, so that they can each run quickly
  - Automating the pre-processing workflow to systematically create a large number of underlying simulation cases
  - Automating the post-processing workflow to compile the simulation predictions into a useful form of information for further interpretation.

Introduction

- Current trends – simulation data management (SDM) tools with the ability to automate the simulation workflow:
  - Sharing and associated democratisation of analysis data – sensitivities
  - 3D risk assessment
  - Coupling explosion CFD codes with FEA for structural response
- Future trends:
  - Optimisation of layout
  - Probabilistic structural response
  - Removal of the equivalent stoichiometric cloud simplification
  - Understanding DDT
- Discussion – keep and develop the fit-for-purpose LPC methods.

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Using CFD to simulate explosions

- Whilst hydrocarbon explosions can, in principle, be simulated using general-purpose CFD codes, this is not common practice in the oil and gas sector
- Instead, a number of explosion-specific CFD codes have been developed, including:
  - FLACS by Gexcon
  - EXSIM by ComputIT
  - AUTOREAGAS (acquired but sadly not developed since) by Ansys
- Each of these codes has been developed to simulate deflagrations (subsonic explosions) and they all follow a similar fit-for-purpose LPC methodology based upon the distributed porosity approach.

Using CFD to simulate explosions

- Within congested spaces, the amount and spatial distribution of small-scale obstructions has a major impact upon the intensity of an explosion due to the Shchelkin mechanism:
  - The turbulence generated by the congestion causes the flame front to become distorted
  - This is manifested as an increase in the surface area of the flame front
  - This causes an increase in the rate of combustion at the flame front.

Using CFD to simulate explosions

(From Gexcon: http://www.gexcon.com/)

- Both configurations contain the same volume of gas and volumetric fill of pipe work
- The configuration on the left comprises a few large diameter pipes
- The configuration on the right comprises many small diameter pipes
- The intensity of the explosion for the right-hand configuration is increased significantly.

Using CFD to simulate explosions

(From DNVGL: https://www.dnvgl.com/)

- Both configurations contain the same volume of gas
- The configuration on the left is entirely filled with small-scale congestion
- The configuration on the right is half-filled with small-scale congestion.

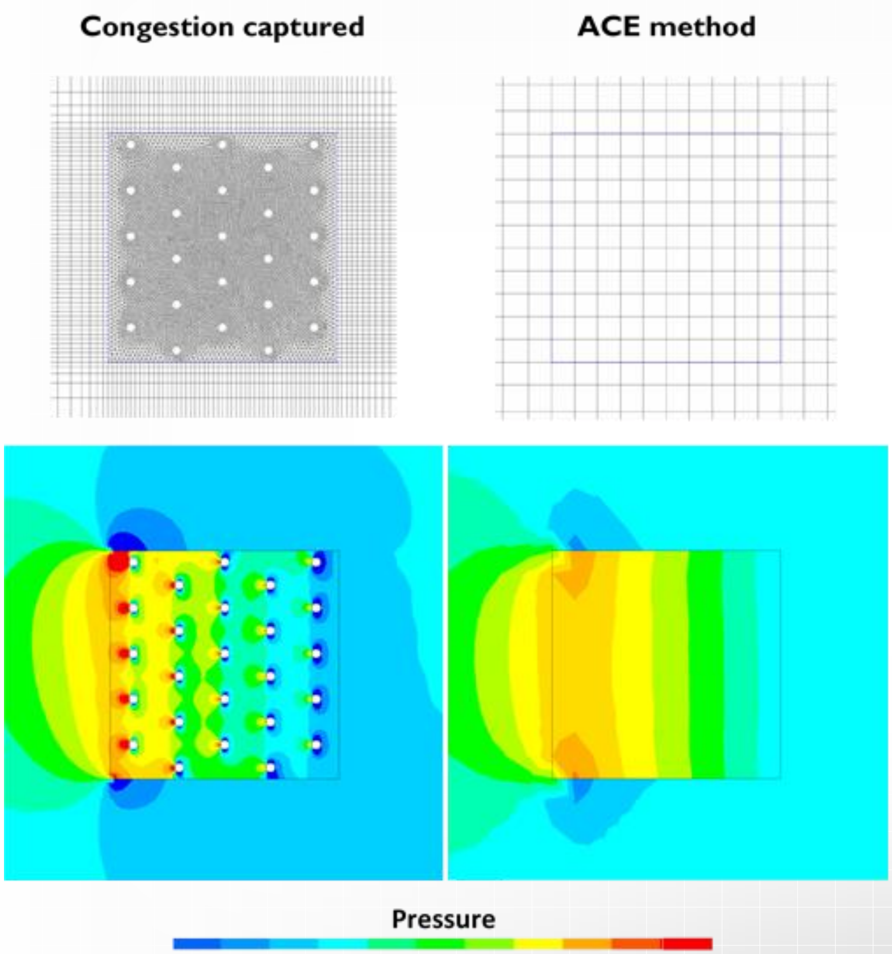
Using CFD to simulate explosions

- In principle, it is possible to capture the small-scale congestion explicitly within a CFD mesh and undertake a combustion simulation to capture the Shchelkin mechanism directly
- This approach, however, is typically prohibitive, both in terms of the cell count of the CFD mesh and the small time-step that would be required to satisfy CFL constraints.
- HPC resources may allow this first-principles approach to be pursued for a few explosion cases within a reasonable time frame
- It is, however, unlikely to be appropriate for a probabilistic approach in the near future, where hundreds or thousands of individual explosion cases may need to be simulated.

Using CFD to simulate explosions

- In contrast, the explosion-specific CFD codes are based upon a distributed porosity approach, similar to the ACE method where a relatively coarse CFD mesh is used and the effect of the sub-grid congestion is captured by allocating equivalent resistance and generation source terms in the momentum and turbulence equations respectively
- Within the combustion model, semi-empirical correlations are used to predict the effect of the Shchelkin mechanism upon the explosion behaviour.

Using CFD to simulate explosions



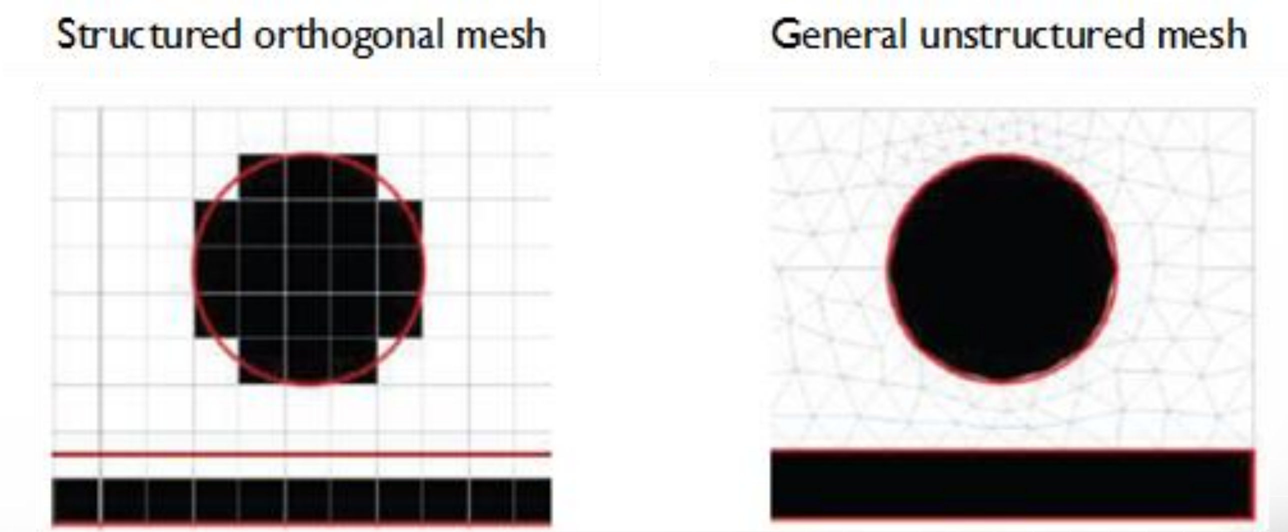
The ACE method was developed to provide a consistent approach for describing the resistance to flow due to the small-scale obstructions which are abundant across the topsides of any offshore platform. The method is demonstrated below for a simple pipe bundle.

On the left hand side, the geometry of the pipe bundle is explicitly captured within the CFD mesh and the corresponding predicted pressure field is shown for cross flow (from left to right). On the right hand side a coarse mesh is used and the effect of the sub-grid congestion is captured by the ACE method where equivalent resistance source terms are allocated in the momentum equations. A comparison of the two pressure predictions shows good agreement for the macro-pressure behaviour but the mesh required for the ACE method, and the associated computational effort, is significantly reduced.

The ACE method is designed for any class of CFD mesh, including general unstructured meshes. The method was first implemented using the UDF functionality of the FLUENT CFD code (by Ansys). This implementation was completed by Alice Ely in 2004 during the course of her MSc at the University of Leeds. Her thesis is available for download from the Abercus website.

Using CFD to simulate explosions

- Each of the explosion-specific codes is based upon the structured orthogonal mesh approach
  - Whilst this can allow the governing equations to be solved more efficiently, this does mean that the actual CFD geometry will resemble a *Lego* model
  - This is a pragmatic fit-for-purpose approach that yields real value.



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Probabilistic explosion assessment

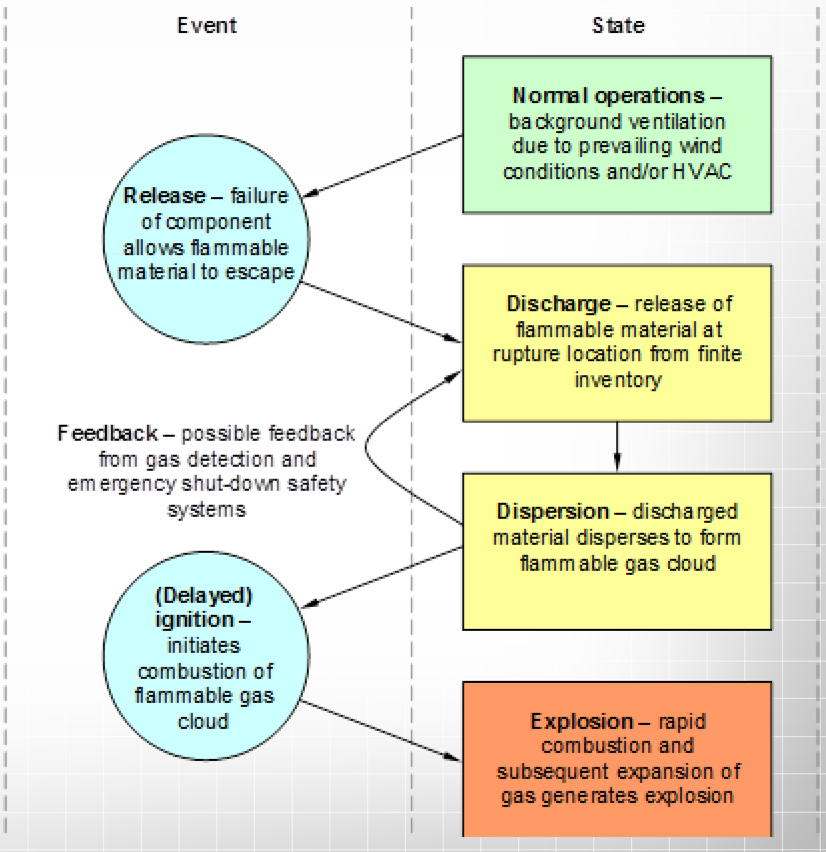
- CFD can be used to simulate a well defined explosion event – this is deterministic
- How do you define which:
  - Flammable cloud
  - Ignition point
- How should the flammable cloud be defined:
  - Geometry (typically rectangular)
  - Composition (typically stoichiometric composition).

