Comment La Simulation Supporte La Certification?

Confidence in simulation for compliance in the energy sector (technical safety)

Dr Steve Howell – 23 May 2023

Abercus 7 Queen's Gardens Aberdeen AB15 4YD www.abercus.com

Dr Steve Howell

Steve is a chartered engineer with 25+ years experience in the application and development of CFD. He founded Abercus, an independent, privately-owned consultancy specialising in advanced engineering simulation, in 2010 to provide specialist simulation and modelling services, initially to the energy sector.

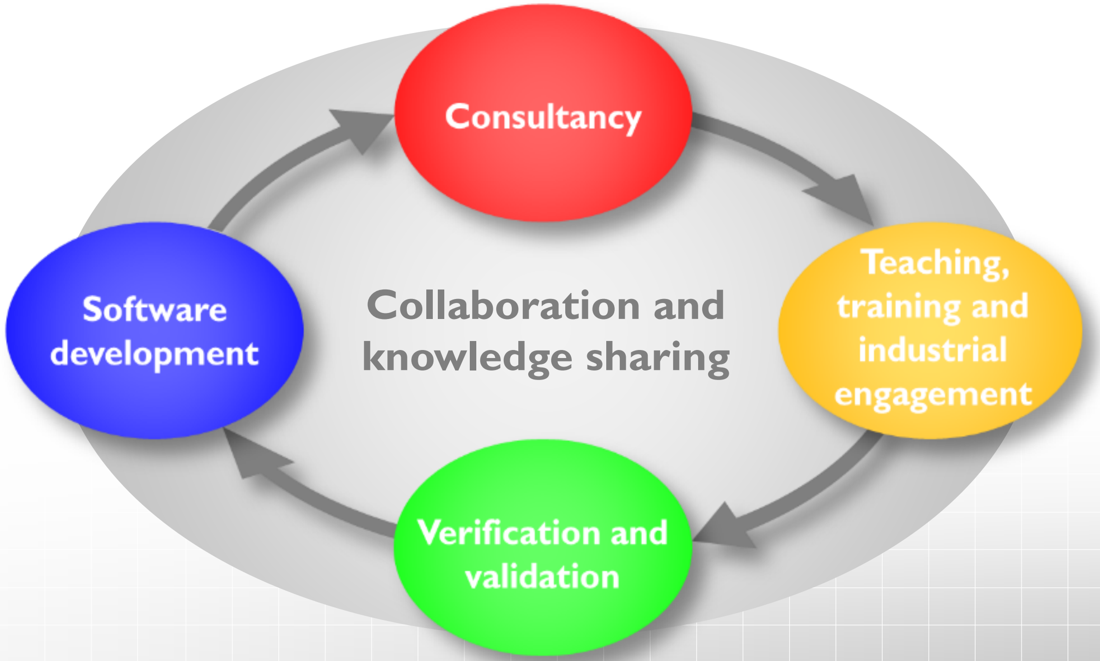
Steve is an active member of the CFD (Chair) and SGM* working groups at NAFEMS, the international organisation for engineering simulation.

NAFEMS

* Simulation governance and management

Abercus

Abercus is an **independent**, privately-owned consultancy specialising in **advanced engineering simulation** – CFD, FEA, bespoke software tools and teaching/training.



Agenda

- Introduction.
- CFD for understanding risk in the offshore industry.
- CFD-based probabilistic explosion risk assessment .
- CFD-based fire risk assessment .
- CFD-based atmospheric dispersion.
- Confidence in simulation for certification.
  - Verification and validation.
  - Understanding the physics – conceptual models, representativeness of the referent.
  - For widespread adoption in industry – develop mature processes, blind benchmarking.
- Summary.

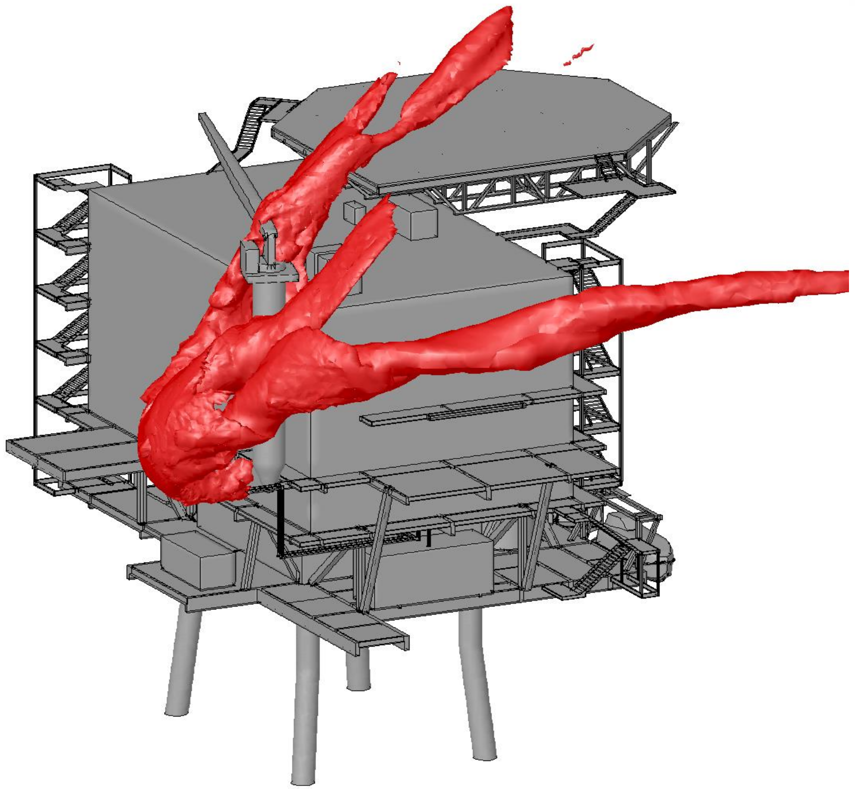
This page is hyperlinked. Click on the title bar to return to this page from anywhere in the presentation, and then navigate from here using the hyperlinks.

Introduction

- The use of engineering simulation is becoming ever more popular:
  - Digital twins.
  - Machine learning.
  - Simulation for certification.
- We need to remember that a simulation prediction is only as good as the verification and validation activities that underpin it.
- In the offshore industry, CFD has been widely used to support the safety case approach since the 1990s, and there are clear lessons to be learned…

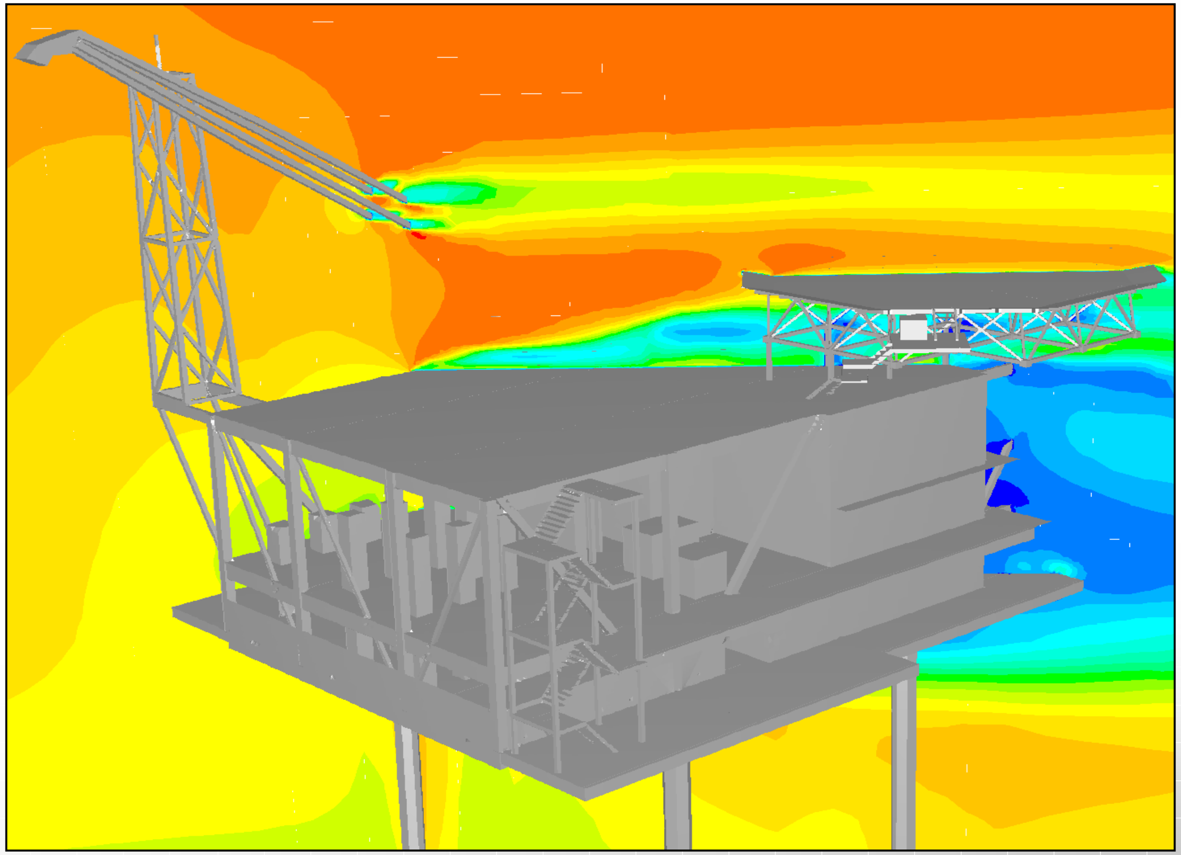
CFD for understanding risk in the offshore industry

Atmospheric dispersion



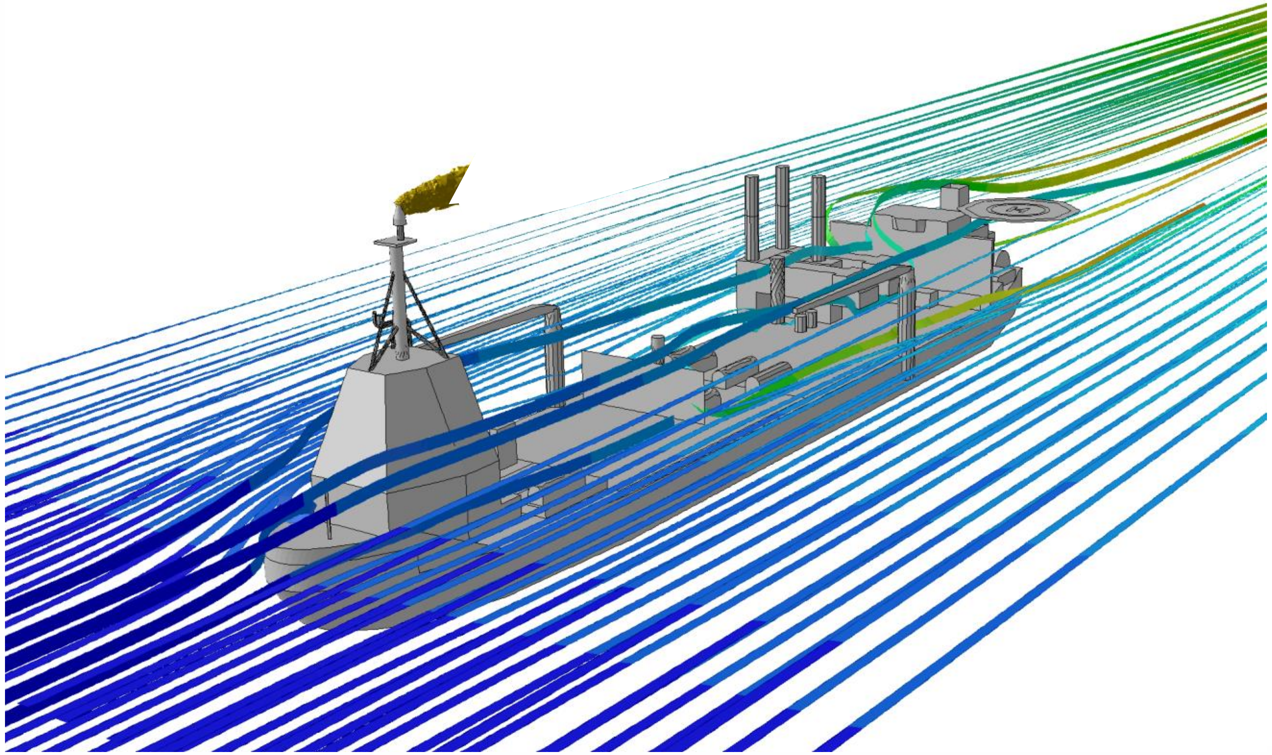
CFD for understanding risk in the offshore industry

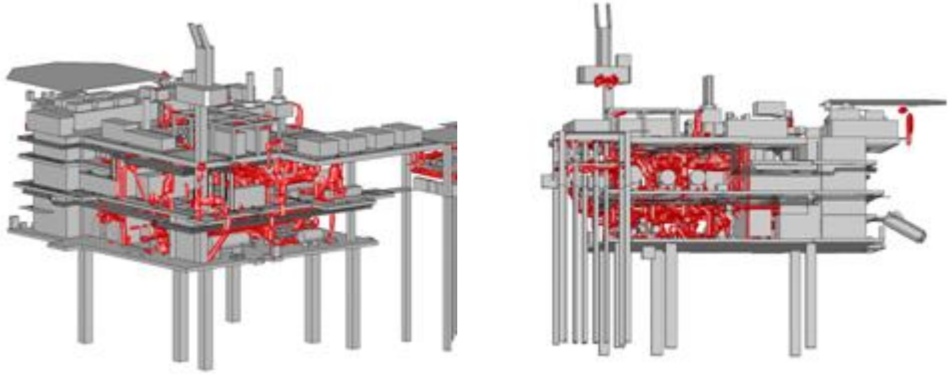
Helideck turbulence



CFD for understanding risk in the offshore industry

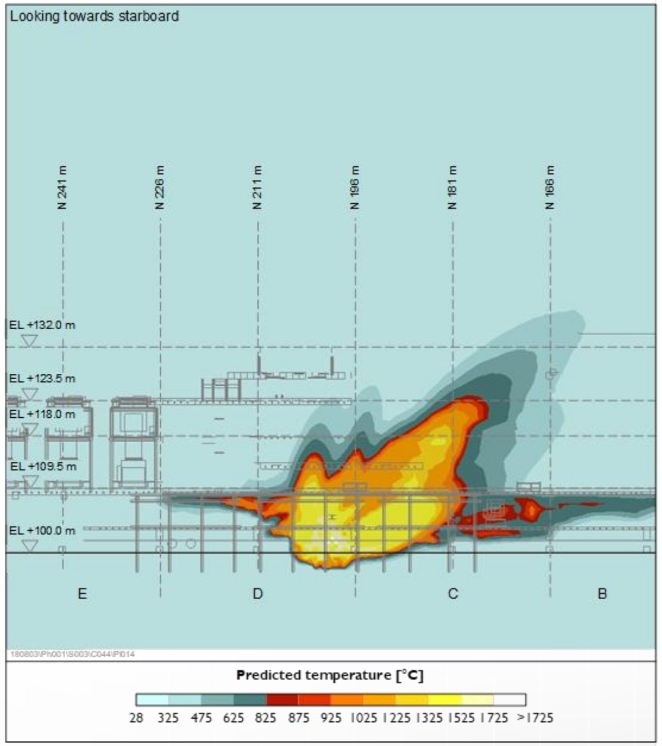
Natural ventilation

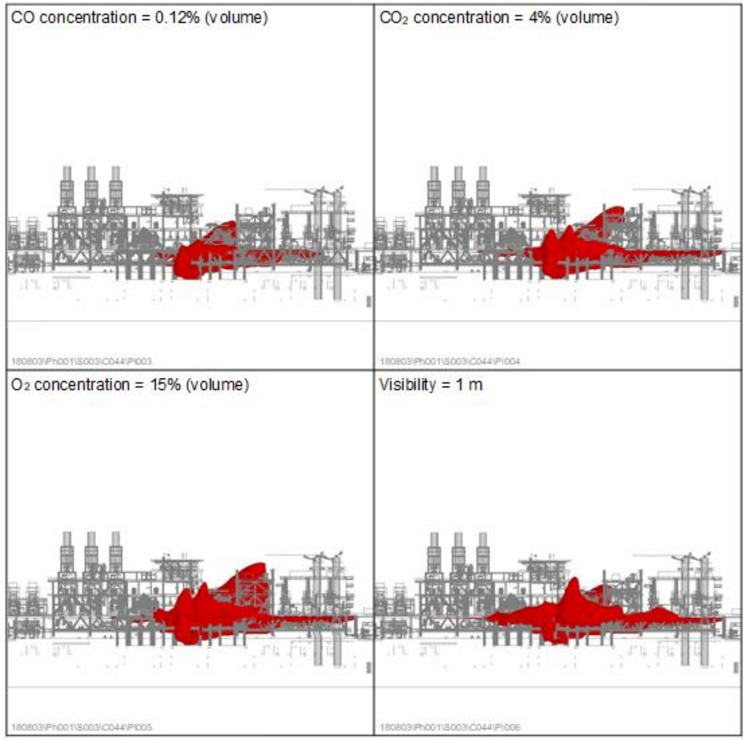




CFD for understanding risk in the offshore industry

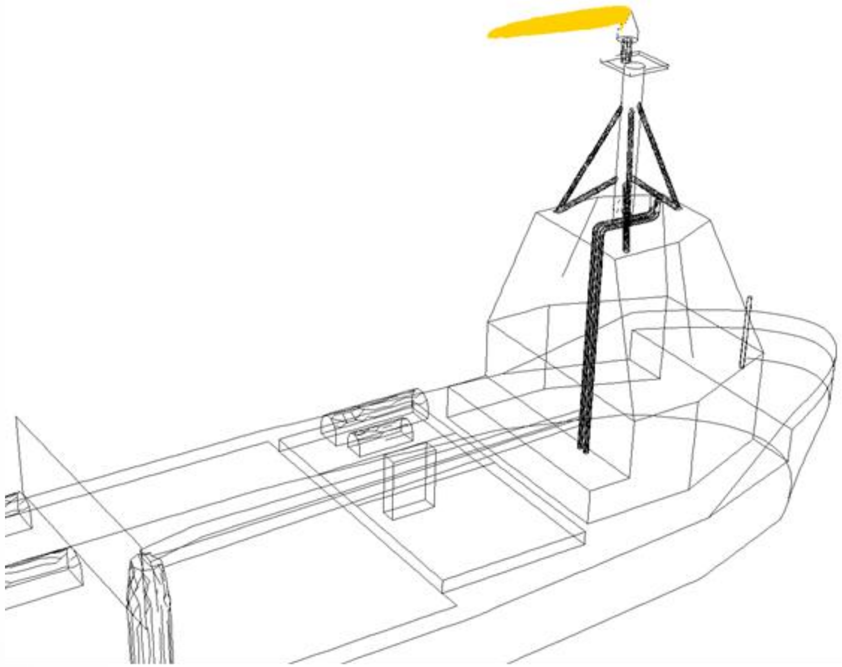
Fire and smoke transport



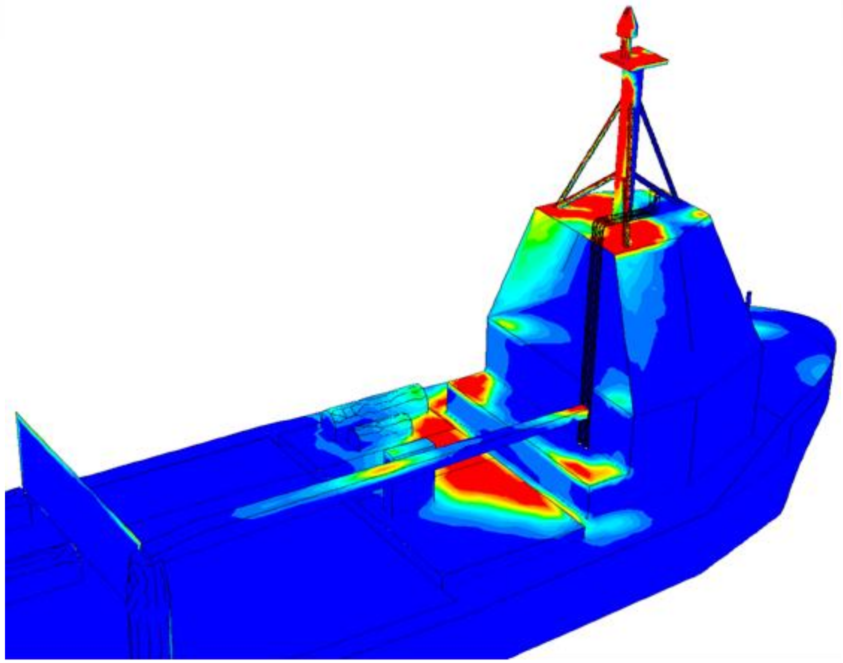


CFD for understanding risk in the offshore industry

Flaring and radiation



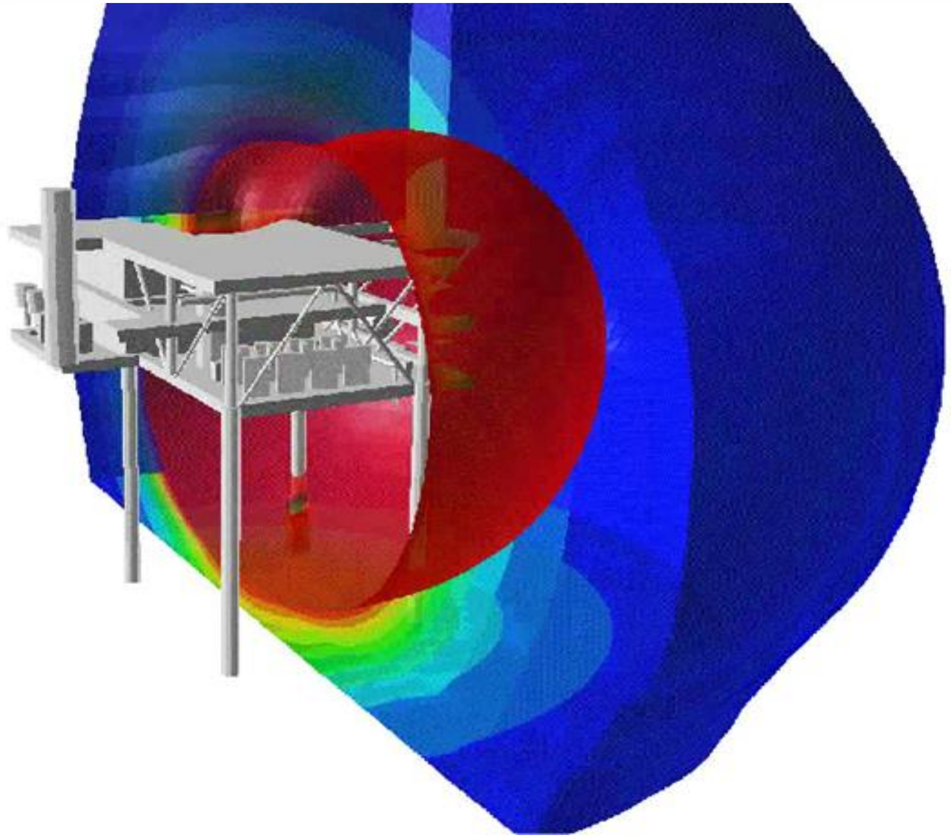
Envelope of combustion zone

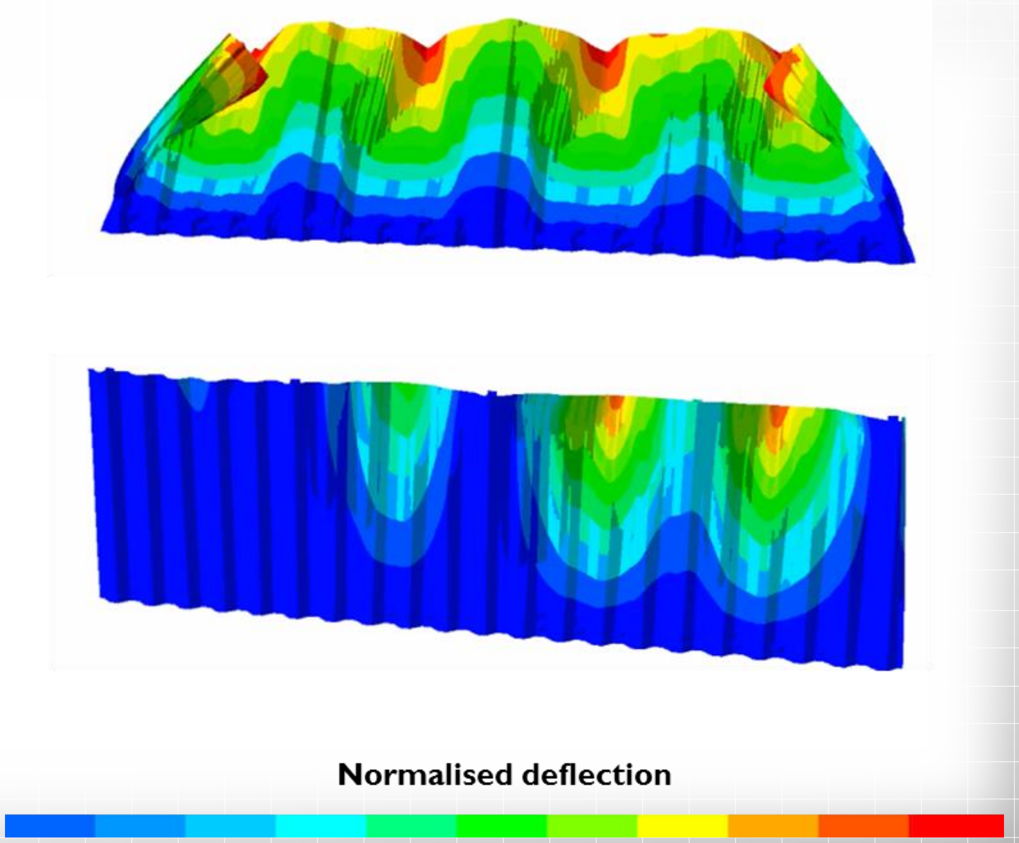


Incident radiation

CFD for understanding risk in the offshore industry

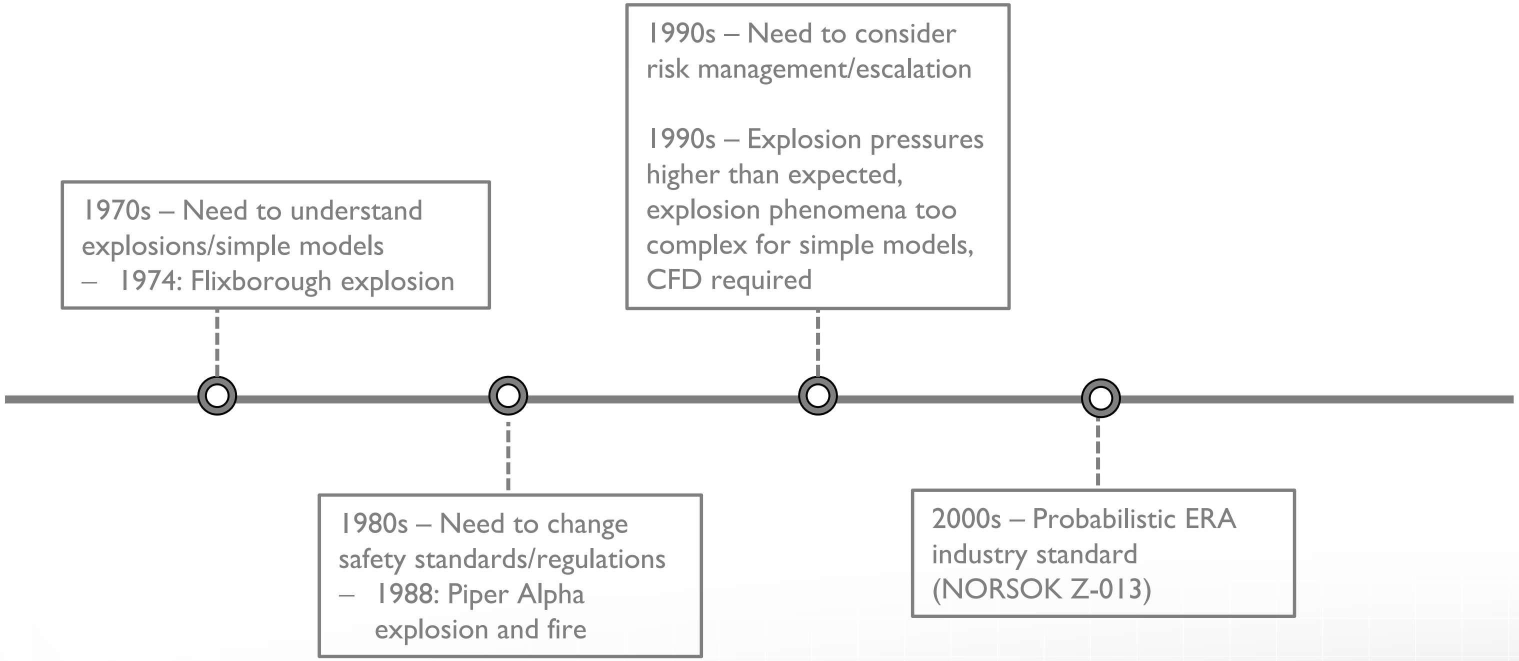
Explosion modelling

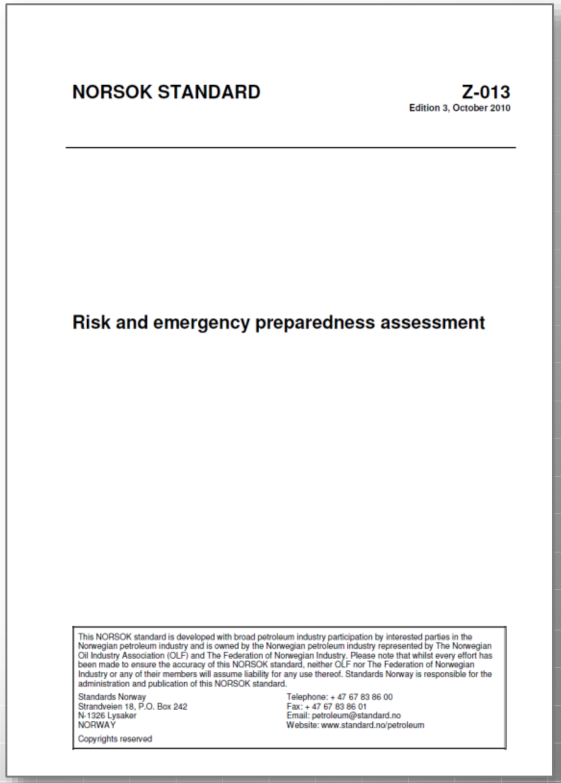




CFD-based probabilistic explosion risk assessment

Explosion safety timeline





NORSOK STANDARD

Z-013
Edition 3, October 2010

Risk and emergency preparedness assessment

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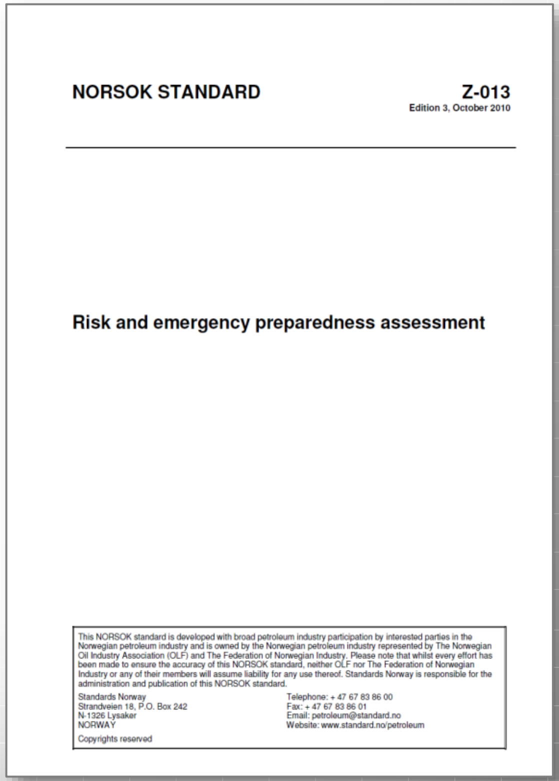
[1] Risk and Emergency Preparedness Analysis, NORSOK standard Z-013 Annex F, Rev 3, 2010.

CFD-based probabilistic explosion risk assessment

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.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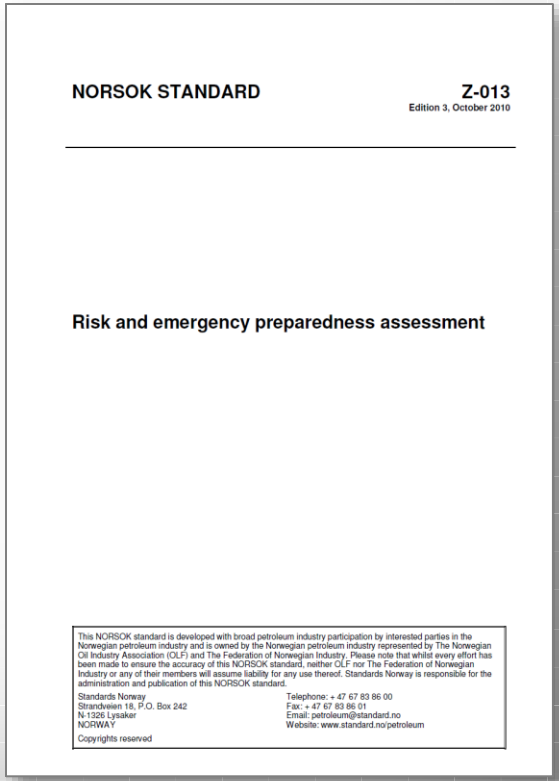
CFD-based probabilistic explosion risk assessment