Probabilistic explosion assessment

Simulate the sequence of events that lead up to any potential explosion event –

- background ventilation during normal operations
- dispersion following a release
- explosion following ignition.

This is a deterministic sequence!

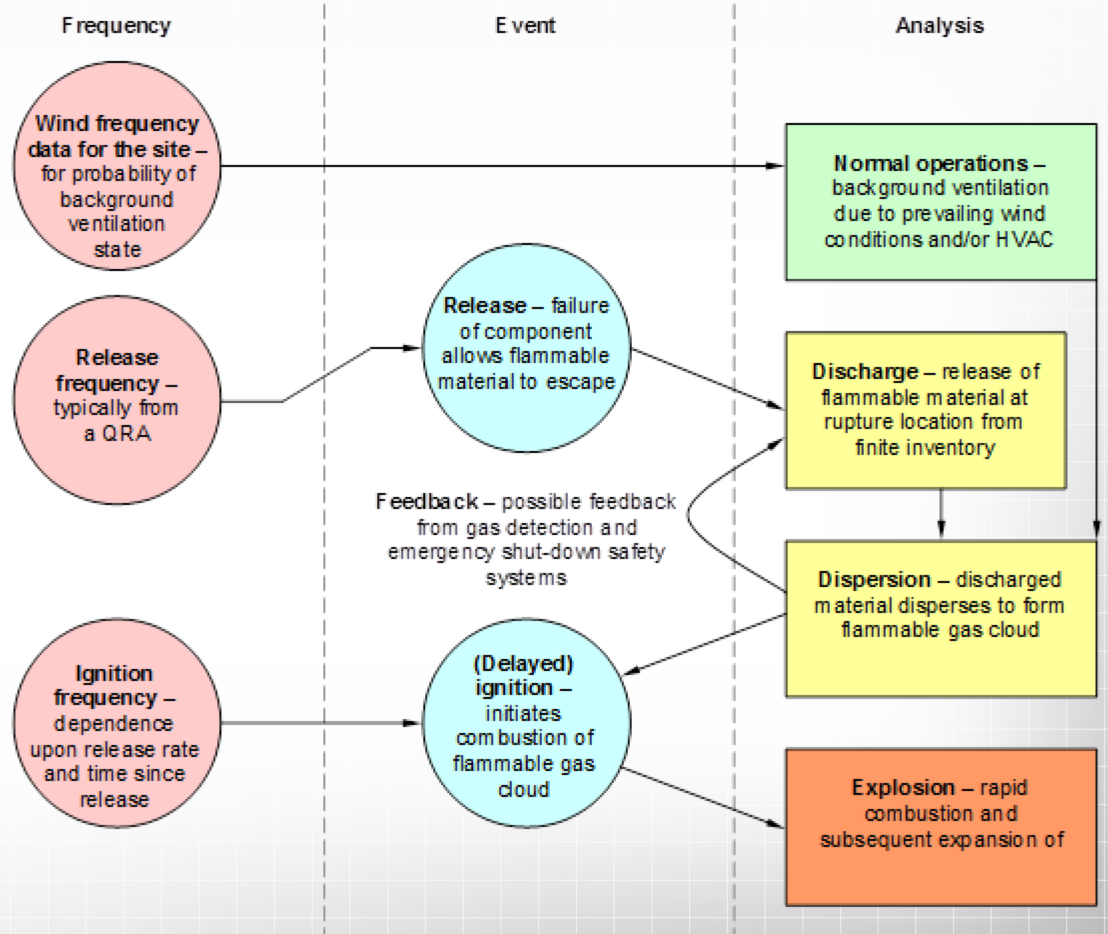


Probabilistic explosion assessment

- Determining a suitable basis for the design explosion load for a structure can be challenging
- Considering a worst-case, large release event will typically lead to explosion loads that are well in excess of what can be realistically designed for
- A more pragmatic option is to adopt a probabilistic approach to construct explosion load exceedance curves describing the probability of a particular load occurring
- This is the recommended procedure outlined in Annex F of *Risk and emergency preparedness assessment*, **NORSOK Standard Z-013** (Edition 3 is dated October 2010).

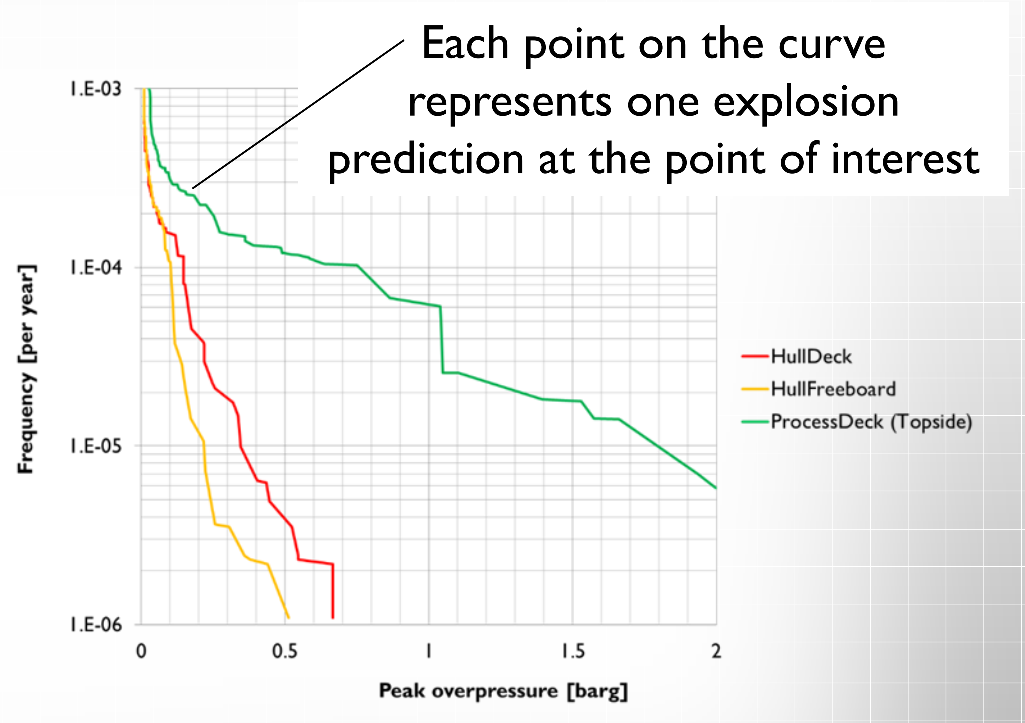
Probabilistic explosion assessment

By simulating a large dataset of scenarios, and with an understanding the frequencies of occurrence at each stage, it is possible to construct exceedance curves for the explosion load at any point of interest.



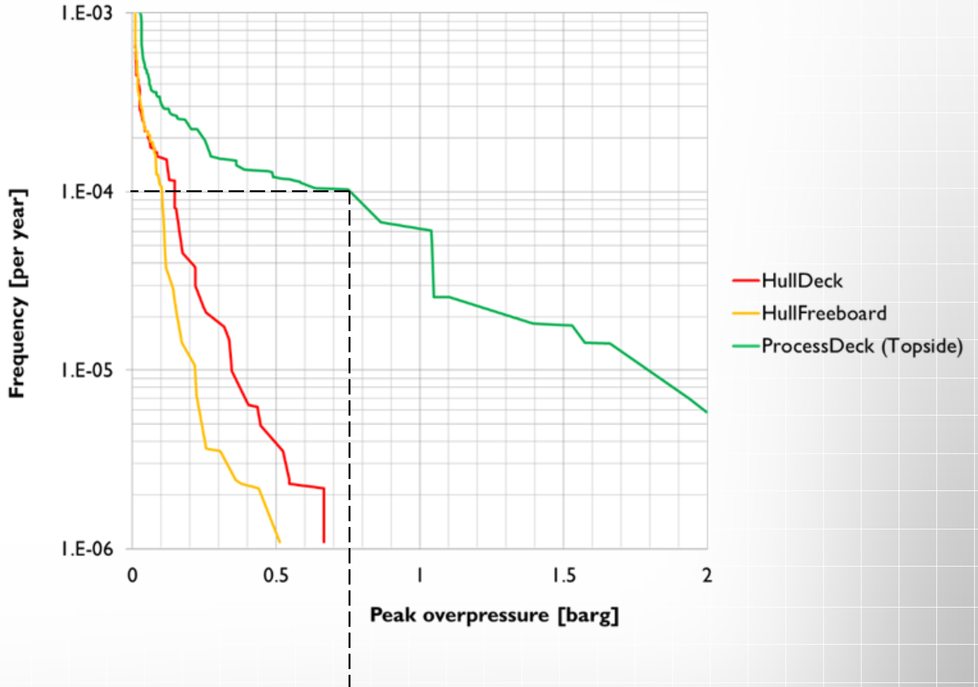
Probabilistic explosion assessment

The figure to the right shows a typical set of exceedance curves for peak overpressure, although similar curves can be constructed for underpressure and positive/negative impulses.



Probabilistic explosion assessment

Typically an allowable frequency of occurrence is taken to be 10^{-4}/yr, and the exceedance curves are used to determine the corresponding explosion loads.



Design explosion load of 0.75 barg for the process deck

Nothing new so far!

Probabilistic explosion assessment

- The challenge is that there are many variables which describe each deterministic sequence
- It is important to keep the underlying dataset of simulated scenarios manageable, so that the assessment can be completed within a reasonable timescale, typically on high-specification desktop workstations

Probabilistic explosion assessment

Normal operations	• Wind speed • Wind direction
Discharge	• Pressure and temperature of the contained material • Magnitude of the inventory of the contained material • Composition of the contained material • Release hole size
Dispersion	• Location of release • Direction of release
Explosion	• Time of ignition following the release • Ignition location

Probabilistic explosion assessment

- The challenge is that there are many variables which describe each deterministic sequence
- It is important to keep the underlying dataset of simulated scenarios manageable, so that the assessment can be completed within a reasonable timescale, typically on high-specification desktop workstations
- For a typical facility there could be +100 000 possible dispersion scenarios and +1 000 000 possible explosion scenarios to consider within the probabilistic framework
- It is not possible to simulate all of these possibilities within a reasonable time frame.