NORSOK Z-013 – typical methodology

- A probabilistic explosion risk assessment in line with NORSOK Z-013 involves three steps:
  1. CFD simulations – use computational fluid dynamics (CFD) to simulate a large number of deterministic cases (for ventilation, gas dispersion and explosion) to form a database of representative scenarios for pre and post (delayed) ignition behaviour following a loss of containment of flammable material.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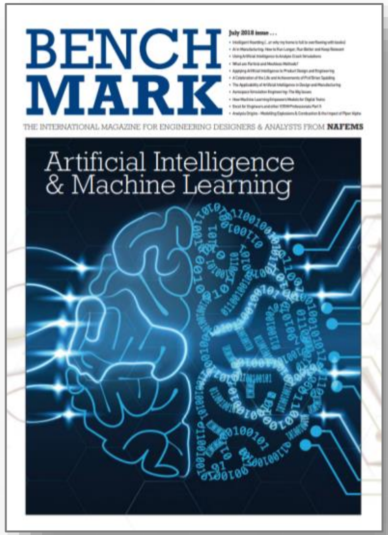
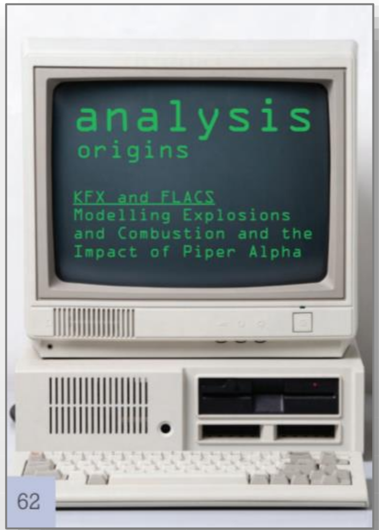
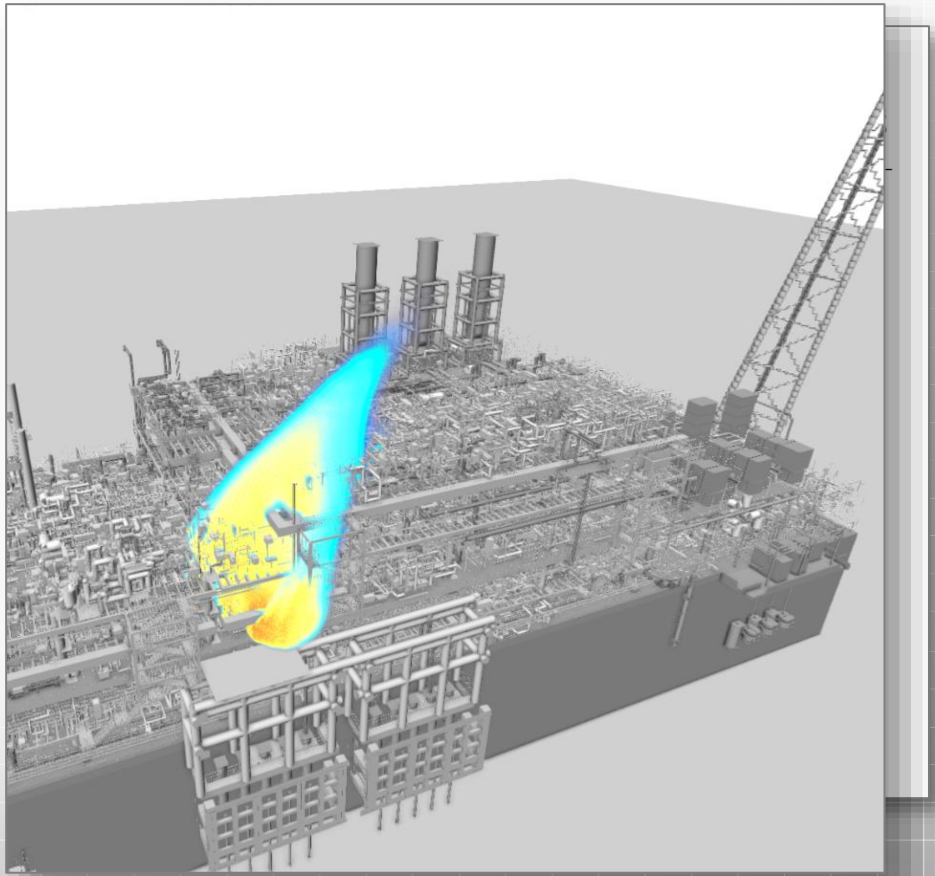
CFD-based probabilistic explosion risk assessment

NORSOK Z-013 – typical methodology

1. CFD simulations
   – Simulate a large number of representative scenarios using an application-specific CFD code (cannot use a general-purpose CFD code).







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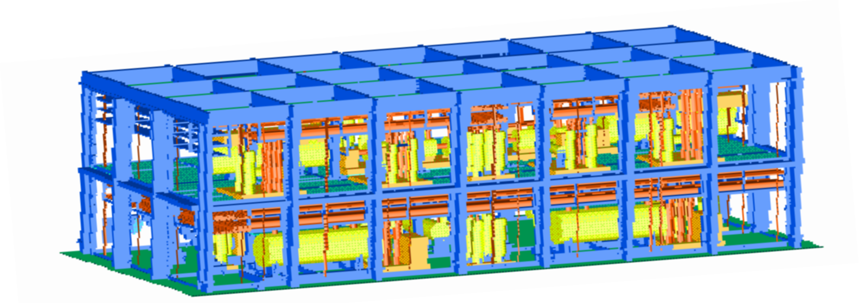
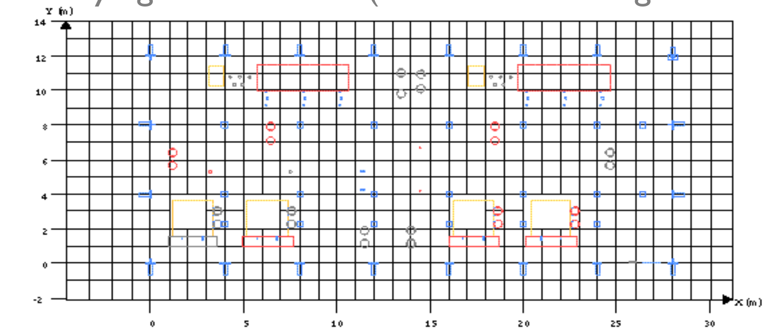
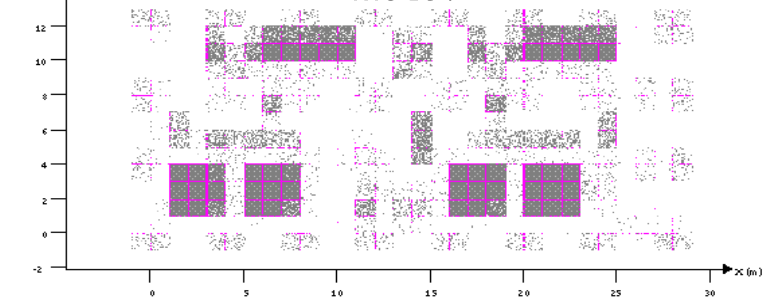


FLACS model for the 2600m^3 full-scale rig at Spadeadam (Courtesy of Gexcon)

Underlying FLACS mesh (structured orthogonal mesh)



Congestion represented by distributed porosity across the model.



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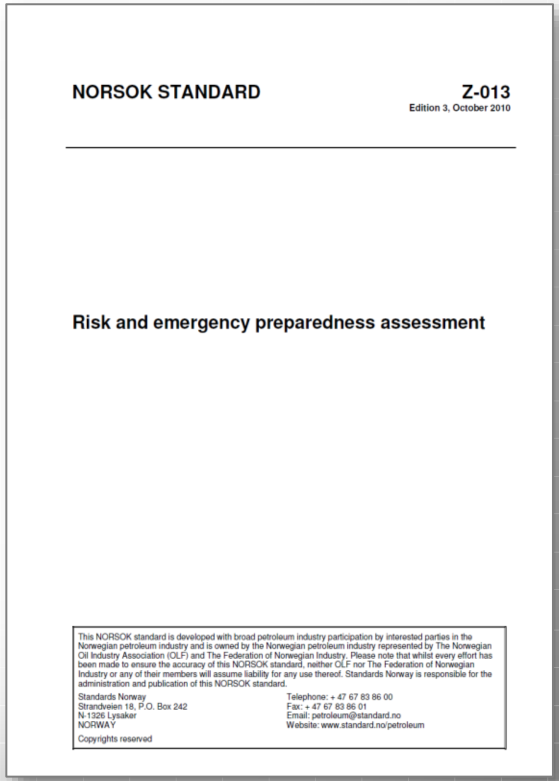
  2. Probabilistic analysis – consider frequencies and probabilities of release and ignition for each simulated scenario to construct exceedance data for blast loads.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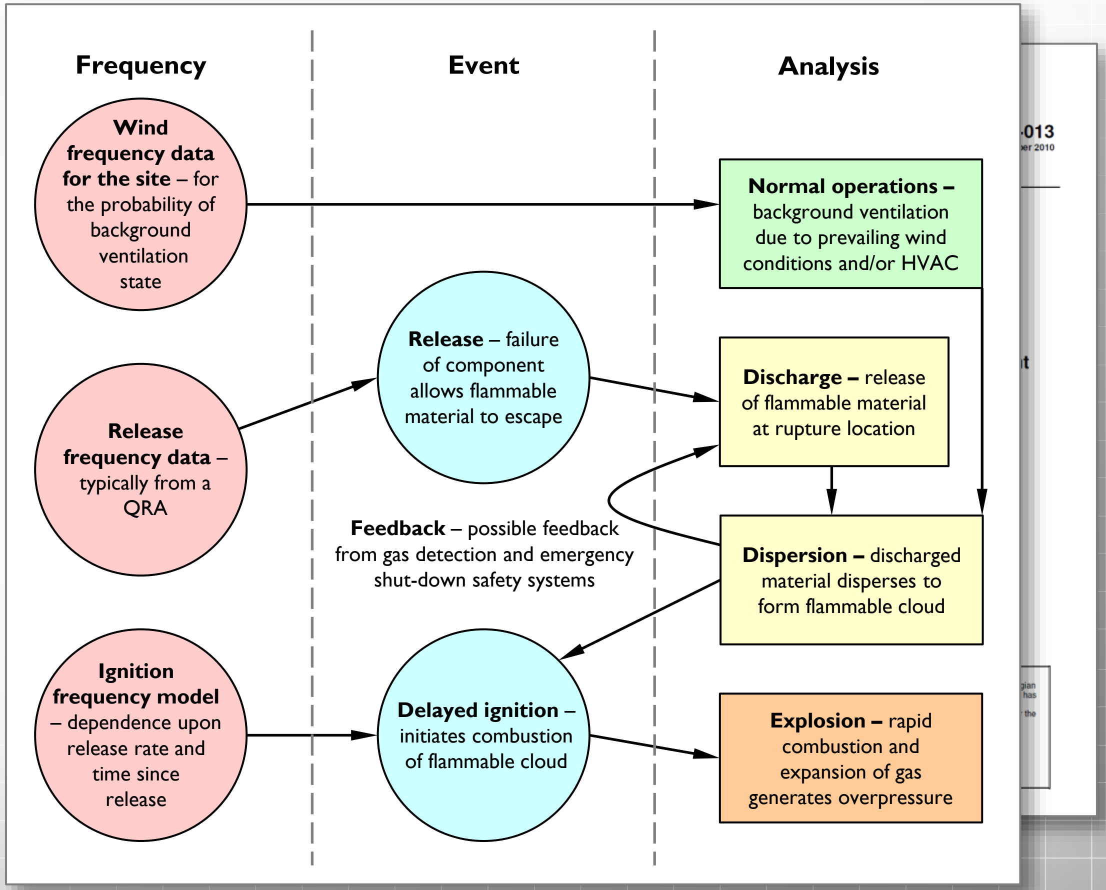
CFD-based probabilistic explosion risk assessment

NORSOK Z-013 – typical methodology

2. Probabilistic analysis
   - Consider frequencies and probabilities of release and ignition for each simulated scenario to construct exceedance data for blast loads.
   - Stages of analysis are 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.



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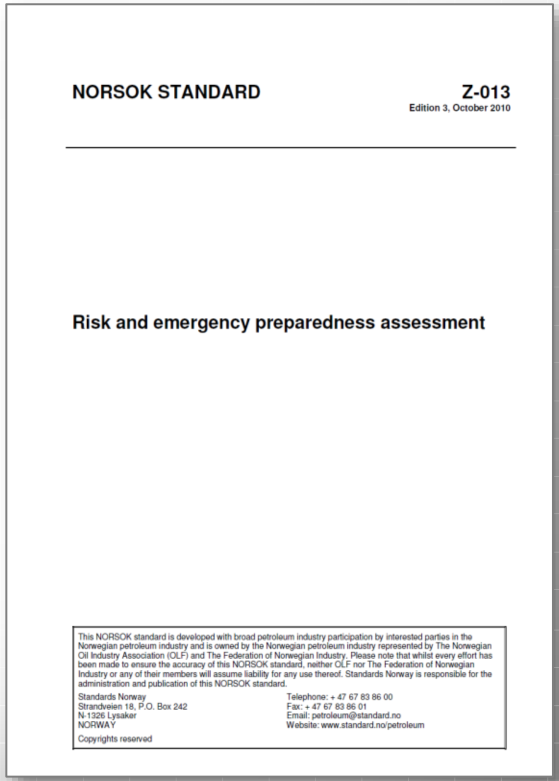
  2. Probabilistic analysis – consider frequencies and probabilities of release and ignition for each simulated scenario to construct exceedance data for blast loads.
  3. Determine the blast loads – from the exceedance data, retrieve the blast load corresponding to the frequency acceptability criterion.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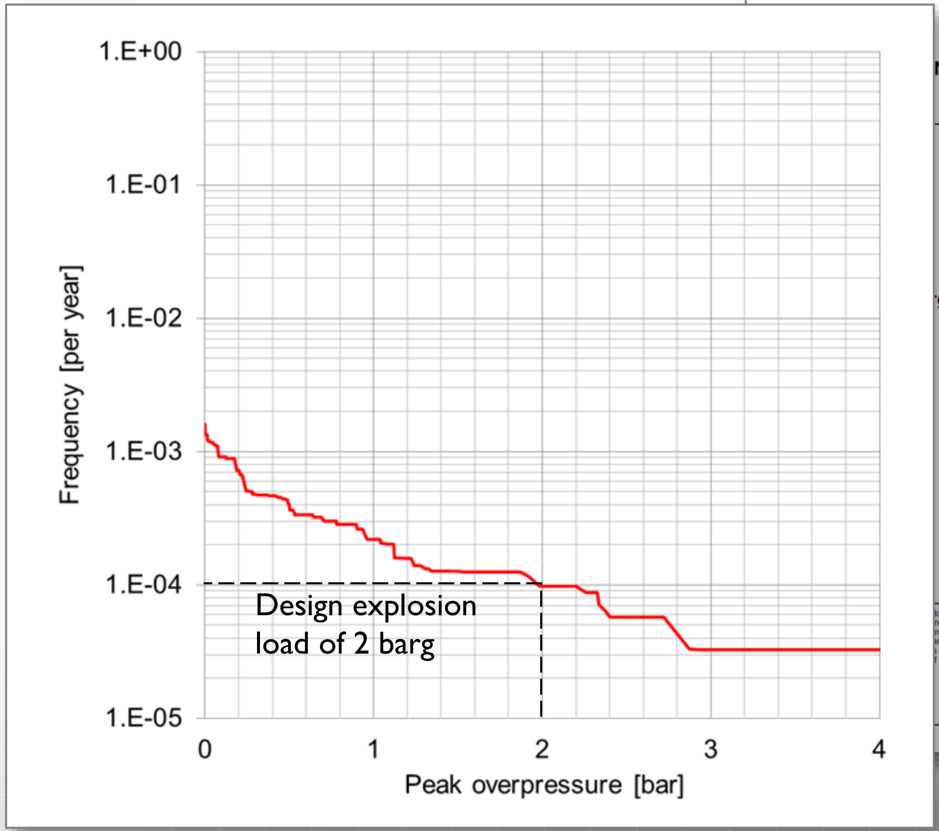
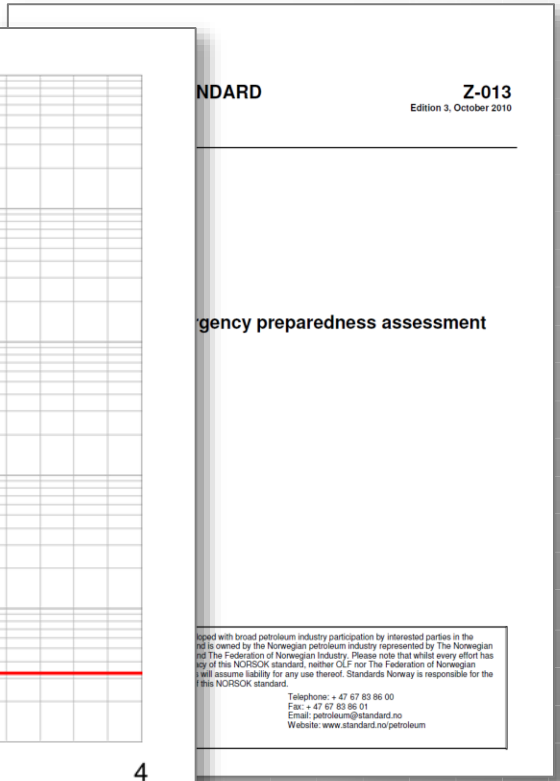
CFD-based probabilistic explosion risk assessment

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

3. Determine the blast loads
   - The exceedance curves show the predicted frequency for explosion loading at a target of interest.
   - For a specified allowable frequency, in this case 10^{-4} /yr, the design load is read from the curve and can be used for structural design.

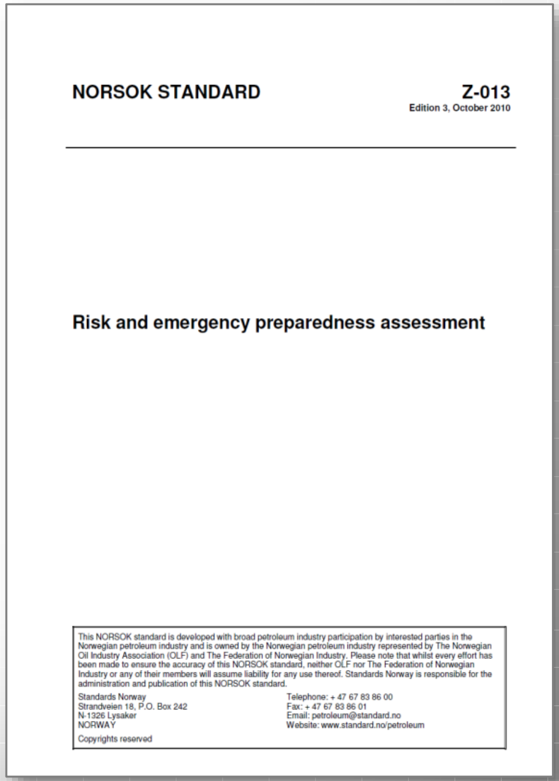




CFD-based probabilistic explosion risk assessment

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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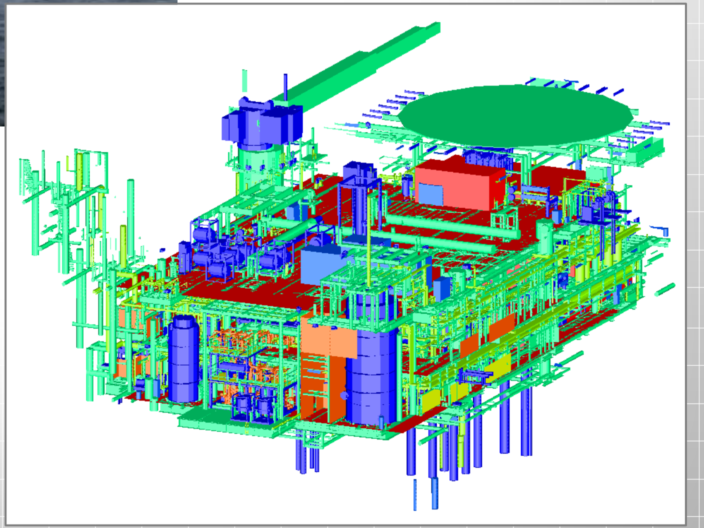
[2] *A review of the Q9 equivalent cloud method for explosion modelling*, Stewart J and Gant S (UK HSE), FABIG newsletter 75, 2019.
[3] *Quantifying risk and how it all goes wrong*, Miller K, Hazards 28, 2018.