Probabilistic explosion assessment

- It is necessary to make assumptions and recognise similarities and symmetries to identify a reduced number of key representative dispersion and explosion scenarios to simulate
- All of the possible scenarios (and their probability of occurrence) are then allocated against one of the scenarios actually simulated
- Provided any assumptions introduced are conservative, the probabilistic analysis should also remain conservative.

Probabilistic explosion assessment

- Ventilation and discharge/dispersion simplifications
  - Don't consider all possible wind conditions – assume low winds prevail
  - Don't explicitly simulate all release rates required by the NORSOK standard – simulate selected releases and then use a conservative interpolation to approximate the dispersion behaviour for intermediate releases
  - Don't simulate all possible release directions – exploit symmetries and restrict to the principal orthogonal directions
- Explosion simplifications
  - Don't maintain direct coupling between the dispersion and explosion stages – de-couple the analysis and represent the spatially-varying flammable clouds from the dispersion stage by an equivalent stoichiometric cloud (ESC) that is homogeneous and cubic.

Probabilistic explosion assessment

- By exploiting these simplifications, a typical probabilistic explosion assessment can be reduced to:
  - Twelve ventilation CFD simulations
  - A few hundred/couple of thousand transient dispersion CFD simulations
  - A couple of hundred explosion CFD simulations
- The associated duration for the assessment may be reduced to:
  - Around one month for the dispersion scope
  - A few days for the explosion scope
  - Typically a couple of months in total.

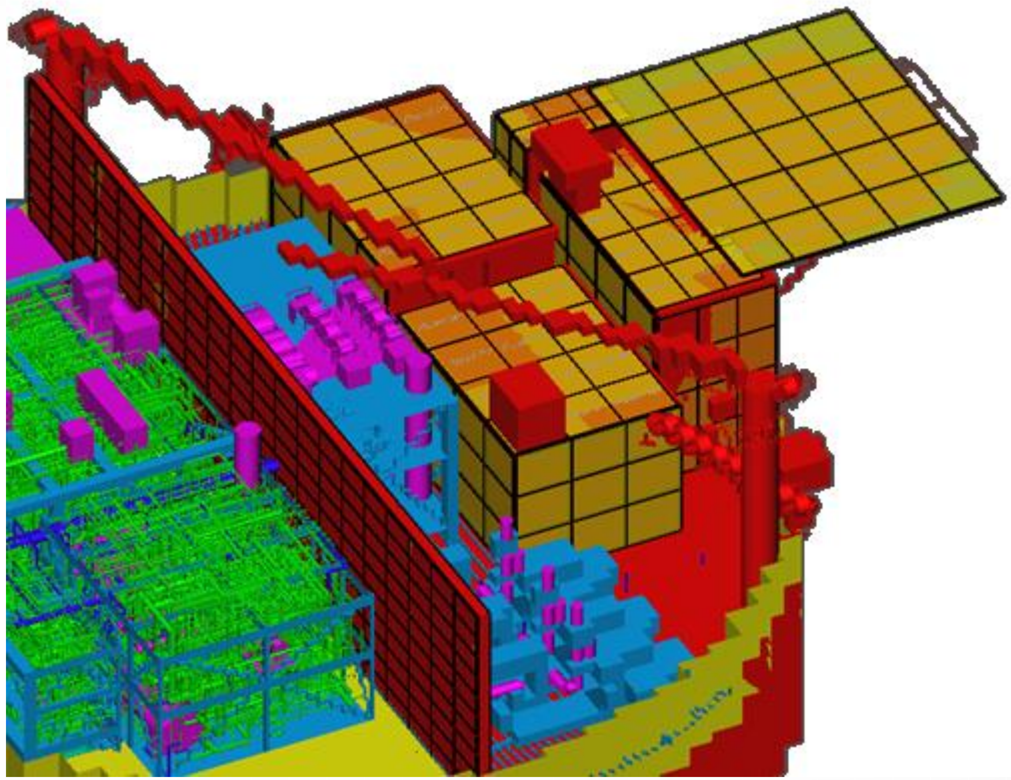
Probabilistic explosion assessment

- Each explosion CFD model may include several thousand monitor points or (2D) panels of interest which the instantaneous explosion overpressure is predicted
  - The pressure trace can be approximated using a triangulation defined by eight parameters, including the maximum predicted overpressure and underpressure, and the positive and negative impulse.

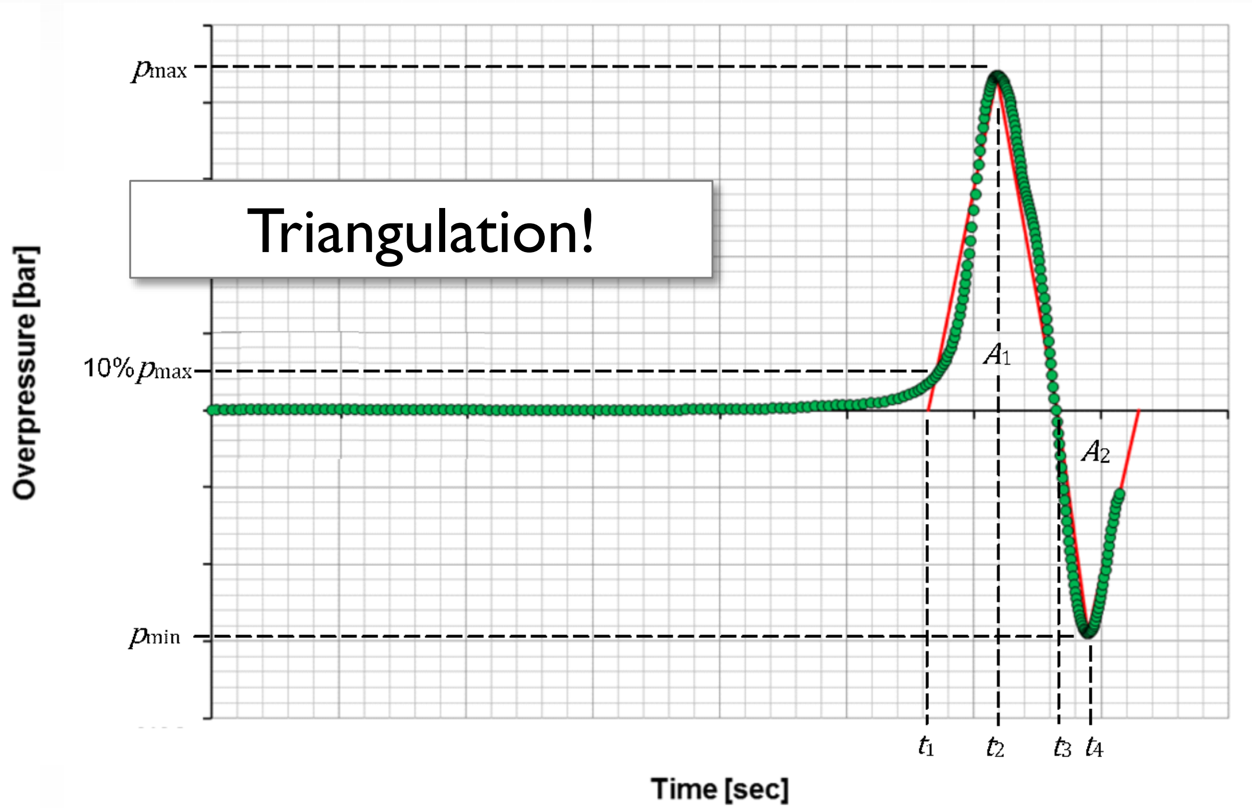
Probabilistic explosion assessment

Example of an FPSO showing arrays of 2D monitor panels across the targets of interest:

- Blast wall
- LQ/TR
- Helideck.



Probabilistic explosion assessment



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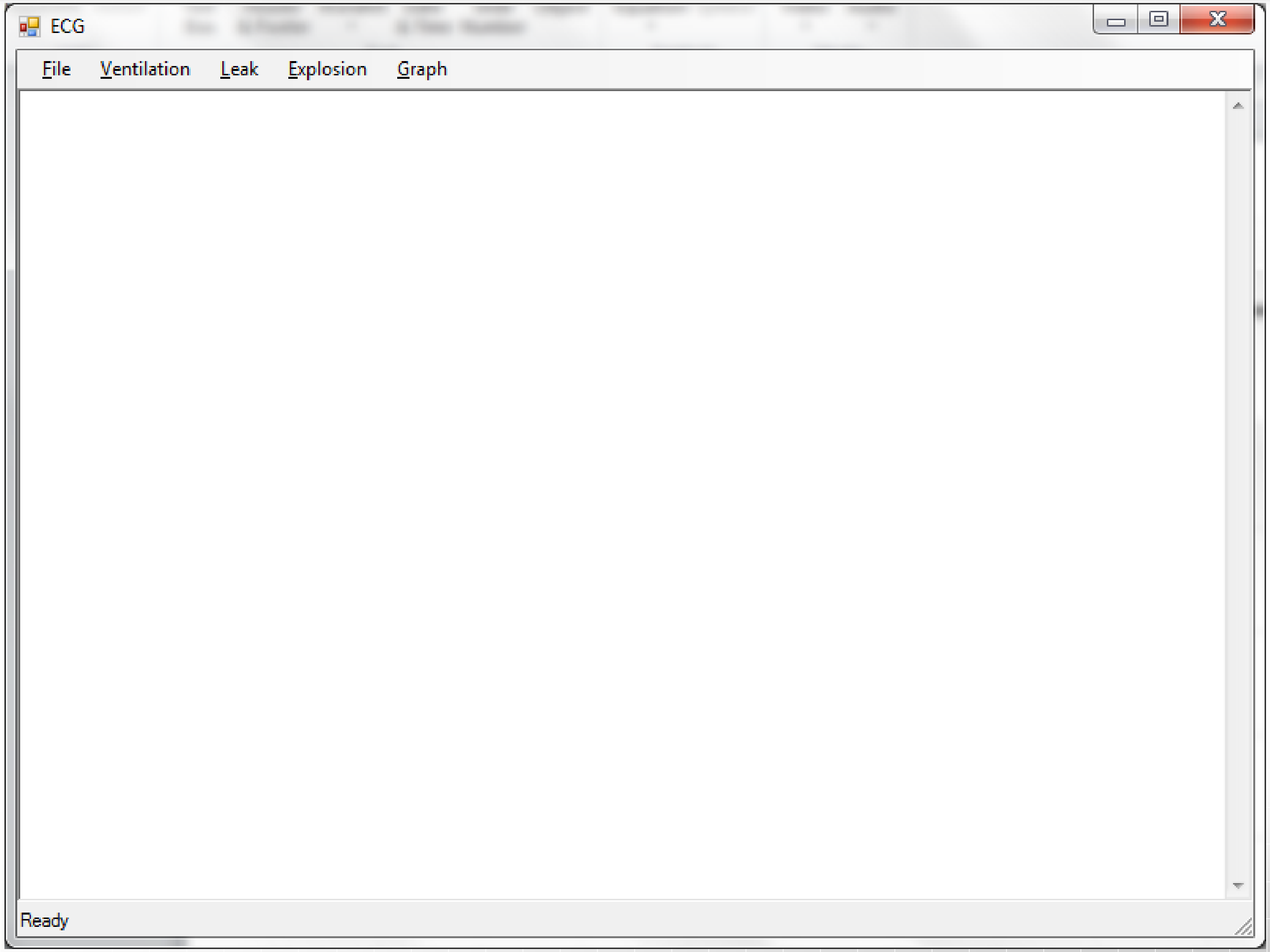
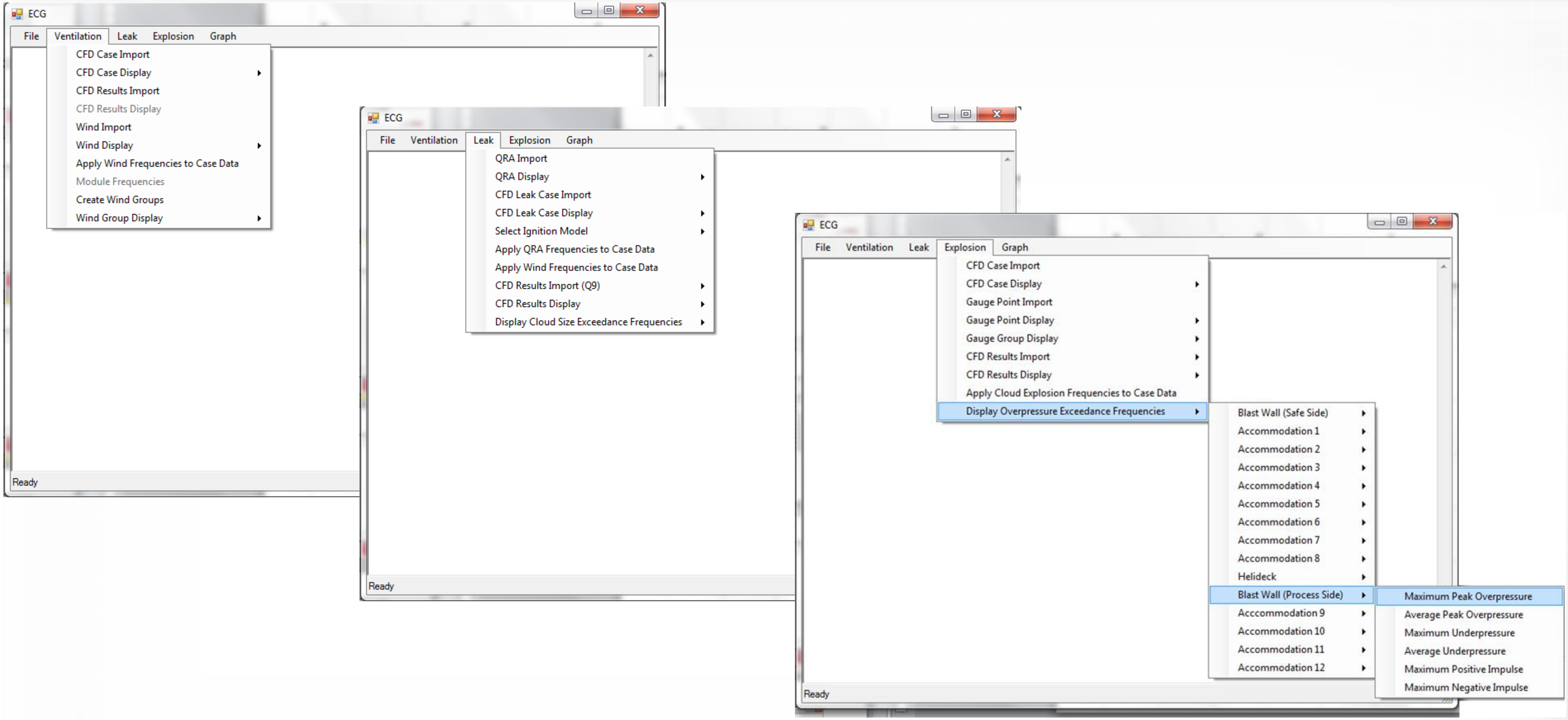
Current trends

- With such a large number of individual simulations within a probabilistic study, the approach is greatly enhanced by a robust simulation data management (SDM) framework with the ability to automate the simulation workflow
  - Setting up the individual simulations that need to be undertaken
  - Running them automatically in batch mode
  - Compiling the CFD predictions automatically into the exceedence data from which the structural design loads can be determined
- Abercus has recognised this and has developed the EXCGEN software to automate this workflow
- Gexcon is also developing a tool, called RISK, for this purpose.

Current trends – EXCGEN



Current trends – EXCGEN



Current trends – EXCGEN

- Some of the major benefits of an automated SDM approach:
  - Can provide a robust, consistent method for the implementation of the NORSOK Standard Z-013, provided the underlying implementation is openly documented
  - Sharing and democratisation of analysis data, allowing the sensitivity of the exceedence data to many of the probabilistic assumptions to be investigated on-the-fly, in the company of the wider design team
  - Automatic compilation of 3D risk assessment information where, for example, the spatial variation of an explosion load can be presented across a structural target of interest, rather than just a single worst-case load that is read from a traditional exceedence curve
  - Automatic mapping of CFD explosion loads on to an FEA model so that the associated structural response can be simulated.

Current trends – democratisation of data

- There is a huge amount of predictive data generated during the course of a probabilistic explosion assessment that could be extremely useful to the structural engineer
- This is often not utilised because the probabilistic explosion assessment and the structural design are typically undertaken by different parties and the sharing of information has not been easy
- The interface between the parties generally comprises the transfer of a single DAL for each target of interest, typically the 10^{-4}/yr DAL, comprising the 10^{-4}/yr peak overpressure and an associated measure of the duration of the 10^{-4}/yr blast.

Current trends – democratisation of data

- Enabling easier data sharing can enable improved interaction between the structural engineer and explosion analyst
- This can allow, for example, the sensitivity of explosion loads with respect to the underlying assumptions to be explored
- Deeper understanding of explosion events should lead to better, safer design.

Current trends – democratisation of data

- Sensitivities to (some of) the probabilistic assumptions can be considered on-the-fly, in the company of the design team
  - Ignition methodology
  - Underlying wind conditions
  - Flammable volume methodology
  - Release frequencies from the QRA
- Typically these sensitivities may not be explored.

Current trends – democratisation of data

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

Sensitivity cases relating to ignition methodology

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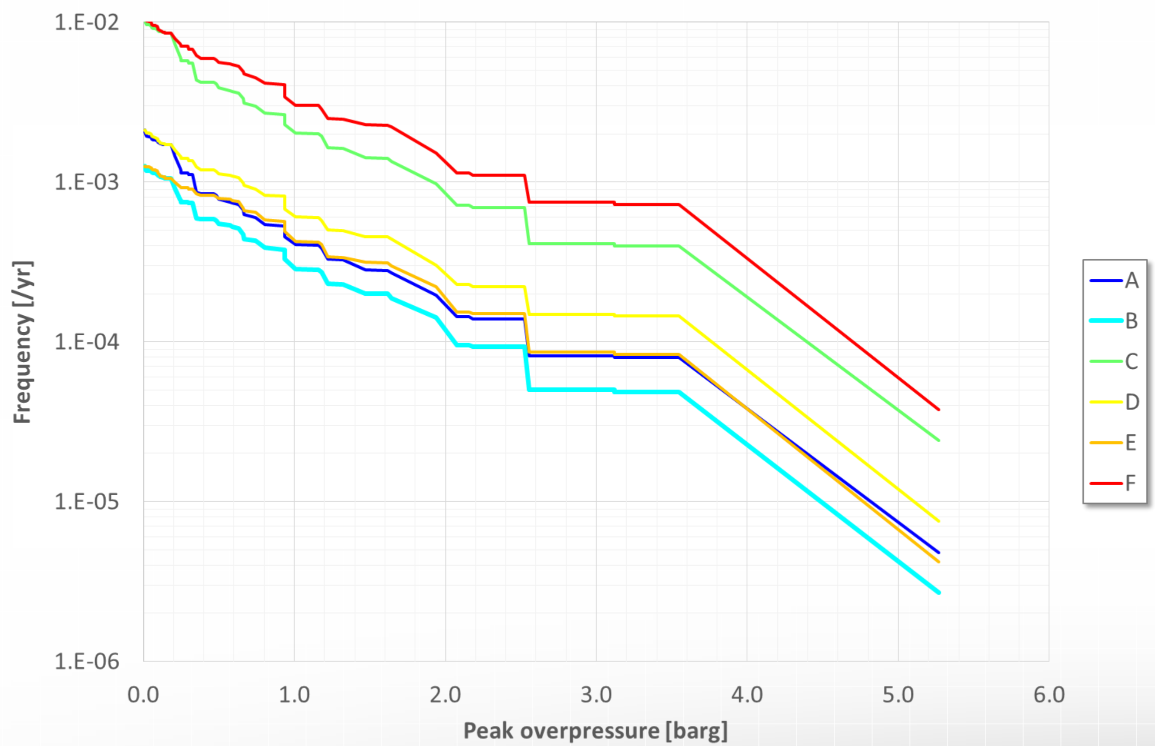
Current trends – democratisation of data