CFD-based probabilistic explosion risk assessment

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 (identified only as A to E).



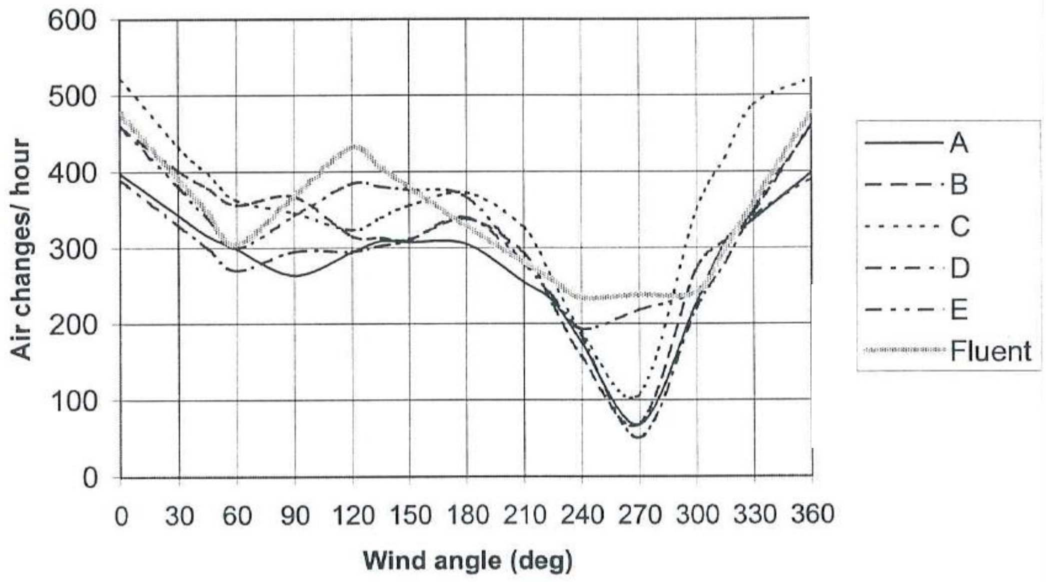
[4] *Comparison of Five Corresponding Explosion Risk Studies Performed by Five Different Consultants*, Holen J, ERA Conference, London, 2001.

CFD-based probabilistic explosion risk assessment

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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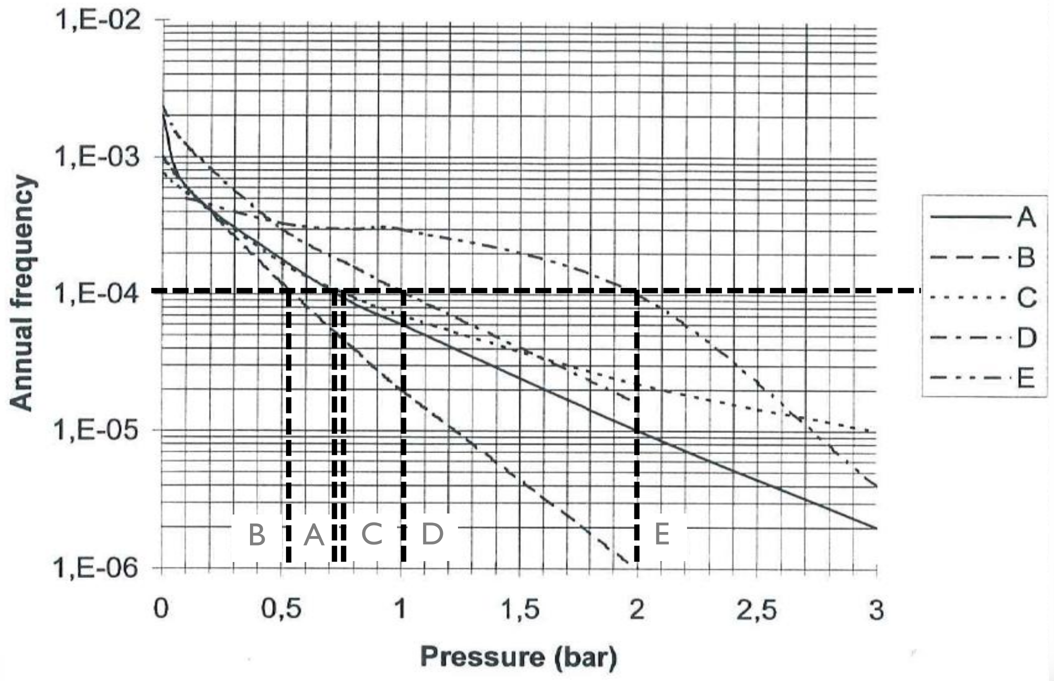
CFD-based probabilistic explosion risk assessment

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 in Norway.
- However, it seems that unfortunately they have diverged again in recent years.

Exceedance curves for overpressure at the firewall



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CFD-based probabilistic explosion risk assessment

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 has reviewed several probabilistic studies and, depending upon the input assumptions, the design blast loads may vary significantly.

CFD-based probabilistic explosion risk assessment

NORSOK Z-013 – concerns with current methodology

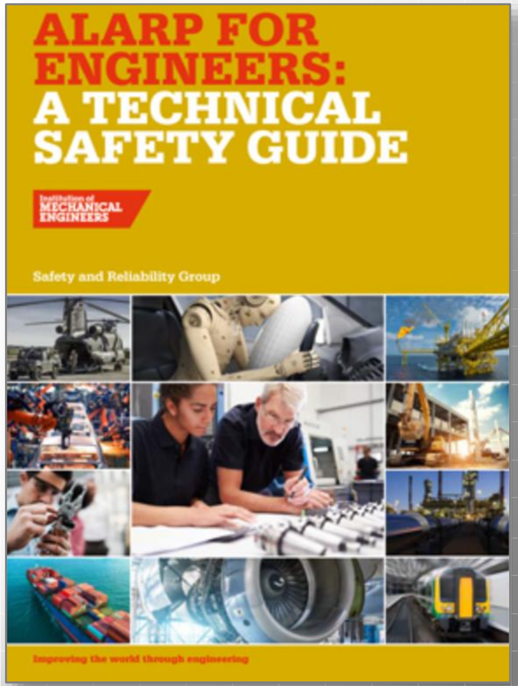
- In recent years, several parties have expressed concerns relating to the consistency of the probabilistic approach.
- Recent work from the UK HSE stated [2]:
  - *Clearer guidance on how probabilistic ERA should be undertaken is needed, along with more rigorous documentation of the assumptions, and 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****.*

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

CFD-based probabilistic explosion risk assessment

NORSOK Z-013 – concerns with current methodology

- In recent years, several parties have expressed concerns relating to the consistency of the probabilistic approach.
- In 2021, the UK Institution of Mechanical Engineers (IMechE) released a technical safety guide – ALARP for engineers [5]:
  - *Page 10 – UK legislation does not require the quantification of risks, and the methods of estimating or calculating them are prone to unacceptable errors and uncertainties.*
  - *Page 60 – **The use of probabilistic prediction methods** such as risk matrices and QRA **are not recommended.***
  - *Page 60 – **Probabilistic mis-judgements may have been a cause in most major accidents**.*
  - *Page 95 – **Probabilistic errors can be notoriously difficult to find**, even by experts, so a sufficiently rigorous quality assurance process, (which interrogates the data collection, its interpretation, the algorithms, and the model's architecture), may not be a realistic proposition.*



[5] *ALARP for engineers: a technical safety guide, IMechE, 2021.*
https://www.imeche.org/page-not-found?aspxerrorpath=/docs/default-source/1-oscar/reports-policy-statements-and-documents/alarp-technical-safety-guide_2021.pdf

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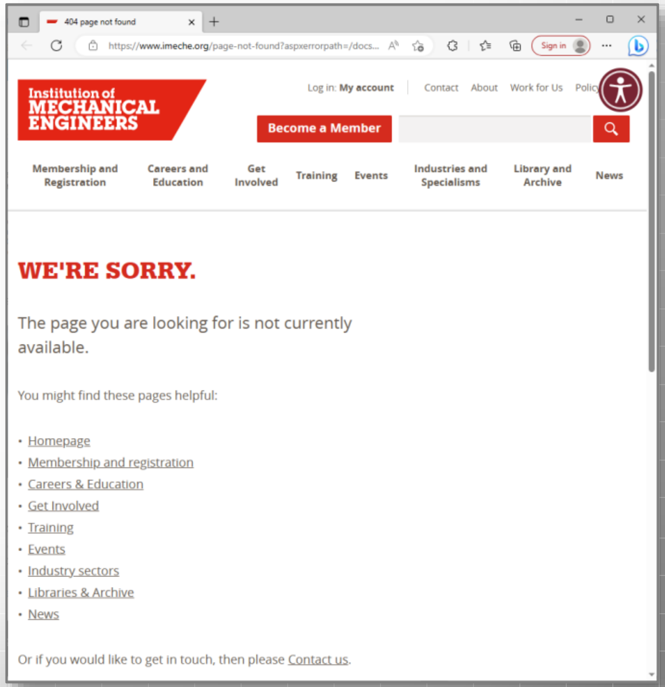

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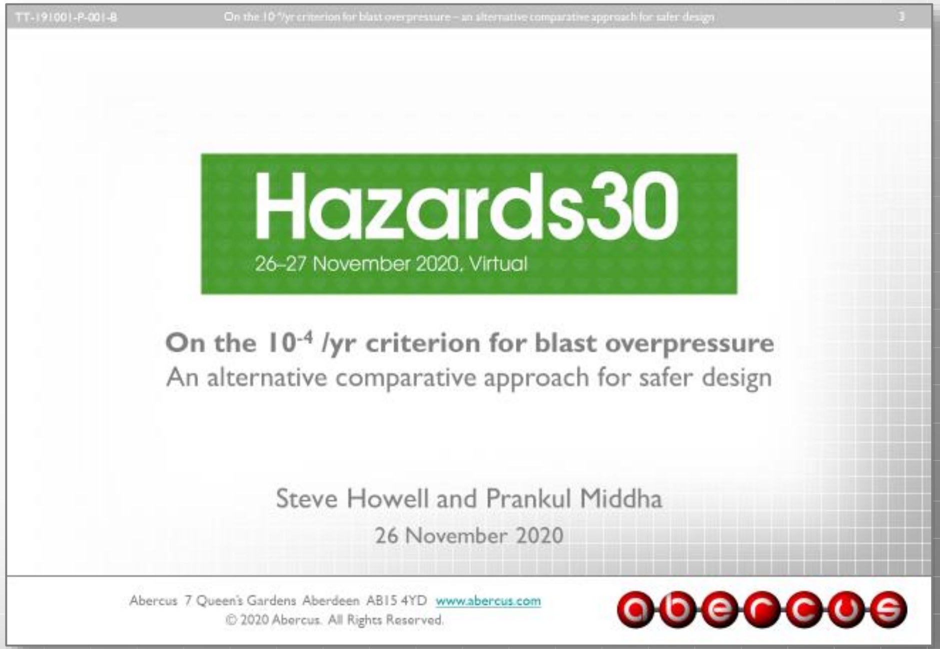
CFD-based probabilistic explosion risk assessment

NORSOK Z-013 – concerns with current methodology

- In recent years, several parties have expressed concerns relating to the consistency of the probabilistic approach.
- Abercus has two recommendations to improve consistency:
  1. Use relative acceptance criteria rather than absolute acceptance criteria [6].
     This approach has the significant benefit that any uncertainties in the input assumptions are inherent in both the acceptance model and the model used to create the relative criterion, so that when they are compared any error will, to a large degree, cancel out.



[6] *On the 10-4 /yr criterion for blast overpressure, An alternative comparative approach for safer design, Hazards 30 conference, 2020.*

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[6] *On the 10-4 /yr criterion for blast overpressure, An alternative comparative approach for safer design, Hazards 30 conference*, 2020.
[7] *The benefits of blind benchmarking of Probabilistic Explosion Risk Analysis (ERA) studies, FABIG Webinar*, 13 January 2021.

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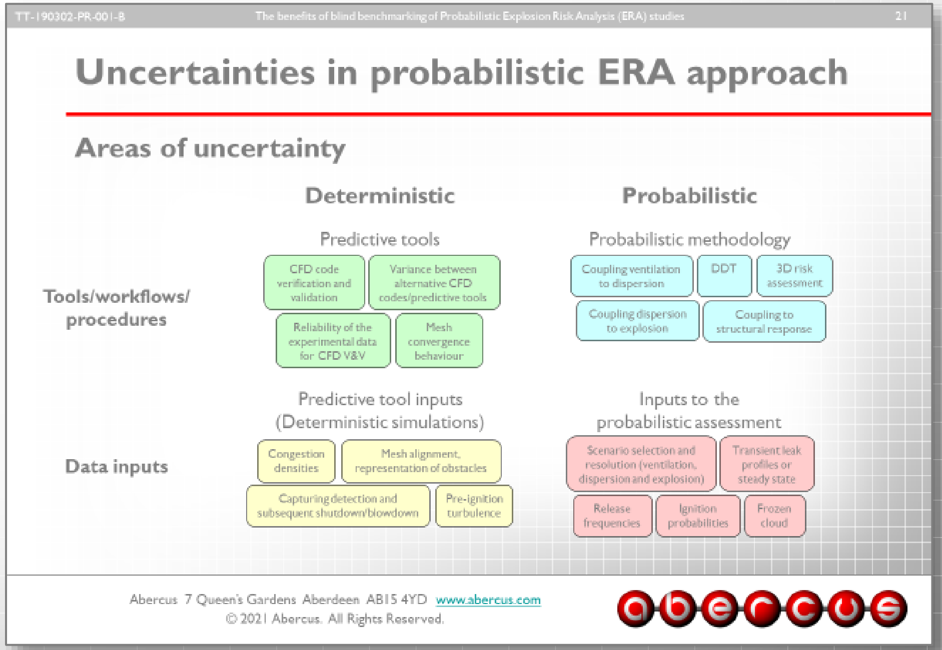


[6] *On the 10-4 /yr criterion for blast overpressure, An alternative comparative approach for safer design, Hazards 30 conference,* 2020.
[7] *The benefits of blind benchmarking of Probabilistic Explosion Risk Analysis (ERA) studies, FABIG Webinar,* 13 January 2021.

CFD-based probabilistic explosion risk assessment

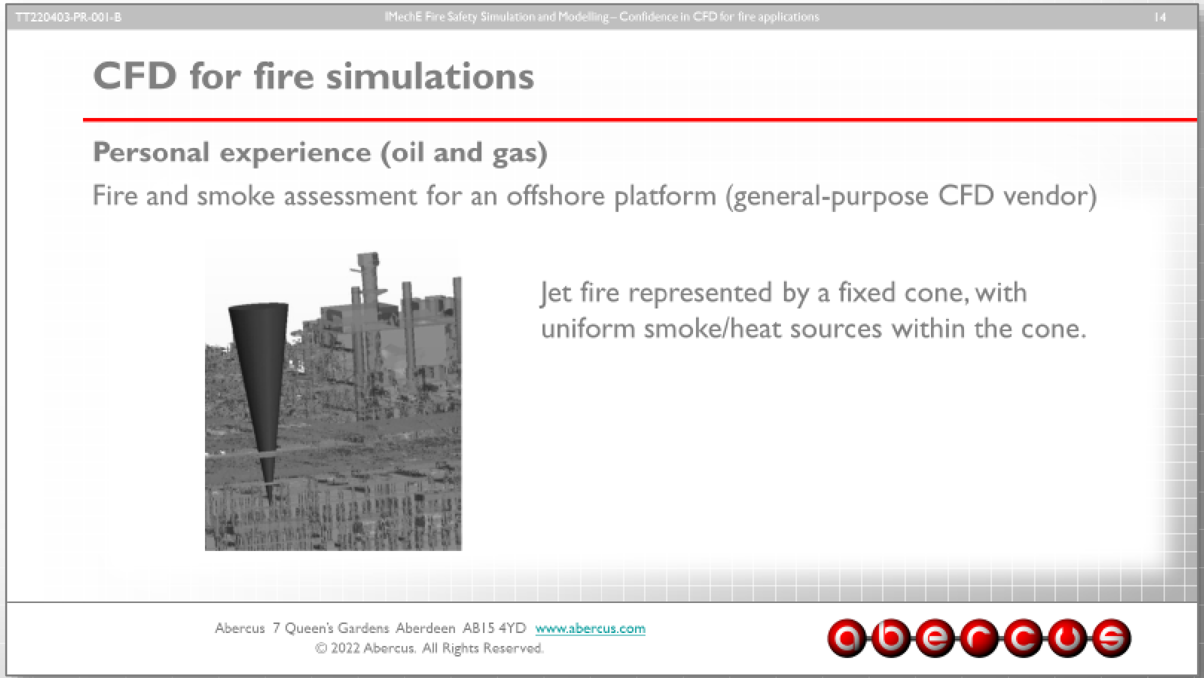
NORSOK Z-013 – concerns with current methodology

- In recent years, several parties have expressed concerns relating to the consistency of the probabilistic approach.
- In the Norwegian sector, it may already be too late for CFD-based methods [8]:
  - Studies have indicated significant uncertainty in the explosion analysis late in detail engineering phase, relating to both the inputs to the analysis the CFD analysis and the probabilistic methodologies used.
  - To address this, *RispEx* has been developed to replace the use of CFD-based methods. It is a simplified tool based on learning (look-up) from previous CFD studies.