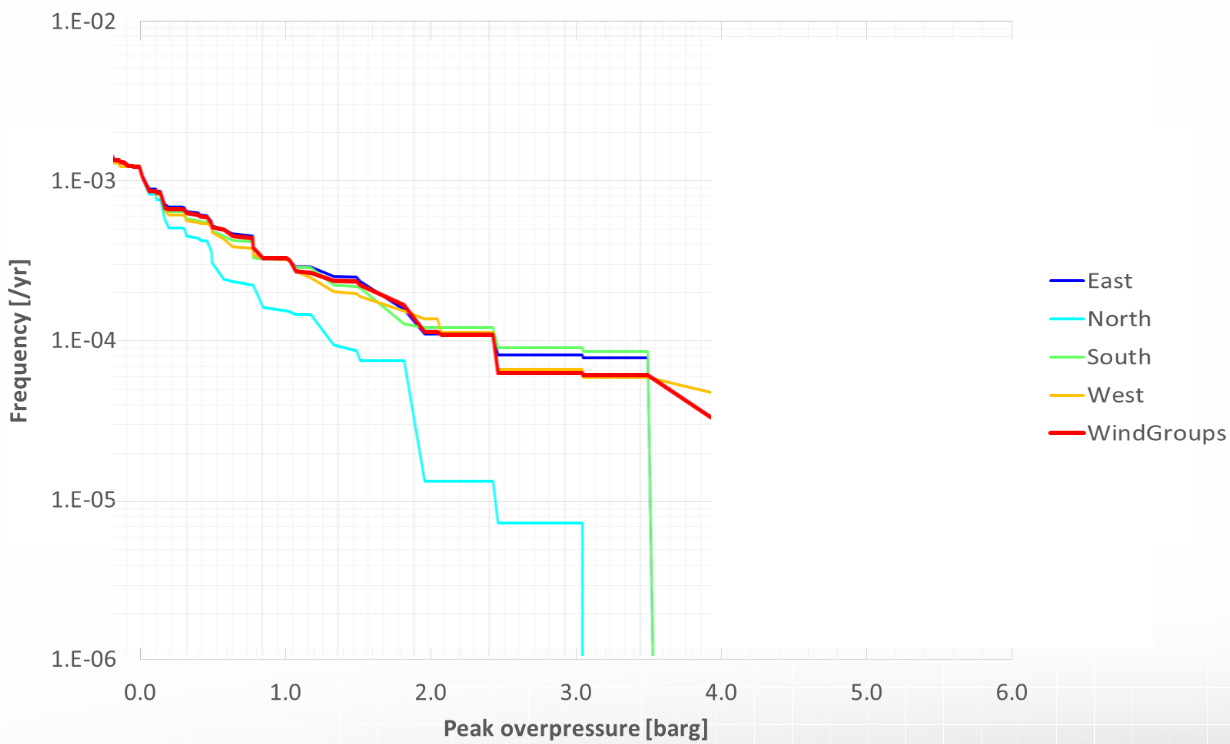
Sensitivity cases relating to ignition methodology



Exceedance curves for peak overpressure

Current trends – democratisation of data

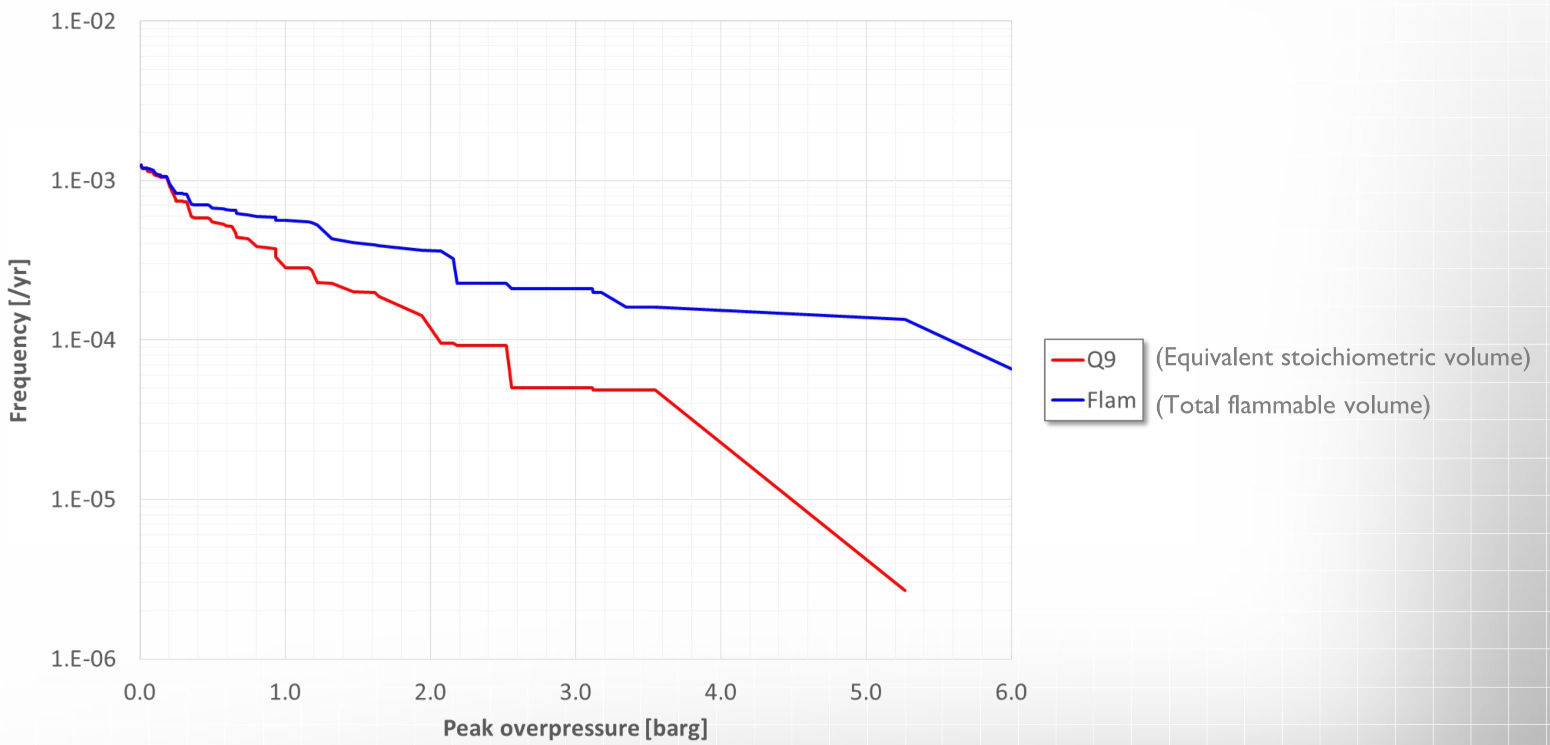
Sensitivity cases relating to underlying ventilation pattern/wind direction



Exceedance curves for peak overpressure

Current trends – democratisation of data

Sensitivity cases relating to flammable volume methodology



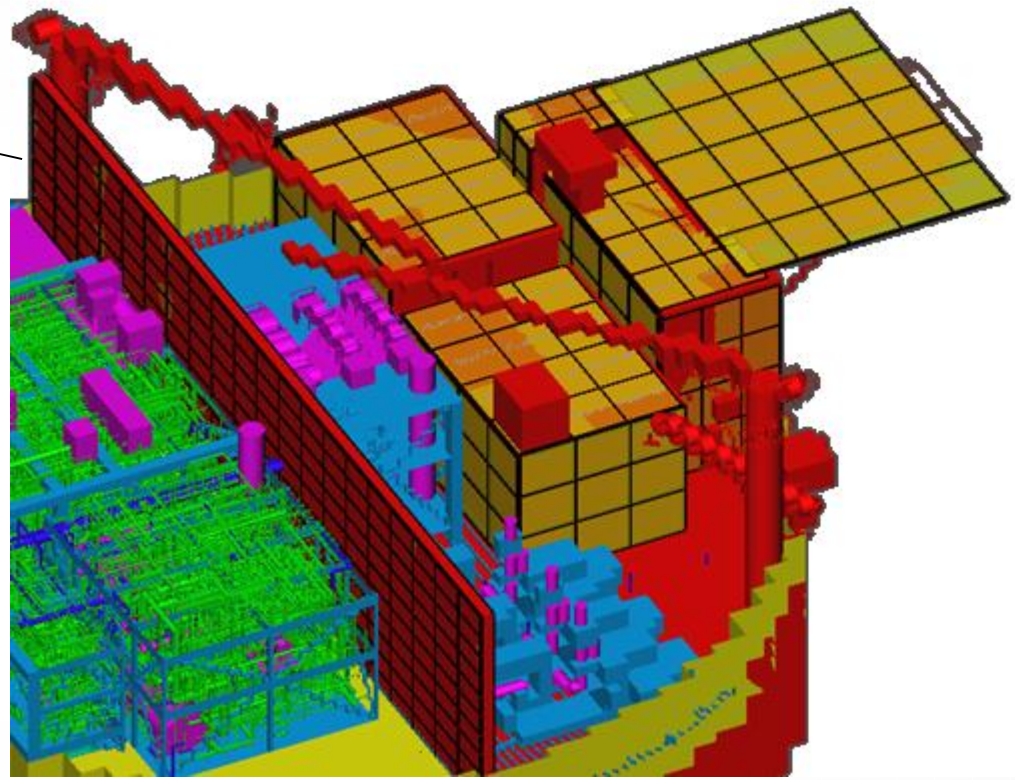
Exceedance curves for peak overpressure

Current trends – 3D risk assessment

- Perhaps because it is not straightforward to share information between different parties, the design explosion loads are typically extracted from the exceedance curve for each structural target and provided to the structural engineer as a single design load for each target
- The explosion loads, particularly for large targets such as blast walls, may vary across the target so providing a single value for the design load may be overly conservative.

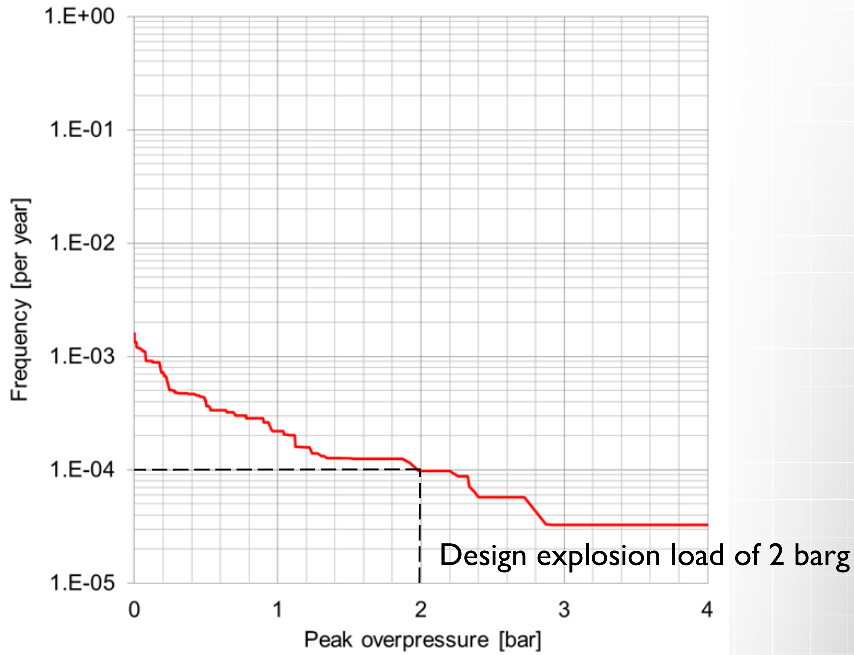
Current trends – 3D risk assessment

Blast wall, represented by a discretised array of monitor panels within the FLACS model



Current trends – 3D risk assessment

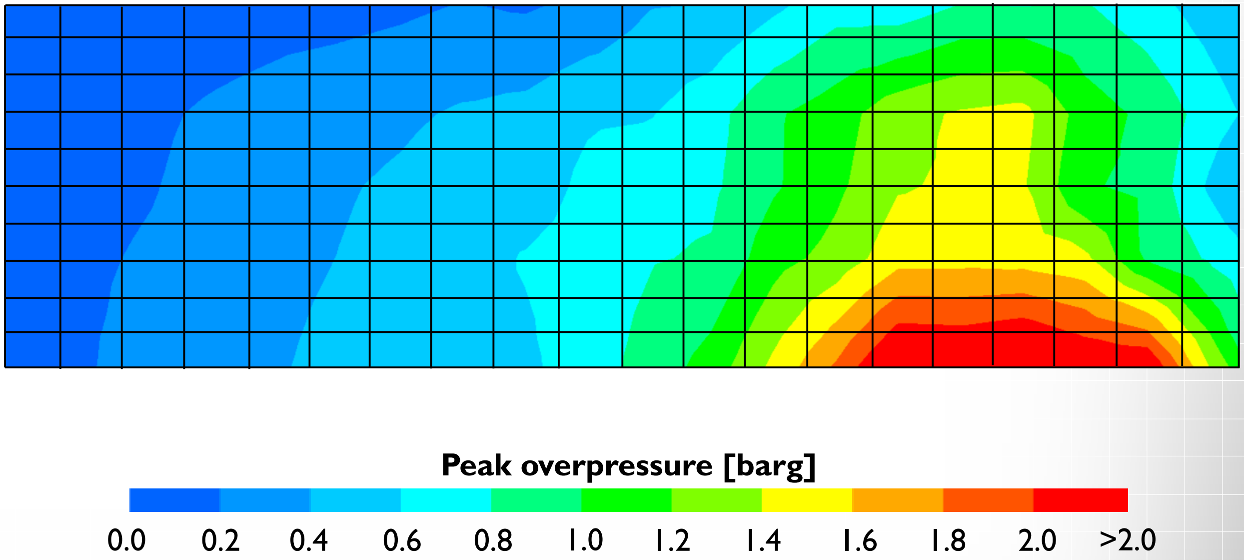
For this example, the 10^{-4}/yr peak overpressure for the blast wall is 2 barg.



Current trends – 3D risk assessment

The design explosion load retrieved from the exceedance curve (2 barg) is localised – the 10^{-4}/yr overpressure for the majority of the blast wall is significantly less than 2 barg.

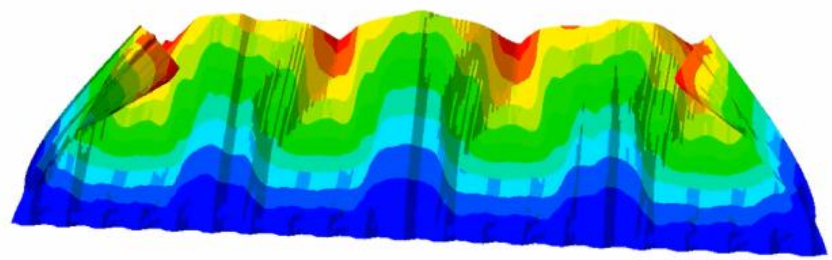
Contour plot of 10^{-4}/yr peak overpressure



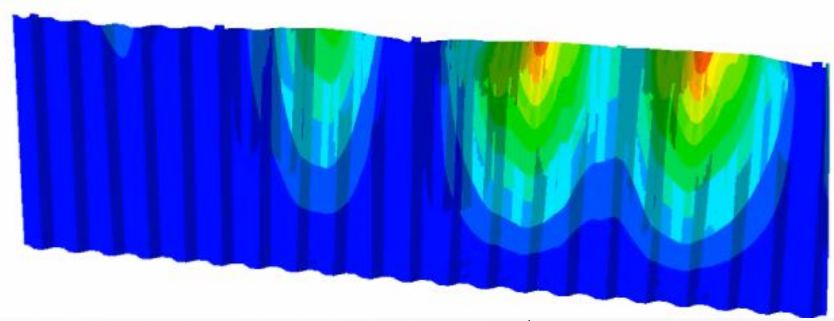
Current trends – 3D risk assessment

This can have a significant impact upon the structural response of the blast wall under DAL loading.

Contour plot of normalised deflection



2 bar overpressure uniformly applied



Contours of overpressure for 10^{-4}/yr pseudo-event

Normalised deflection

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Future trends

- HPC will offer new opportunities in future
- By using HPC for probabilistic explosion assessments, the typical project timeframe of around two months can be shortened, perhaps halved
- Within the oil and gas industry, projects often last for months or even years, so the benefit of saving perhaps one month from a probabilistic assessment could easily be missed in the scale of the rest of the overall project
- Instead of simply shortening the time taken to complete an assessment, there may be better ways to exploit HPC which could add more value in future.

Future trends – optimisation of layout

- At present, because of the long simulation times, the dispersion and explosion scenarios are often simulated for just one instance of the geometry of the installation and the entire probabilistic study is an assessment of that single geometry instance
- If the simulation time can be shortened to just a few days for the dispersion/explosion stages then several geometries could be considered within the typical two-month project window which could provide significant value to the project team and allow some optimisation of the facility layout.

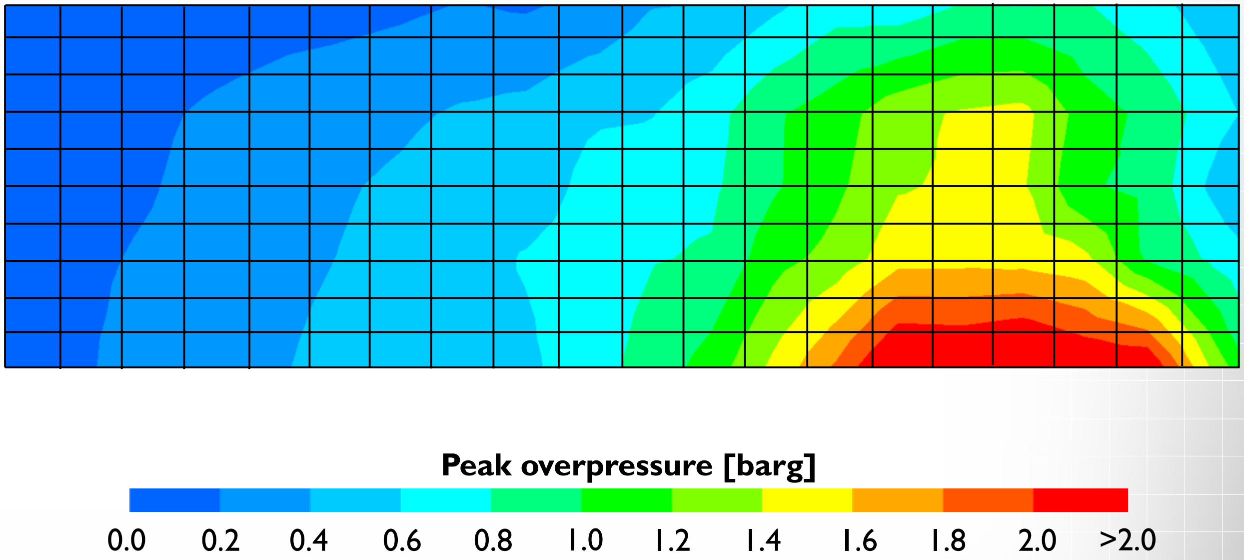
Future trends – coupling with FEA

- It is generally not straightforward to identify any single individual event from the underlying simulated explosion events as a representative 10^{-4}/yr event (see Abercus' recent IMechE paper)
- The contour plots of 10^{-4}/yr overpressure receive contributions from a wide range of explosion events
- Is it possible to construct a 10^{-4}/yr pseudo-event?

Future trends – coupling with FEA

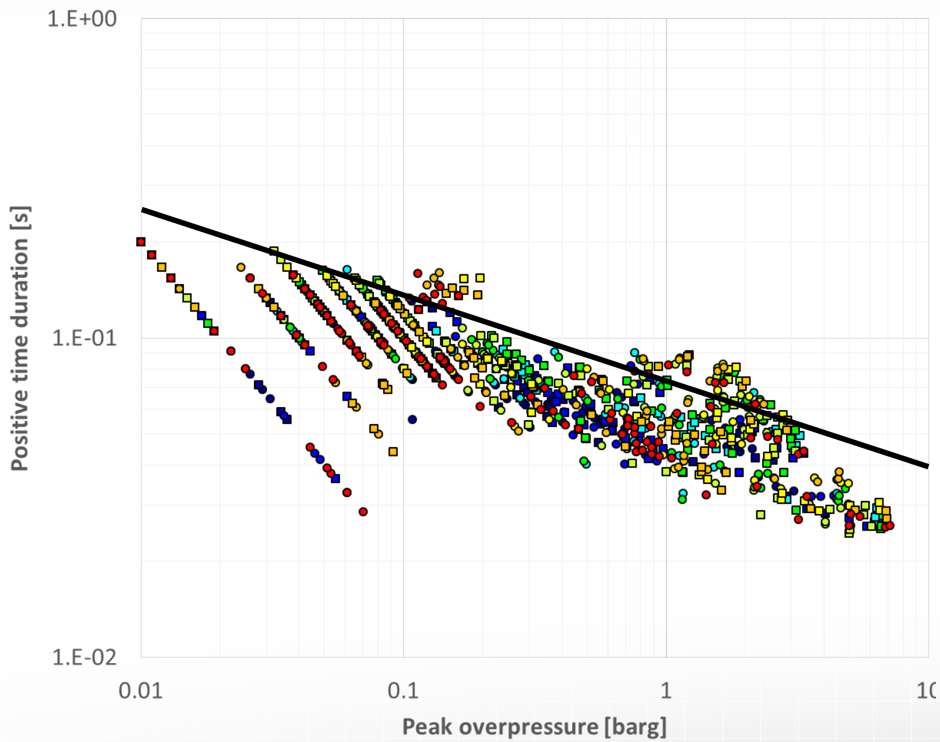
The 10^{-4}/yr overpressure is just part of the DAL definition – need to consider the dynamic behaviour with respect to the duration of the blast and how the blast might travel across the blast wall.