[8] *RispEx - Simplified tool for explosion load decision support, FABIG Webinar*, 9 December 2020.

CFD-based fire risk assessment

- Another common CFD application for offshore safety is modelling fire risk.
- Again, the approach is not prescriptive, and there is plenty of scope for inconsistency.



[9] *Confidence in CFD for fire applications, IMechE Seminar,* 27 September 2022.

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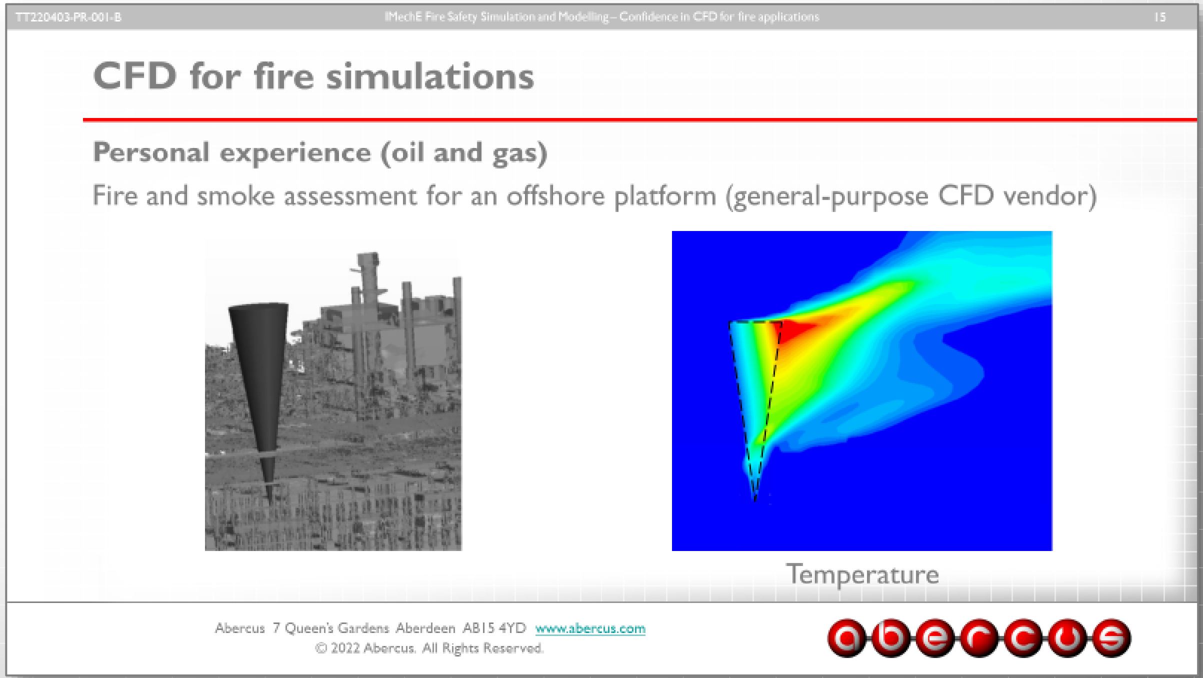

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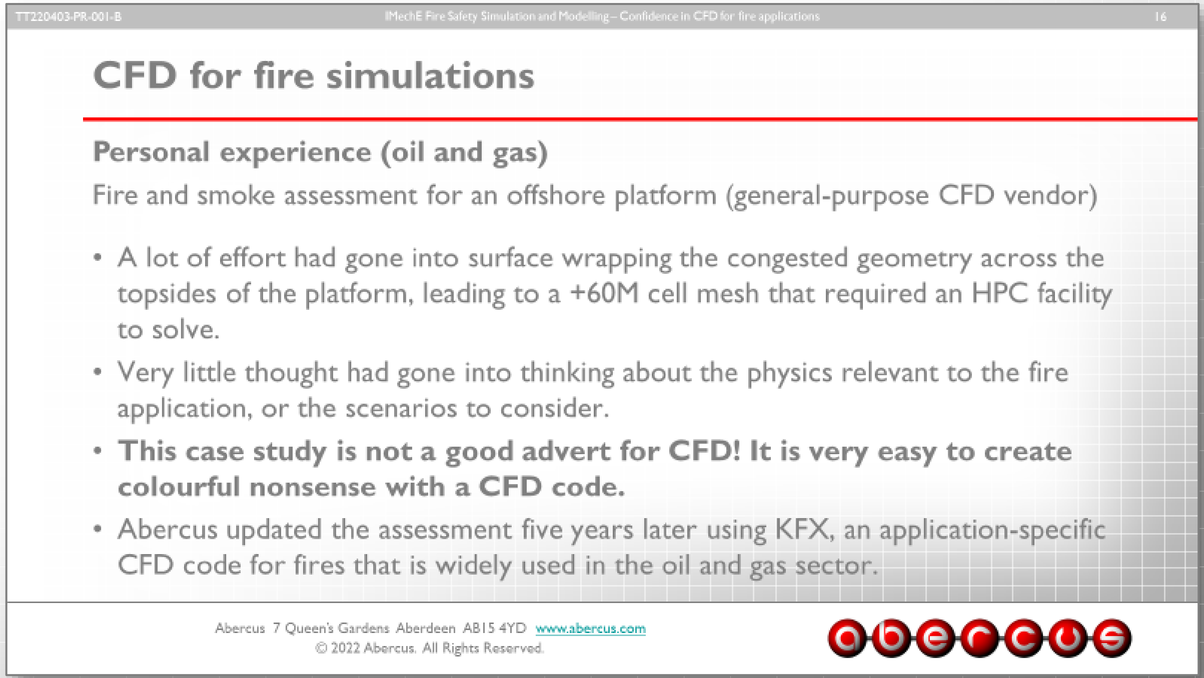

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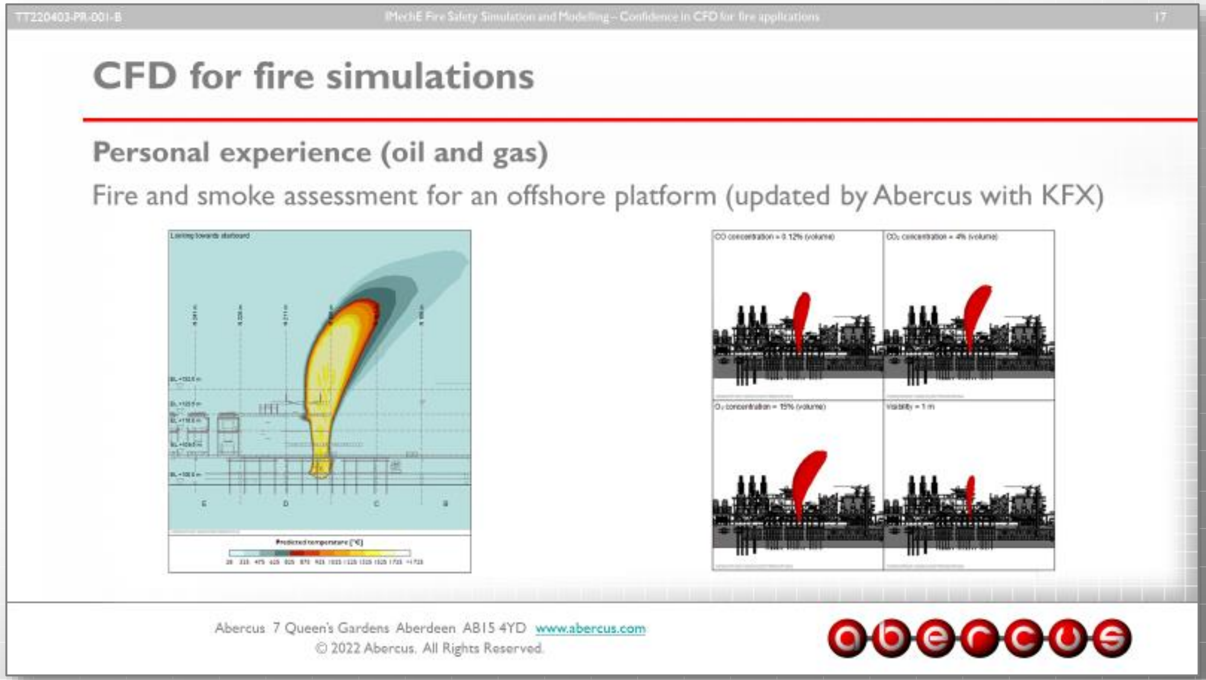

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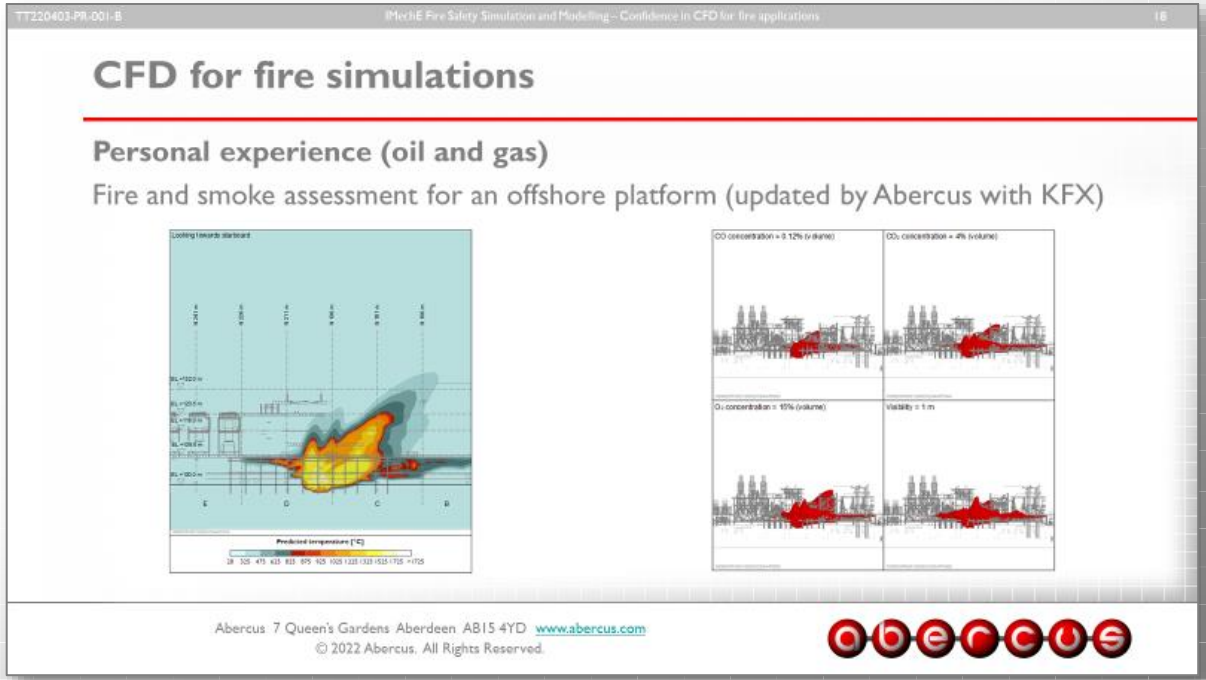

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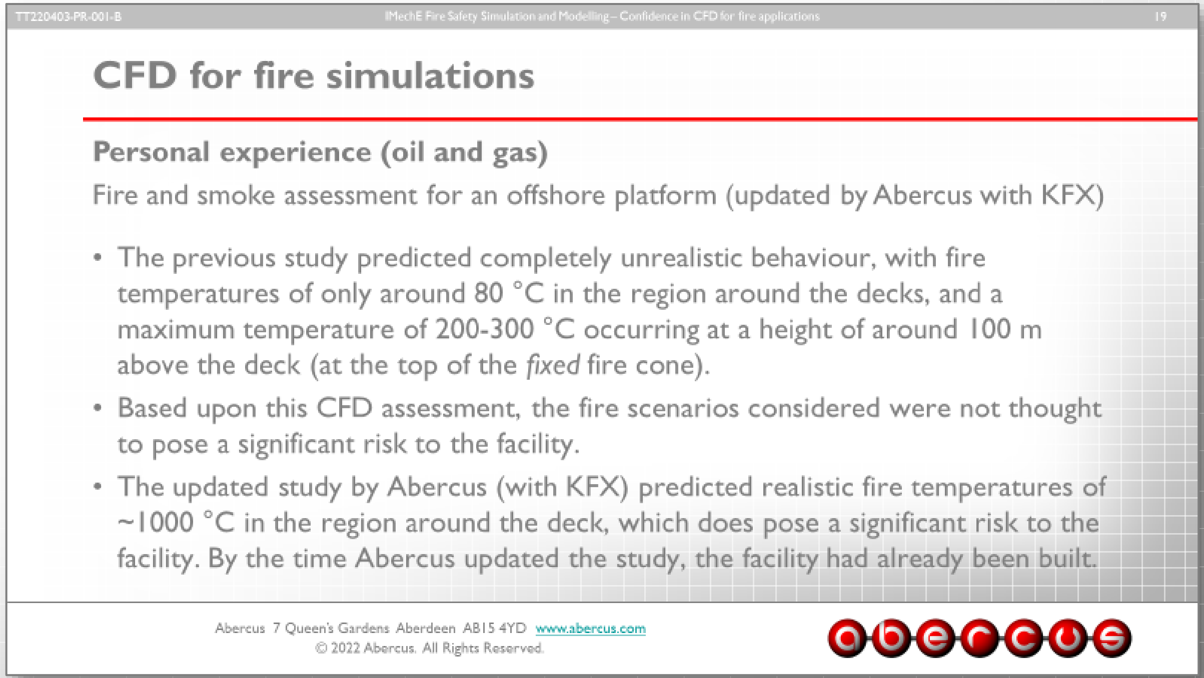

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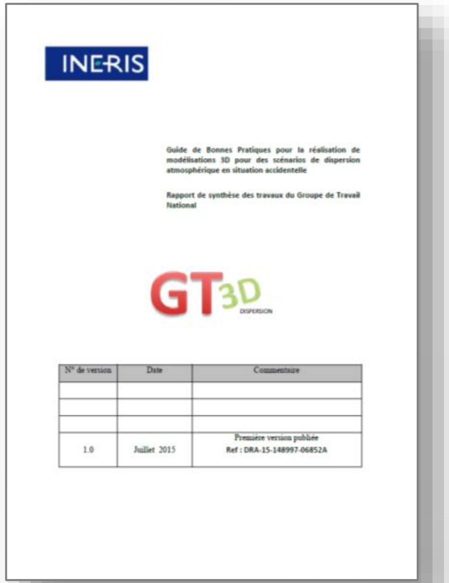
CFD-based atmospheric dispersion

- In ~2010, CFD was withdrawn as an option for simulating atmospheric dispersion for onshore regulatory compliance in France – this was because there had been too much inconsistency between practitioners with the CFD-based approach.


INERIS

Guide de Bonnes Pratiques pour la réalisation de modélisations 3D pour des scénarios de dispersion atmosphérique en situation accidentelle

Rapport de synthèse des travaux du Groupe de Travail National

GT3D DISPERSION

N° de version	Date	Commentaire
1.0	Juillet 2015	Première version publiée Ref : DRA-15-148997-06852A

- A blind benchmarking exercise was subsequently established to explore inconsistency between practitioners, in order to re-establish confidence in the CFD approach [10].

[10] *Guide de bonnes pratiques pour la realisation de modelisations 3D pour des scenarios de dispersion atmospherique en situation accidentelle*, Ineris report DRA-15-148997-06852A, July 2015.

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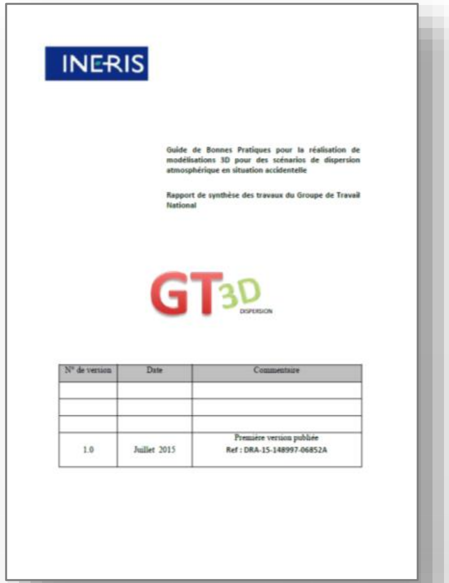

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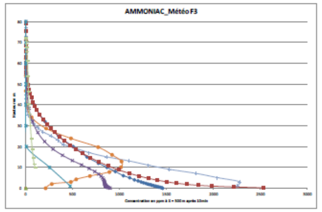
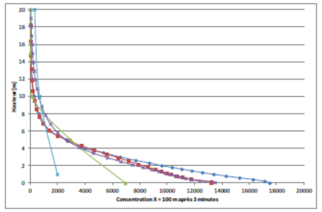
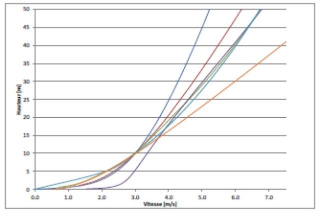


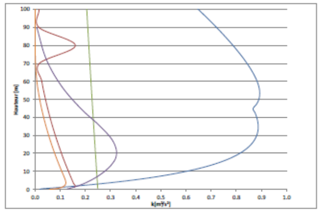
Rejet d'ammoniac en condition F3, concentration 500 m en aval du point de rejet après 10 minutes.