Contour plot of 10^{-4}/yr peak overpressure



Future trends – coupling with FEA

Sensitivity cases relating to flammable volume methodology



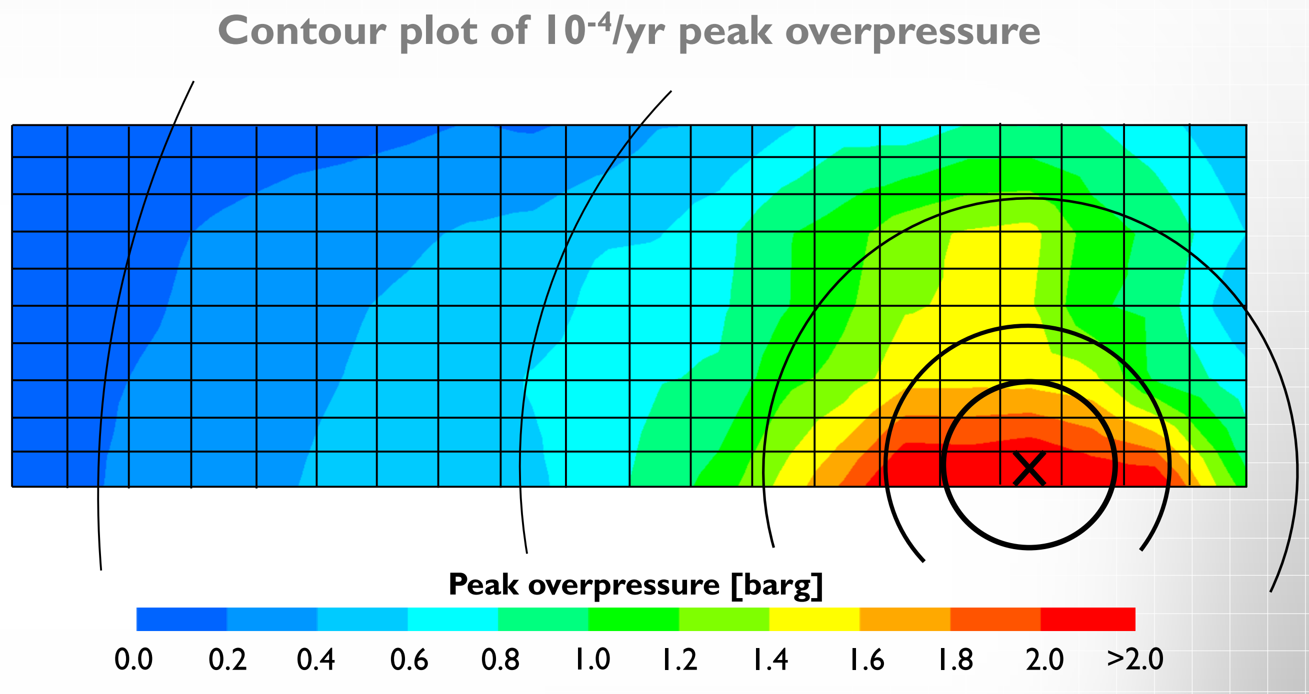
Scatter plot showing time duration of the positive blast phase with peak overpressure

Future trends – coupling with FEA

- The 10^{-4}/yr overpressure is just part of the DAL definition – need to consider the dynamic behaviour with respect to the duration of the blast and how the blast might travel across the blast wall
- Identifying trends from the underlying explosion data set can allow us to define the associated time duration of the positive blast phase
- The same approach can be used for the negative blast phase, so that the shape of a (triangulated) 10^{-4}/yr pseudo-blast can be fully described
- A blast, however, will not impinge everywhere instantaneously.

Future trends – coupling with FEA

If it can be assumed that the initial impingement is at the location of the peak, the time delay across the blast wall can be included into the pseudo-event blast behaviour.

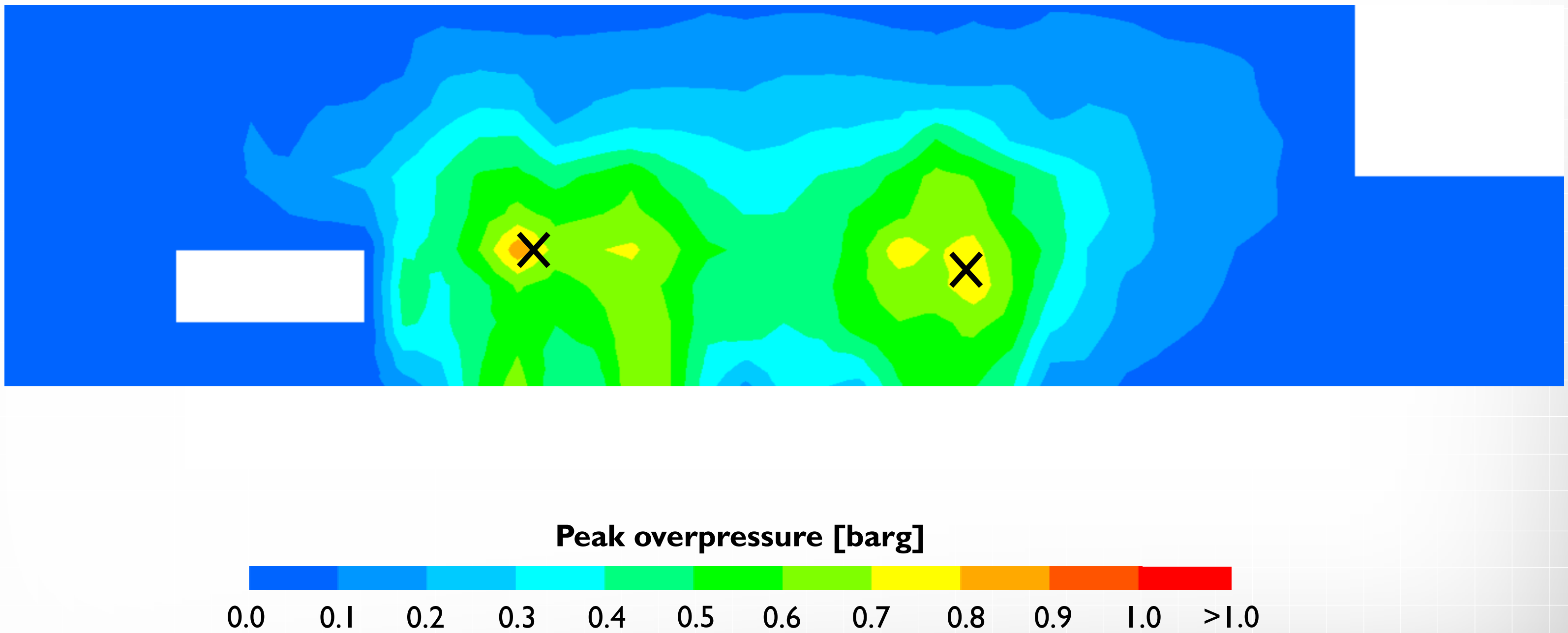


Future trends – coupling with FEA

- If it can be assumed that the initial impingement is at the location of the peak, the time delay across the blast wall can be included into the pseudo-event blast behaviour, based upon an assumption of the local speed of sound
- What happens if there are two local peaks in the 10^{-4}/yr peak overpressure?

Future trends – coupling with FEA

Contour plot of 10^{-4}/yr peak overpressure

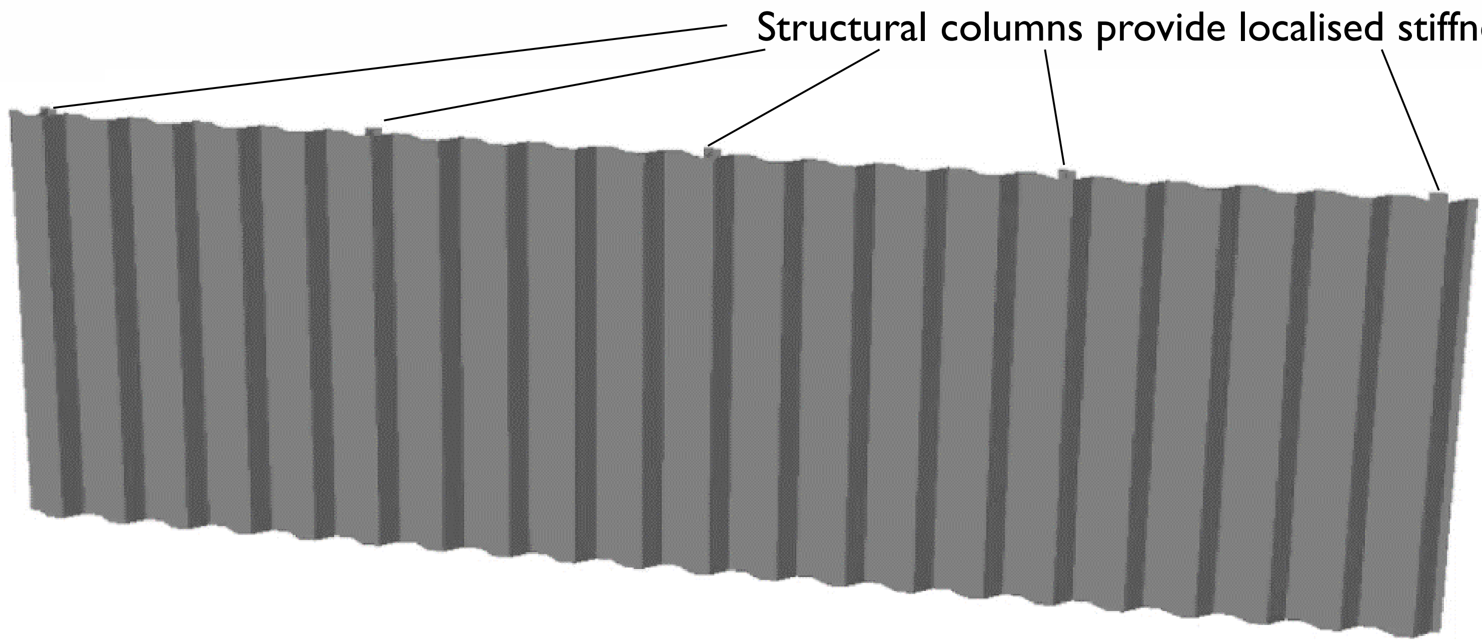


Future trends – probabilistic structural response

- Rather than construct a single pseudo-event, undertake a probabilistic assessment for the structural response instead:
  - One-to-one coupling between every explosion simulation and an associated FEA structural simulation
  - The probability of occurrence for each underlying explosion event and, therefore, each corresponding FEA simulation is already known
  - Compile exceedance curves for structural measures (for example, stress and/or deflection) at every monitor panel
  - Compile into plots of 10^{-4}/yr stress and/or deflection
- No need to make assumptions regarding the pseudo-event
- Faster computers at least make this a realistic alternative.