Rejet de propane en condition D5, concentration 100 m en aval du point de rejet après 3 minutes.



Profils de vitesse utilisés en entrée de domaine de calcul pour une classe de vent F3



Profils de turbulence (k) utilisés en entrée de domaine de calcul pour une classe de vent F3

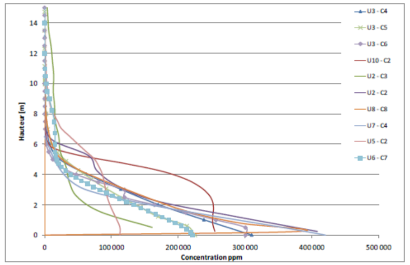


Figure 36 : Profil verticaux de concentration 25 m en aval du point de rejet.

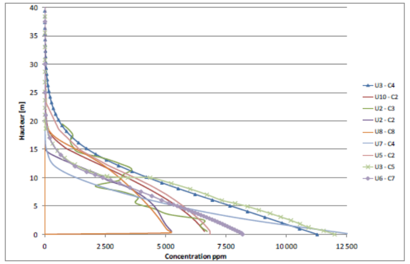


Figure 37 : Profil verticaux de concentration 100 m en aval du point de rejet.

[10] *Guide de bonnes pratiques pour la realisation de modelisations 3D pour des scenarios de dispersion atmospherique en situation accidentelle*, Ineris report DRA-15-148997-06852A, July 2015.

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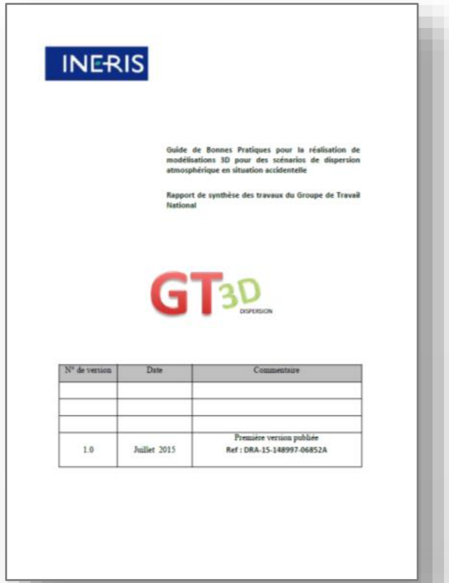

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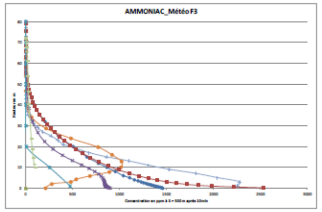

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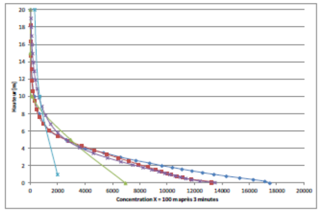
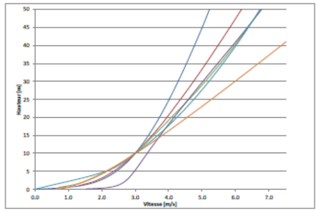
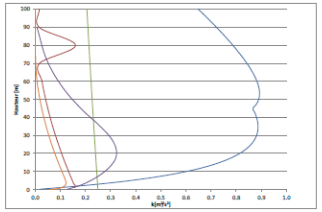


Rejet de propane en condition D5, concentration 100 m en aval du point de rejet après 3 minutes.



Profils de vitesse utilisés en entrée de domaine de calcul pour une classe de vent F3



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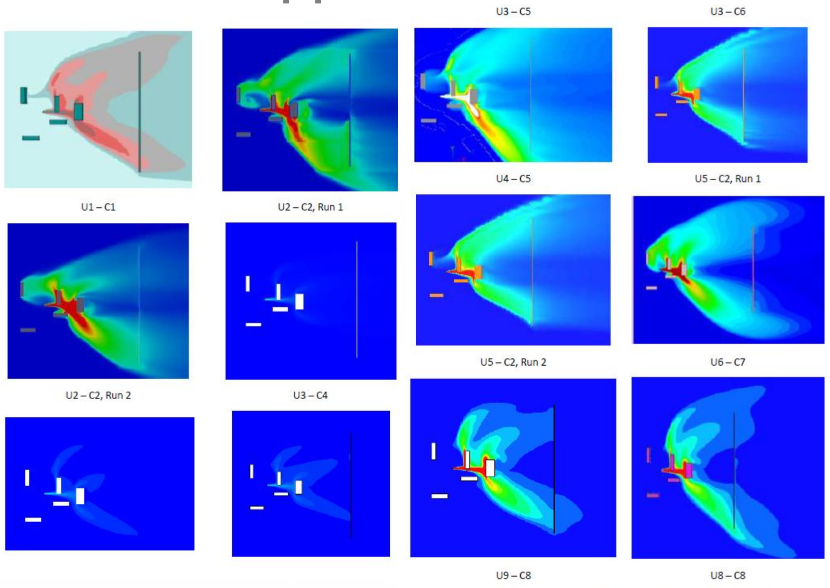


Figure 38 : Champ de concentration dans un plan horizontal à 1,5 m du sol.

[10] *Guide de bonnes pratiques pour la realisation de modelisations 3D pour des scenarios de dispersion atmospherique en situation accidentelle*, Ineris report DRA-15-148997-06852A, July 2015.

Confidence in simulation for certification

How can we achieve confidence in simulation for certification?

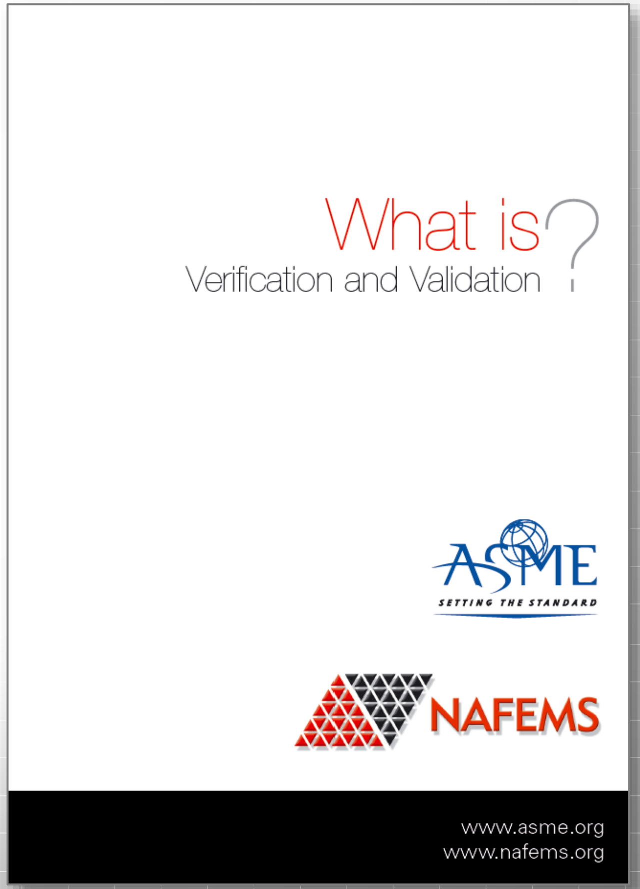
- Through rigorous verification and validation, capturing all relevant physics
  - This requires significant effort that should not be underestimated.

- For widespread adoption in industry:
  - Develop mature processes – embed best practice within a workflow approach.
  - Competence – training and accreditation for both CFD users and CFD codes/workflows.
  - Improve confidence in the CFD process through blind benchmarking.
  - How to interpret the CFD predictions – absolute or relative criteria.
  - Standard templates for certification using CFD.

Confidence in simulation for certification

Verification and validation

- ASME and NAFEMS have published a *What is?* guide that is freely available for download: http://www.nafems.org/publications/browse_buy/browse_by_topic/qa/verification_and_validation/



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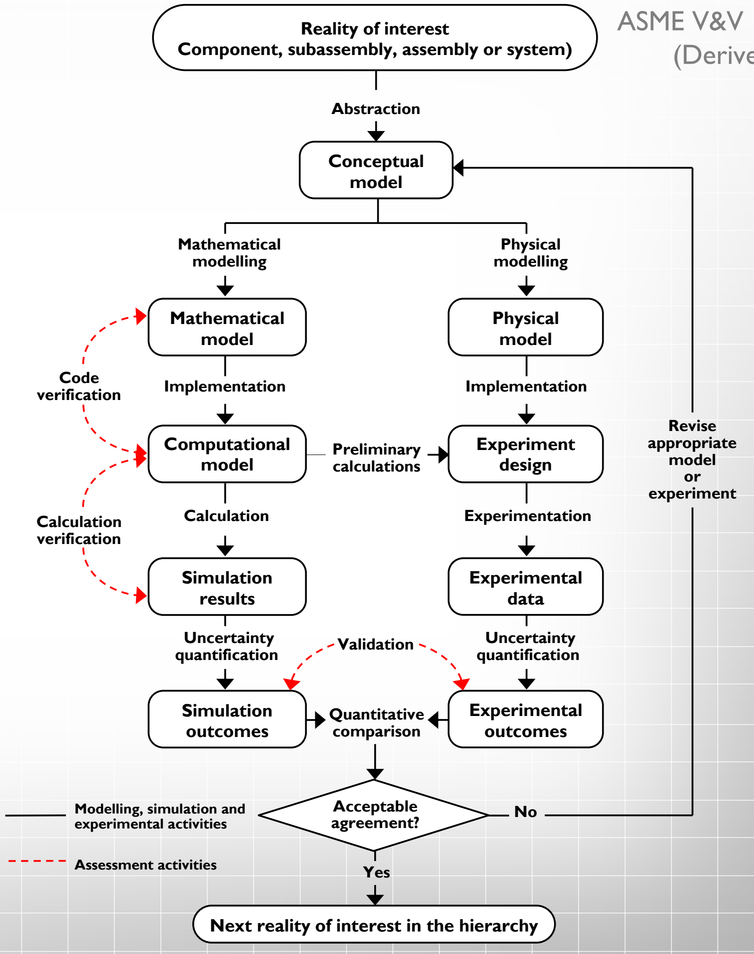
  http://www.nafems.org/publications/browse_buy/browse_by_topic/qa/verification_and_validation/
- Verification is:
  – the process of determining that a computational model accurately represents the underlying mathematical model and its solution.
- Validation is:
  – the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.



ASME V&V 10-2006
(Derived from)

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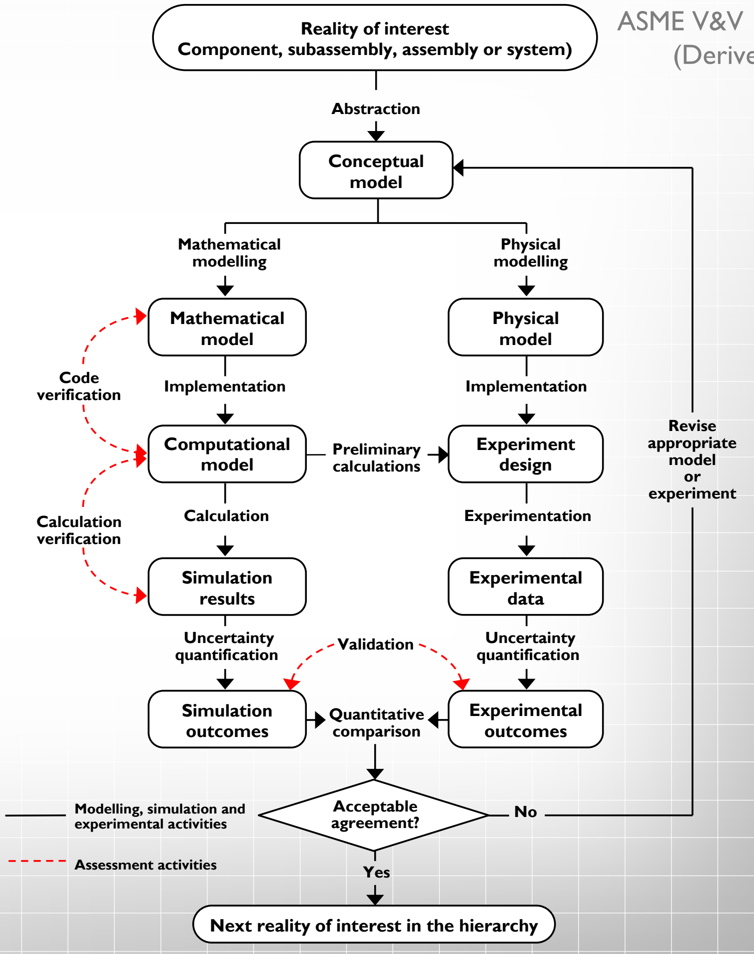
- Verification is:

  Are the underlying equations being solved correctly?

- Validation is:

  Are the underlying equations being solved the correct equations?

ASME V&V 10-2006
(Derived from)



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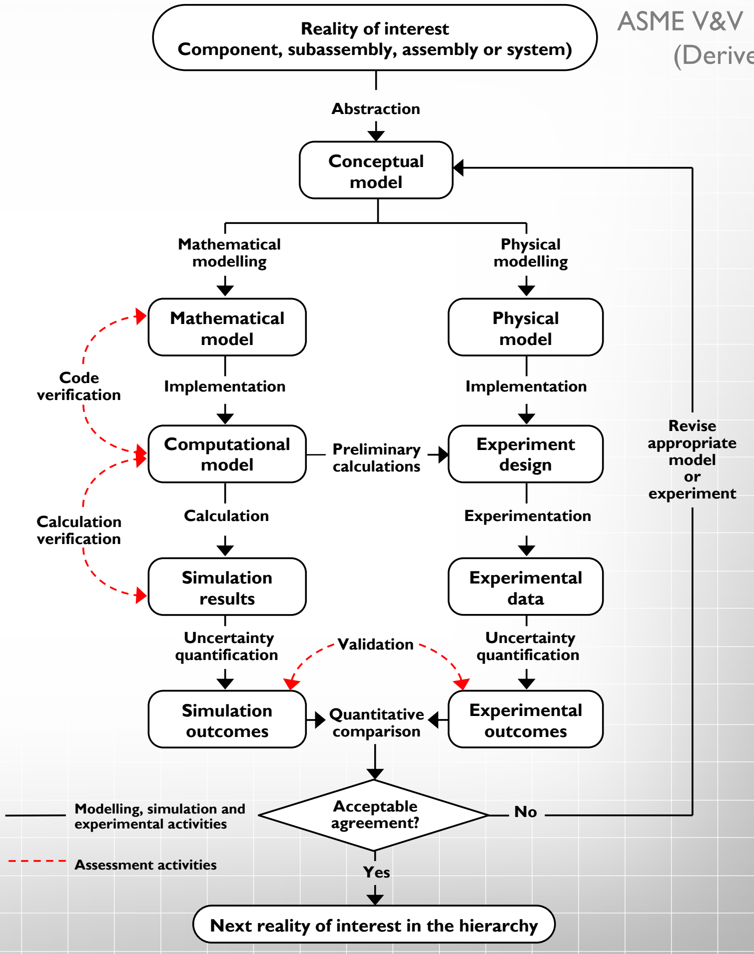
- Verification is:

  Mathematics

- Validation is:

  Physics



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Confidence in simulation for certification

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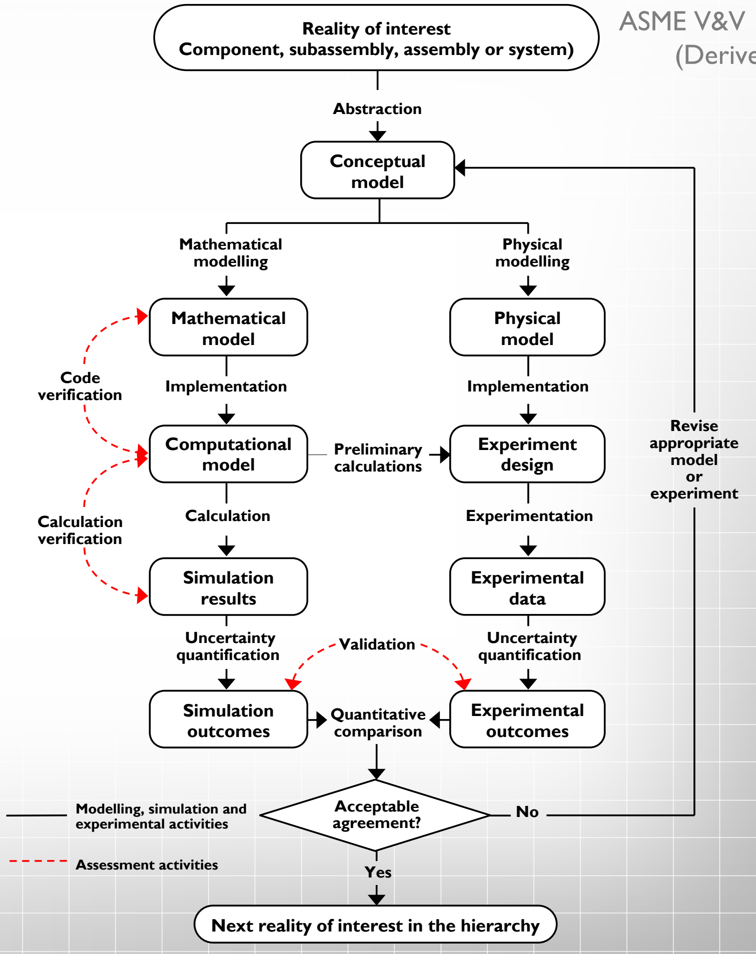

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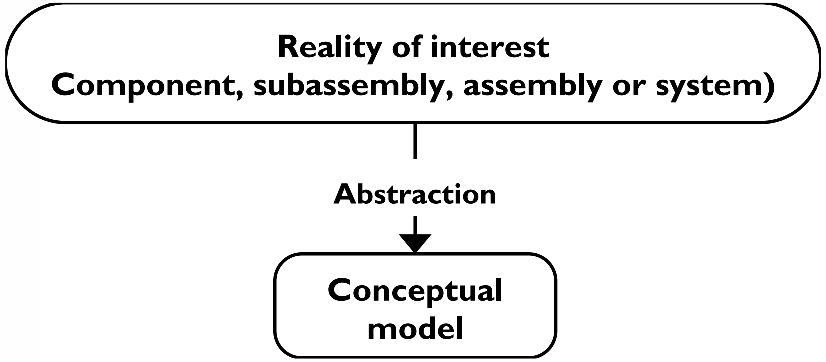

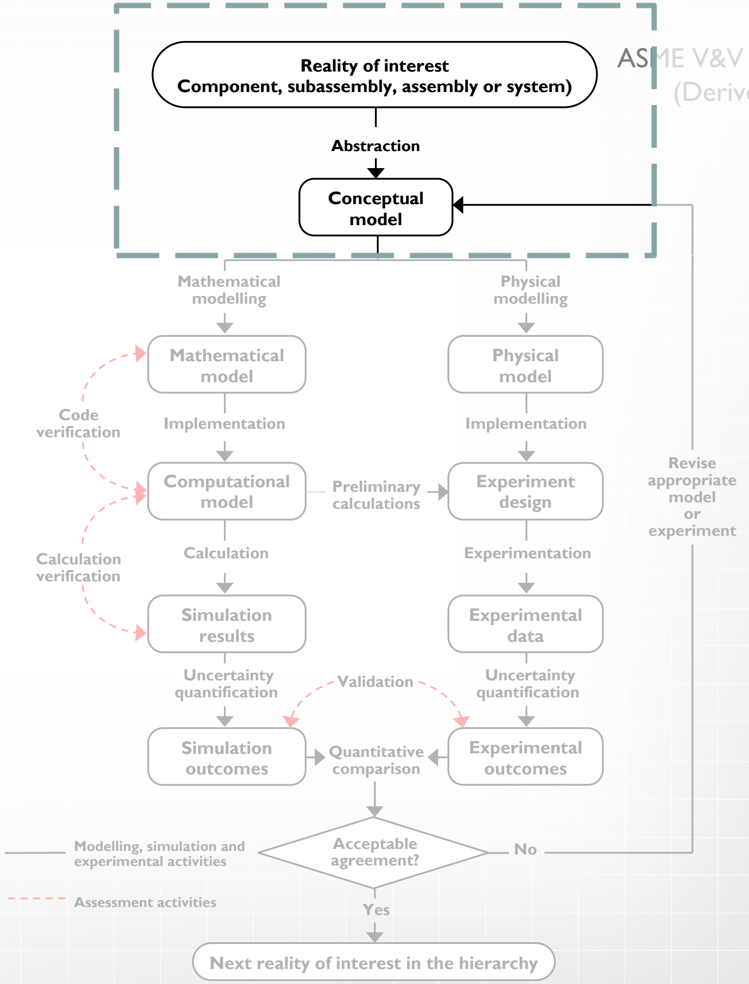

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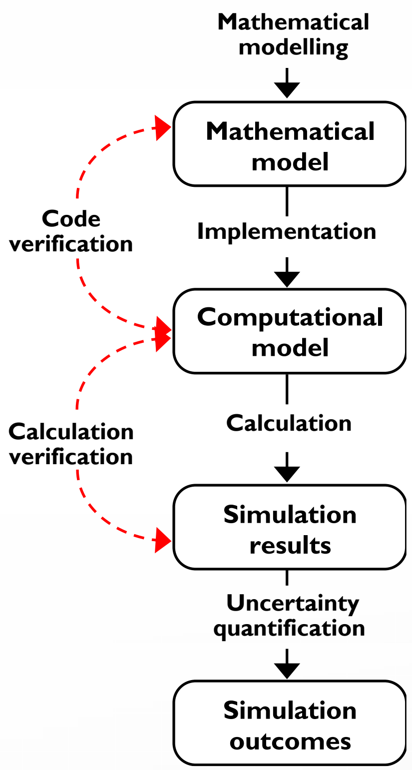

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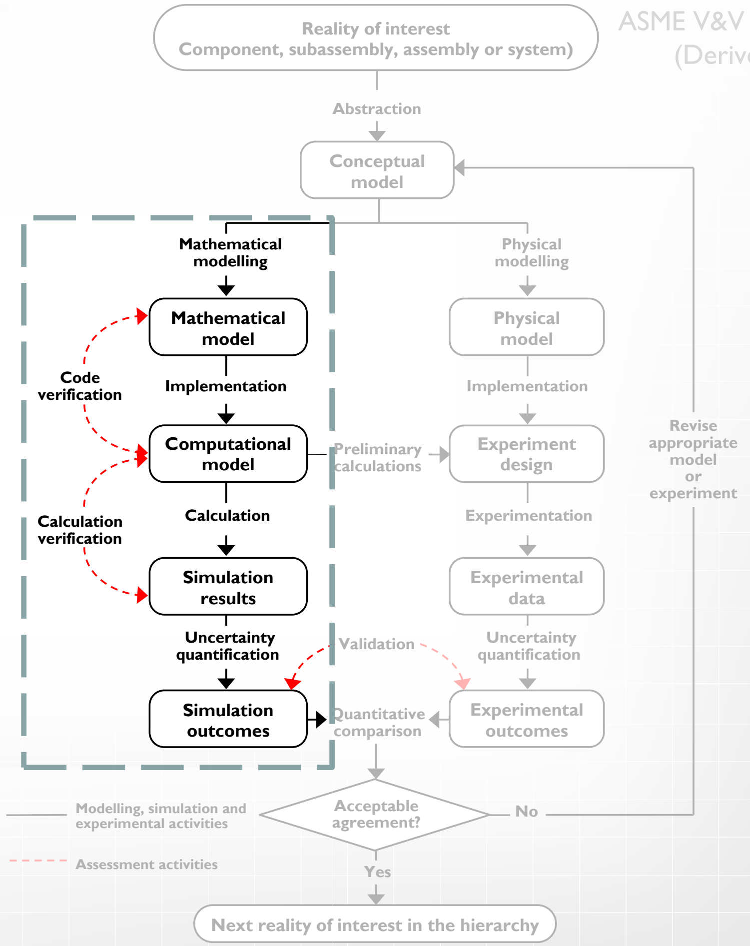

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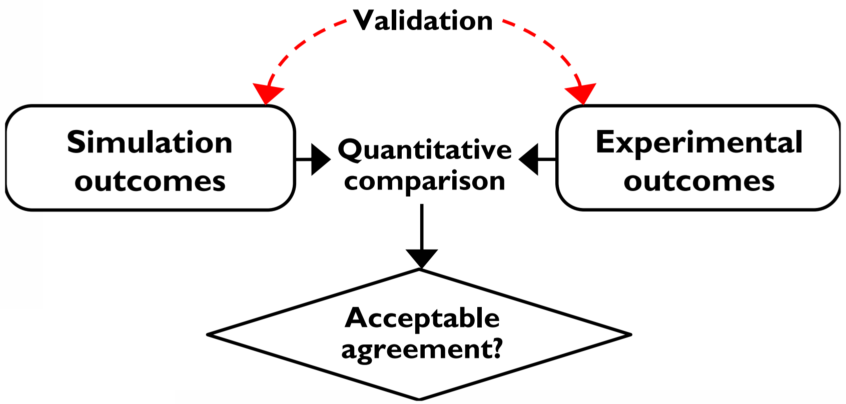

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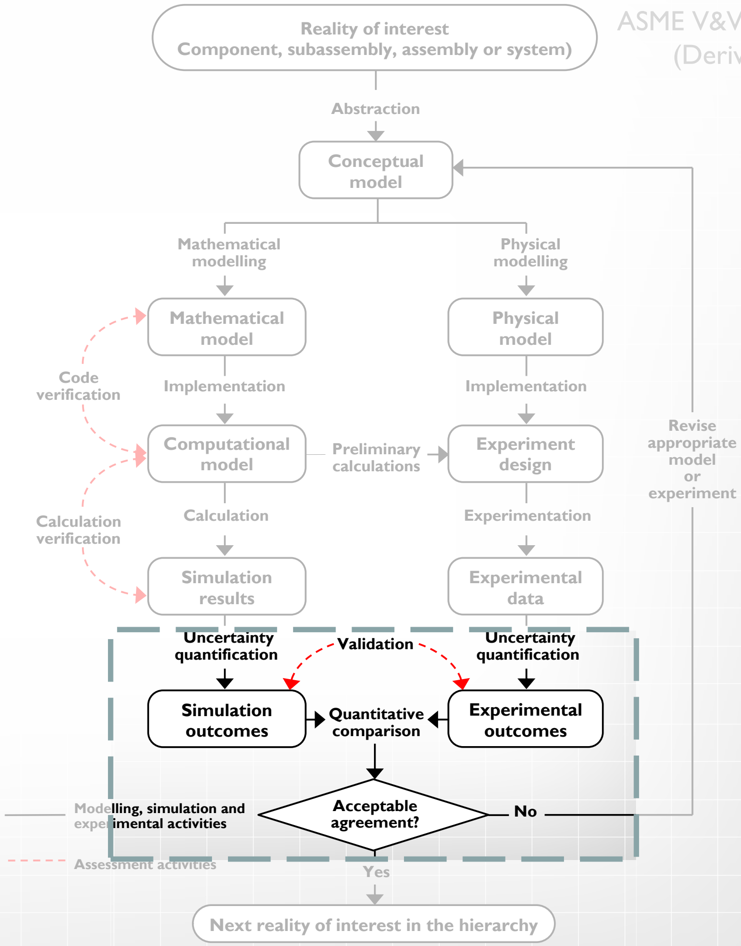


Confidence in simulation for certification

Verification and validation

Abstraction validation

What is being validated? Is it the conceptual model?
It is certainly not the reality of interest.

Code verification

Are the numerical algorithms correctly implemented in the computer code?
Are they functioning as intended?
Does the code correctly solve the underlying equations, as intended?

Calculation verification

Are the simulation errors sufficiently small?
(Round-off error, iterative error, discretization error, stochastic error.)

Uncertainty quantification

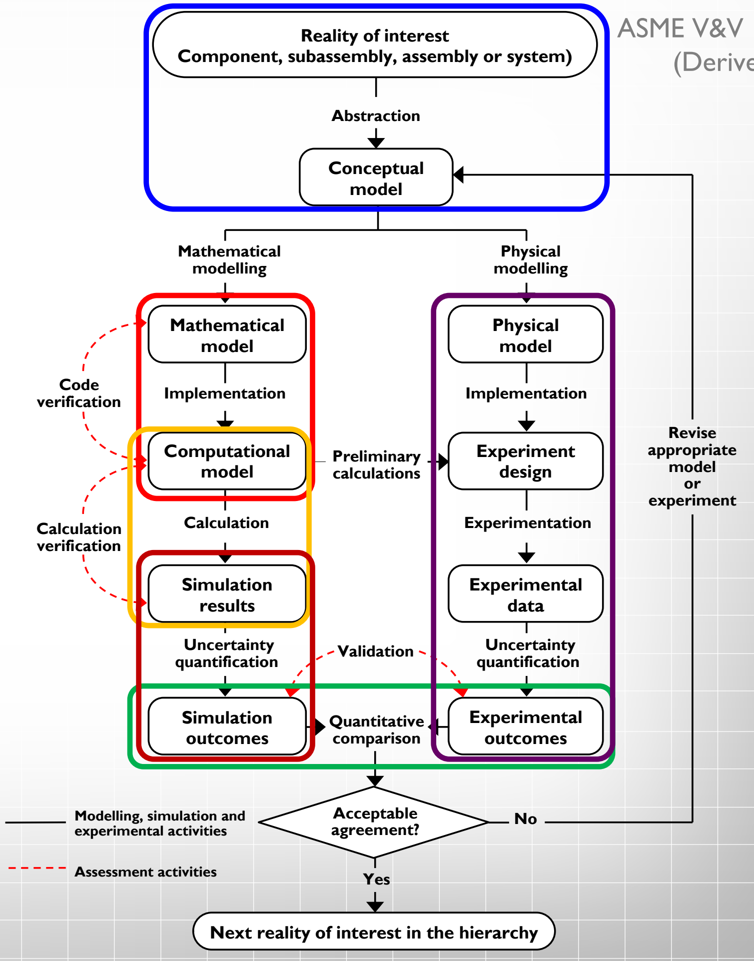
Are the simulation results sensitive to the simulation inputs?
UQ margins of uncertainty accumulate on top of any errors due to code and calculation verification.

Experimental branch

Similar verification and UQ activities mirrored along the experimental branch.

Validation

Quantitative comparison of simulation outcomes with experimental outcomes.
Is the prediction within the required bounds?
Not a comparison of single point data, but of predictive/experimental bounds.



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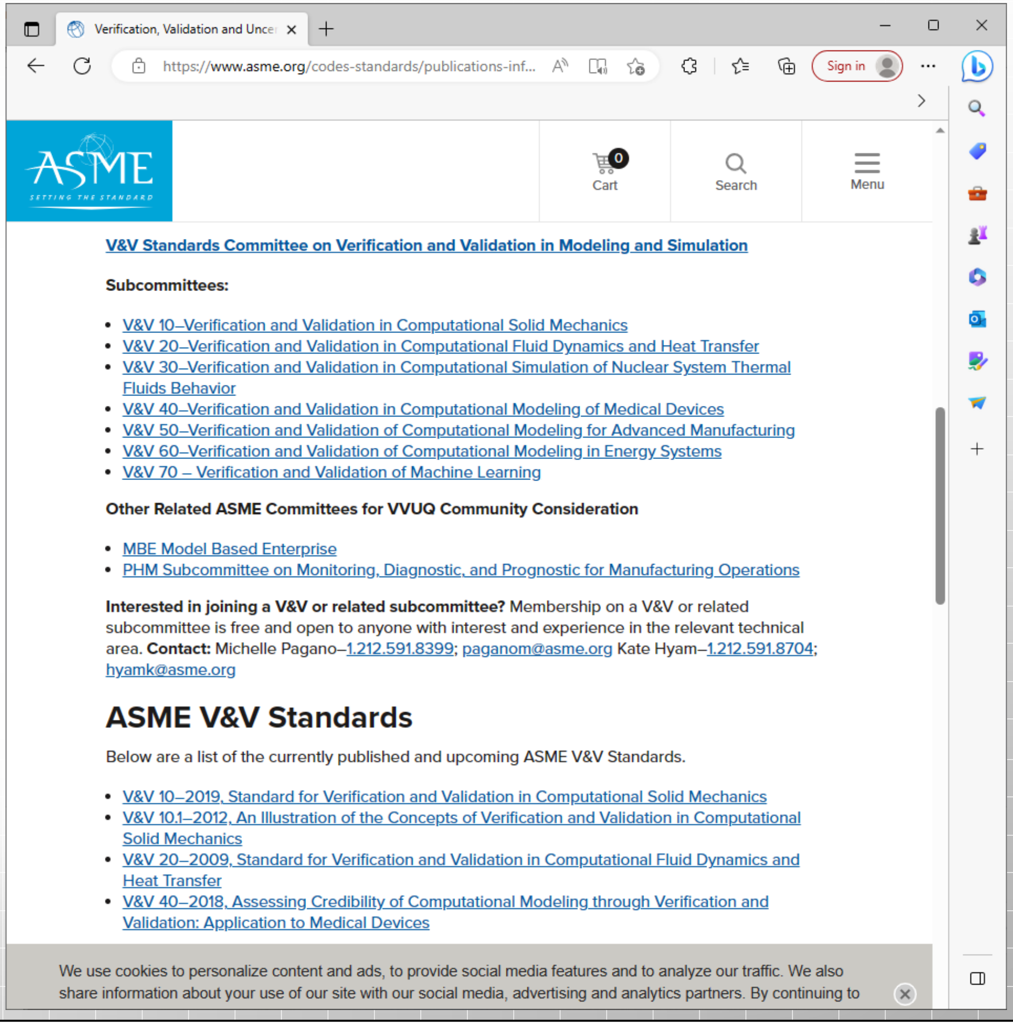
Confidence in simulation for certification

Verification and validation

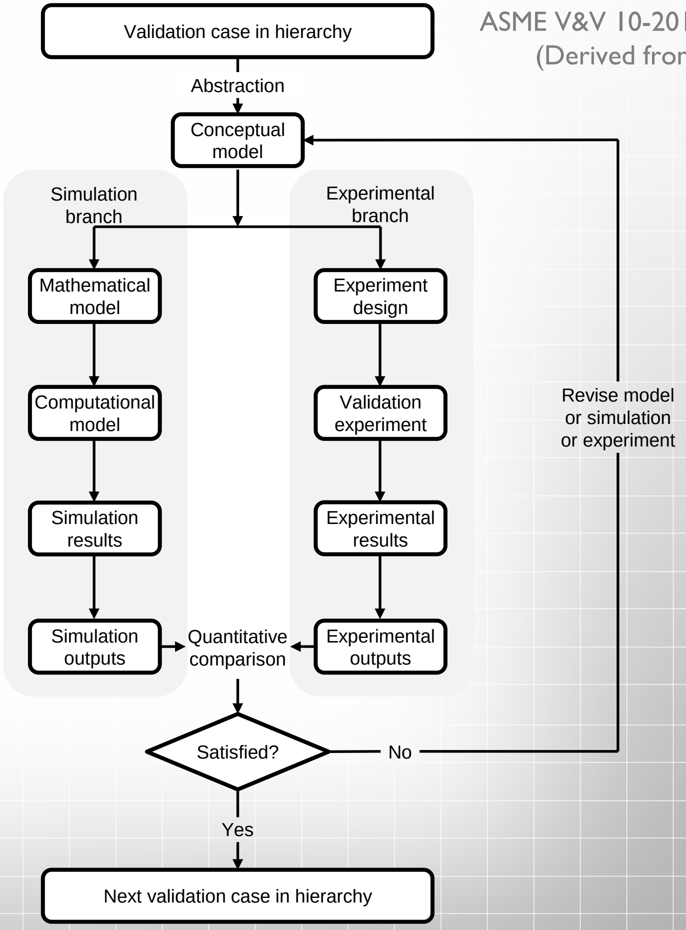
Updated in 2019



Confidence in simulation for certification

Verification and validation

- What is validation?
  - From ASME V&V 10 2019:
    Validation is the process of determining the degree to which the model is an accurate representation of *corresponding physical experiments* from the perspective of the intended uses of the model.
  - This is different to NAFEMS WT09 and V&V 10 2006:
    Validation is the process of determining the degree to which a model is an accurate representation of *the real world* from the perspective of the intended uses of the model.