Future trends – probabilistic structural response

Case study – using a probabilistic structural response approach (with one-to-one CFD/FEA coupling)

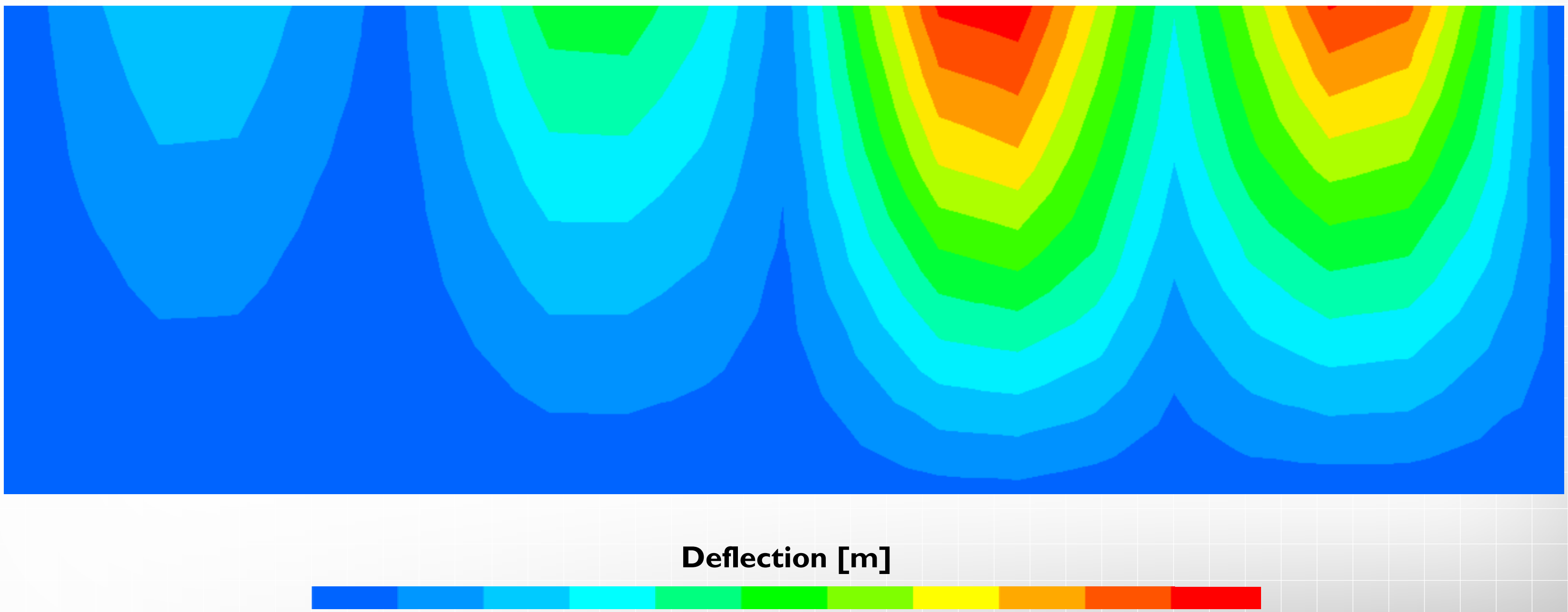


Structure of the blast wall

Future trends – probabilistic structural response

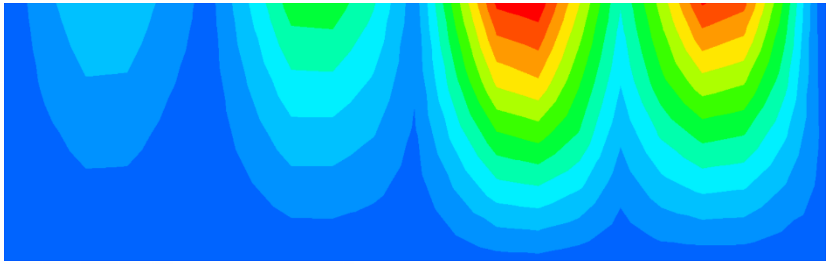
Case study – using a probabilistic structural response approach (with one-to-one CFD/FEA coupling)

Contour plot of 10^{-4}/yr deflection

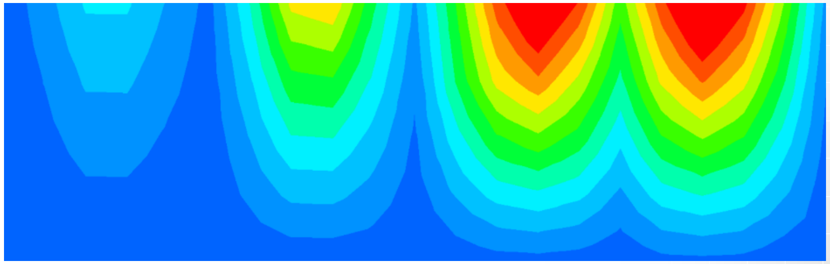


Future trends – probabilistic structural response

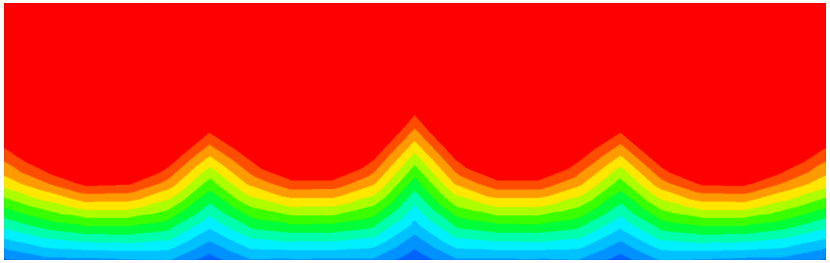
Contour plot of 10^{-4}/yr deflection



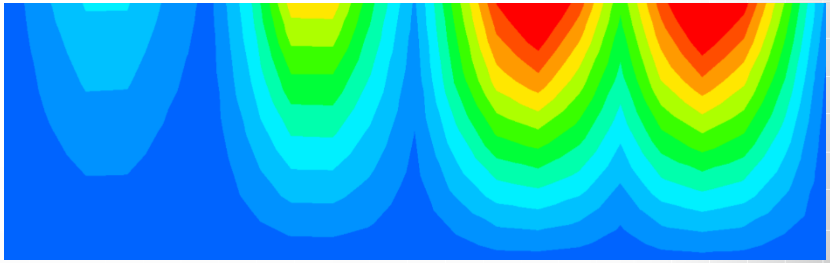
Using a probabilistic structural response approach



Using the 10^{-4}/yr pseudo-event without time delay



Traditional approach – uniformly applying the 10^{-4}/yr overpressure (2 barg) from the exceedance curve



Using the 10^{-4}/yr pseudo-event with time delay

Deflection [m]

Future trends – probabilistic structural response

- For the case study presented here, it turns out that there is reasonable agreement between the pseudo-event and probabilistic structural response approaches (top left, top right and bottom right contour plots on the previous page)
- However, we need to consider a much wider range of examples to determine whether this is generally the case
- The traditional approach with a uniformly applied 10^{-4}/yr load (bottom left contour plot on the previous page) is overly conservative when compared to the probabilistic structural response and pseudo-event approaches.

Future trends – remove the ESC assumption

- HPC could allow a direct one-to-one coupling between the spatially-varying clouds at the dispersion stage and the simulated explosion cases
- Each snapshot of each cloud from the dispersion stage could then be simulated explicitly at the explosion stage, making redundant the current simplification where an equivalent stoichiometric cloud (ESC) is used instead
- However, the additional workload involved with this approach would probably preclude the other potential value-adding extensions to the probabilistic approach discussed previously.

Future trends – remove the ESC assumption

- Perhaps comparisons could be undertaken using HPC for a range of projects to investigate whether the outcome of a probabilistic assessment is sensitive to the equivalent stoichiometric cloud assumption
- If it is demonstrated that this assumption is indeed fit-for-purpose then it can be retained for use with confidence, without attracting criticism in future.

Future trends – capturing DDT

- The explosion-specific CFD codes are currently verified for subsonic deflagrations – they are not verified for DDT (deflagration-detonation transition) where the explosion becomes so intense that it becomes supersonic and, importantly, self-sustaining
- Whilst DDT has traditionally been considered a rare event, there is a growing body of evidence, particularly following the Buncefield inquiry, to suggest that DDT may be more common than previously thought.

Future trends – capturing DDT

- Understanding the onset of DDT is an active research topic and the use of HPC to investigate DDT numerically from first principles using general-purpose CFD codes may provide useful understanding of this phenomenon
- Methods to capture the onset of DDT and the dynamics of the subsequent detonation might then be incorporated into the existing LPC explosion-specific codes for use in industry.

Agenda

- Introduction
- Using CFD to simulate explosions
- Probabilistic explosion assessment
- Current trends
- Future trends
- Discussion
- Summary.

Discussion

- The statistician George Box said: *all models are wrong but some are useful*
- Over the past couple of decades there has been a continued effort to validate the explosion-specific CFD codes and whilst they could generally be improved, they are certainly useful and generally considered to be fit-for-purpose tools for undertaking probabilistic explosion assessments.

Discussion

- With modern HPC there is the prospect to more accurately model the underlying physics of the flow behaviour at each stage of the probabilistic analysis, but – *is it really worth it?*
- Whilst it may be possible to model an explosion from first principles by explicitly capturing congestion in an unstructured CFD mesh and simulating the detailed combustion physics at the flame front, would this actually add any additional value?

Discussion

- Given that there are already many assumptions and limitations required to make the probabilistic framework a manageable approach, and this is likely to remain the case even with HPC for the foreseeable future, and there will continue to be uncertainties relating to the density and distribution of small-scale obstructions in congested spaces, we must ask ourselves: *how accurately should we simulate what is potentially the wrong case?*

Discussion

- HPC may allow a first principles approach to be pursued for a handful of explosion cases, but this approach is unlikely to be used within a probabilistic framework in the near future, where hundreds of individual simulated explosion cases may be required
- Even if the most powerful super-computers were available and this approach was possible, it's probably not going to provide any more value to a project than using a simpler verified explosion-specific CFD code.

Discussion

- Higher fidelity simulations may provide additional understanding about the underlying physical mechanisms and DDT which could be used to improve the LPC-focussed distributed porosity methods currently used by the explosion-specific CFD codes (which could also be incorporated into the general-purpose codes if their vendors wanted to)
- But keep the pragmatic LPC simplifications, rather than jettison this knowledge in favour of a significantly more computationally intensive first principles approach that is reliant upon ever more powerful HPC resources.

Agenda

- Introduction
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Summary

- CFD is used for many types of technical safety study, including probabilistic explosion assessments – ventilation, dispersion and explosion
- There is a huge amount of predictive data generated during the course of a probabilistic explosion assessment that could be extremely useful to the structural engineer
- This is often not utilised because the probabilistic explosion assessment and the structural design are typically undertaken by different parties and the sharing of information has not been easy.

Summary

- The industry needs a tool to provide a robust method of implementation of the probabilistic methodology outlined in NORSOK Z013
- Abercus has developed the EXCGEN tool for this purpose
- Gexcon is currently developing RISK for the same purpose
- Other tools may follow?
- EXCGEN enables:
  - Sharing and associated democratisation of analysis data – sensitivities
  - 3D risk assessment
  - Probabilistic structural response.

Summary

- The more you look at something, very often, the more interesting it gets – when information becomes easily available other points of discussion follow:
  - How to select representative 10^{-4}/yr events?
  - How to construct 10^{-4}/yr pseudo-events?

Summary

- Is it worth pursuing a probabilistic structural response approach?
  - For the example considered there is reasonable agreement between the pseudo-event and probabilistic structural response approaches, but we need to consider a much wider range of examples to determine whether this is generally the case
- Is it worth removing the equivalent stoichiometric cloud (ESC) assumption?
  - Comparisons could be undertaken for a range of projects to investigate whether the outcome of a probabilistic assessment is sensitive to the equivalent stoichiometric cloud assumption
  - If it is demonstrated that this assumption is fit for purpose then it can be retained for use with confidence, without attracting criticism in future.

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