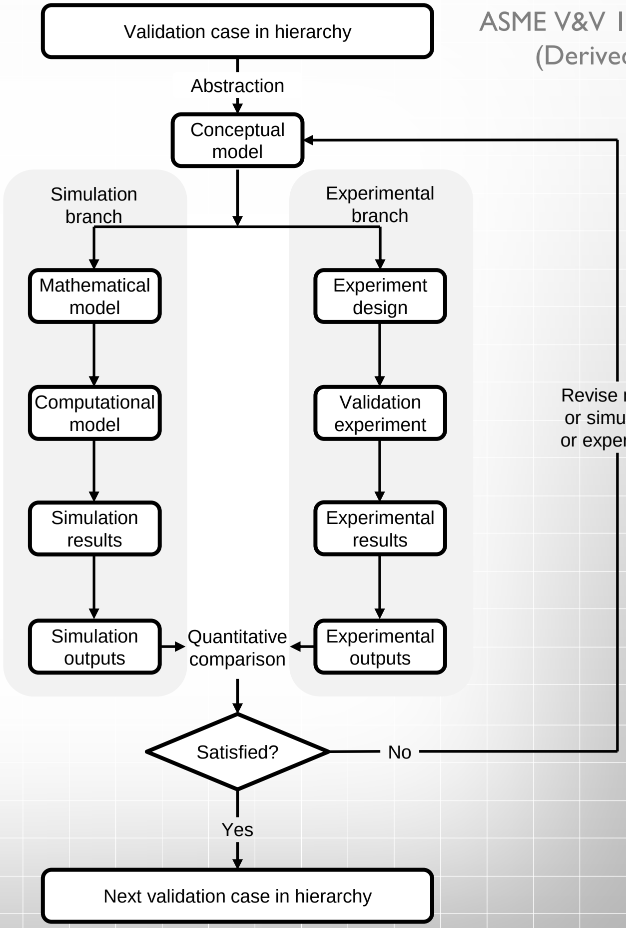


ASME V&V 10-2019 (Derived from)

Confidence in simulation for certification

Verification and validation

- NAFEMS validation spectrum
  - Essentially V&V 10 requires a quantitative comparison of the simulation outputs with the outputs of a validation experiment.
  - Whilst this might represent best practice, often it is not possible to undertake physical testing within the scope of a real project.
  - NAFEMS recognises this and has developed the validation spectrum.



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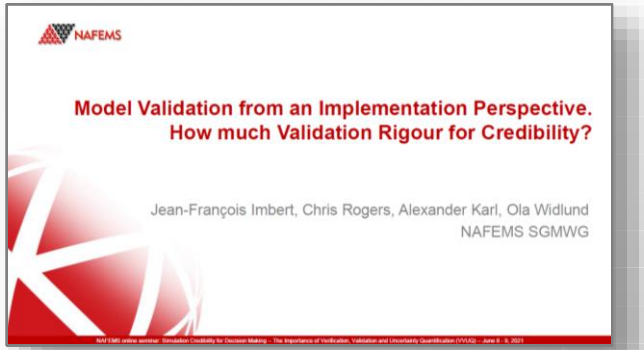
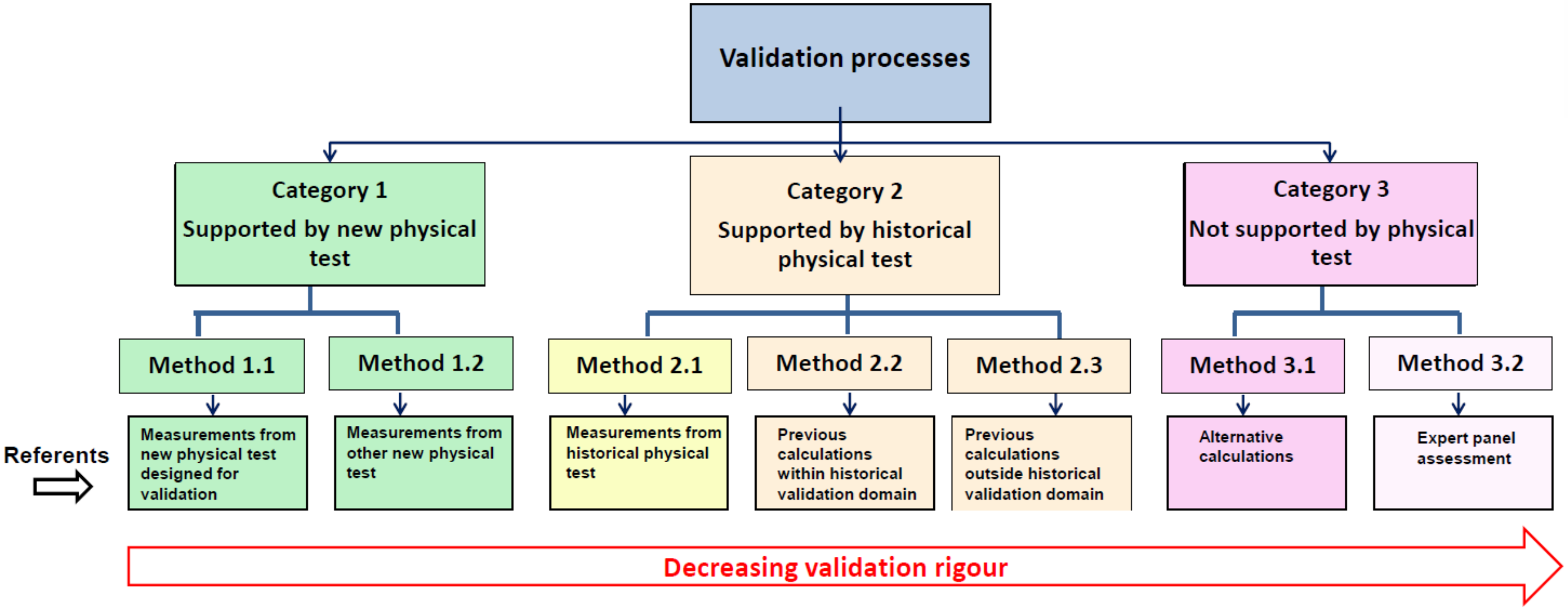
Verification and validation

- NAFEMS validation spectrum





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Verification and validation

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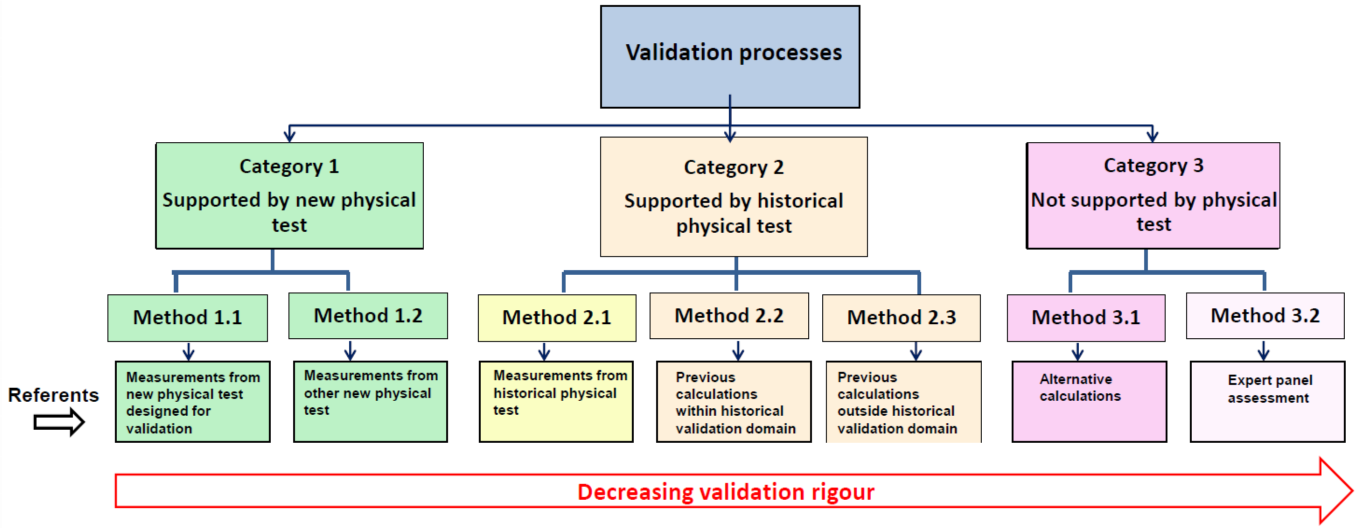

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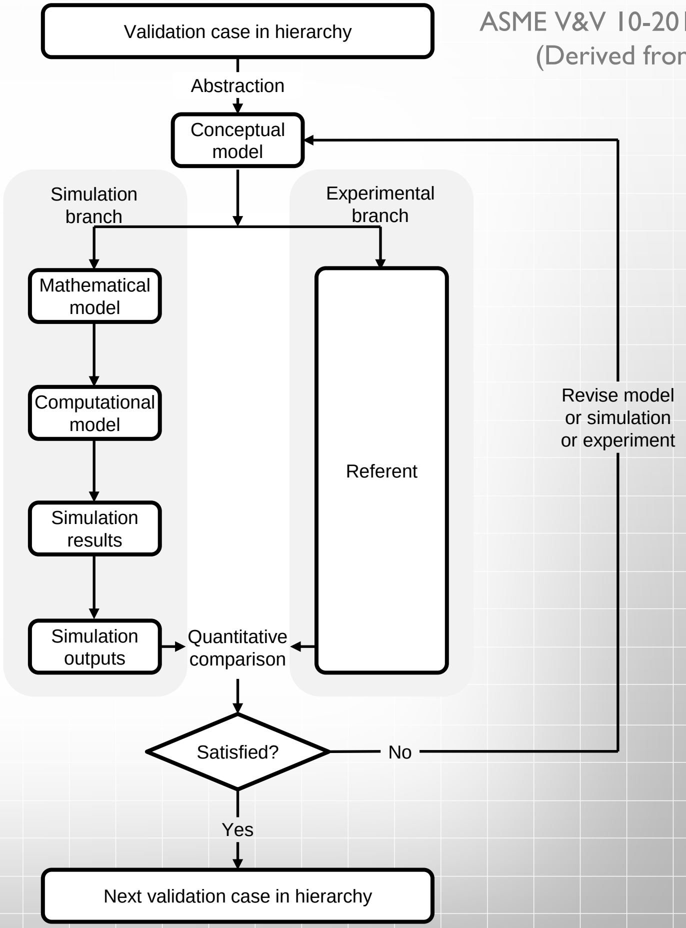

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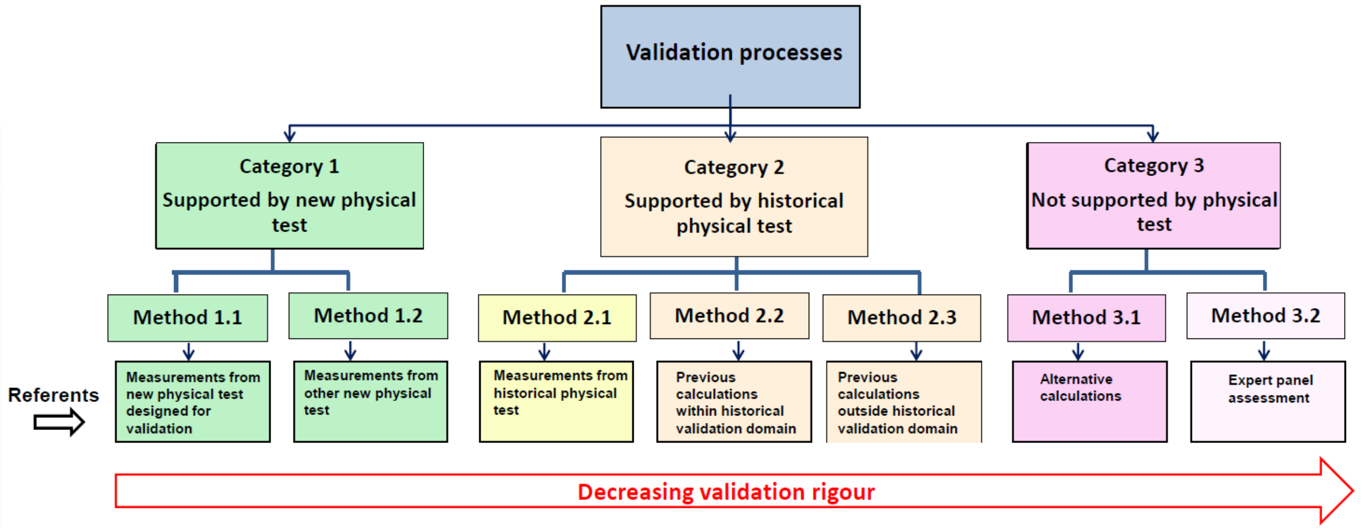

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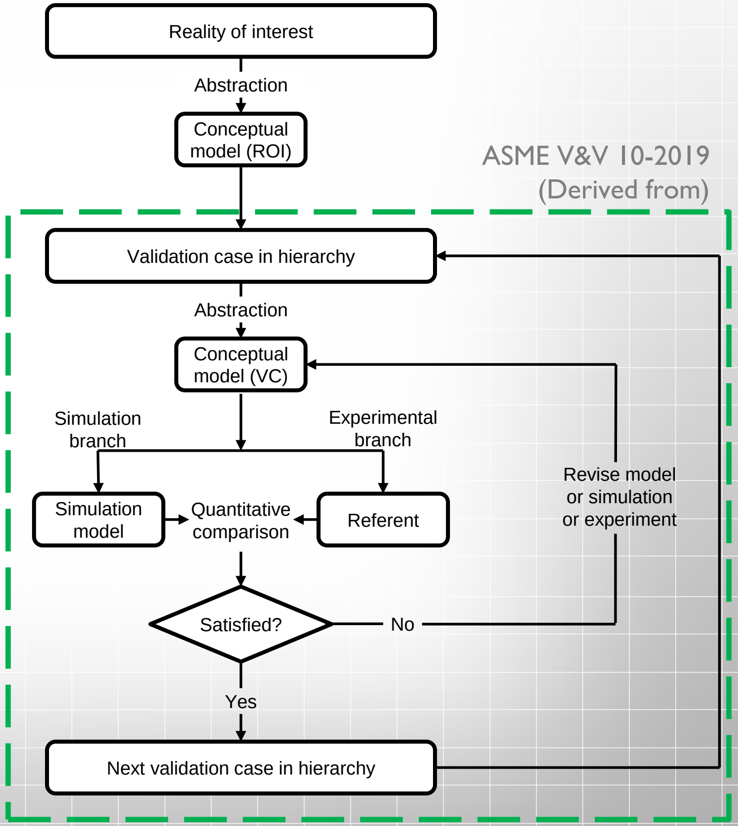
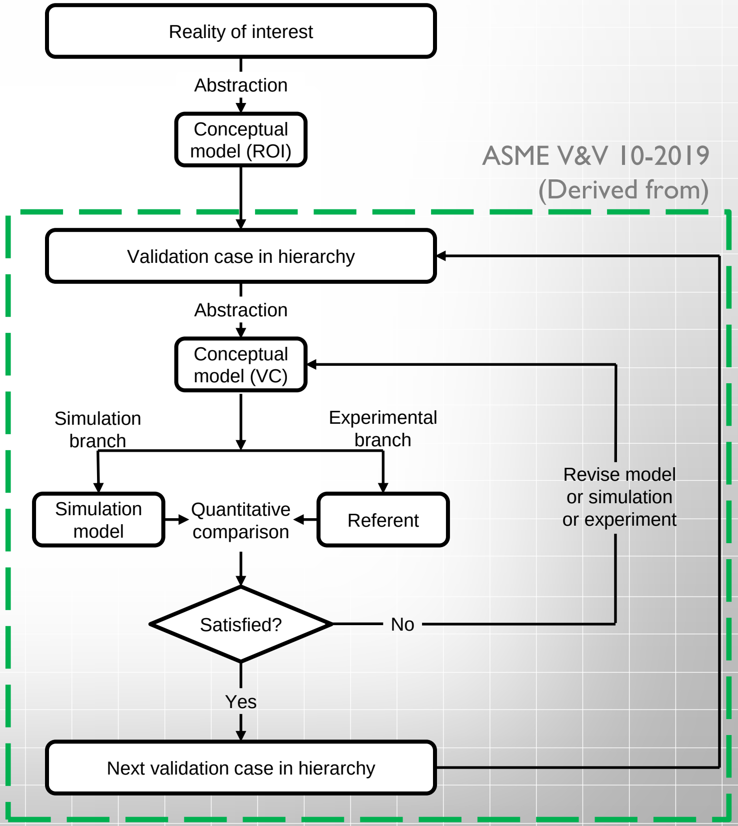


Confidence in simulation for certification

Understanding the physics

- Conceptual model
  - The collection of assumptions and descriptions of physical processes representing the solid mechanics behavior from which the mathematical model and *referent* can be constructed.
  - Think of this as a free body diagram for the simulation.



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Confidence in simulation for certification

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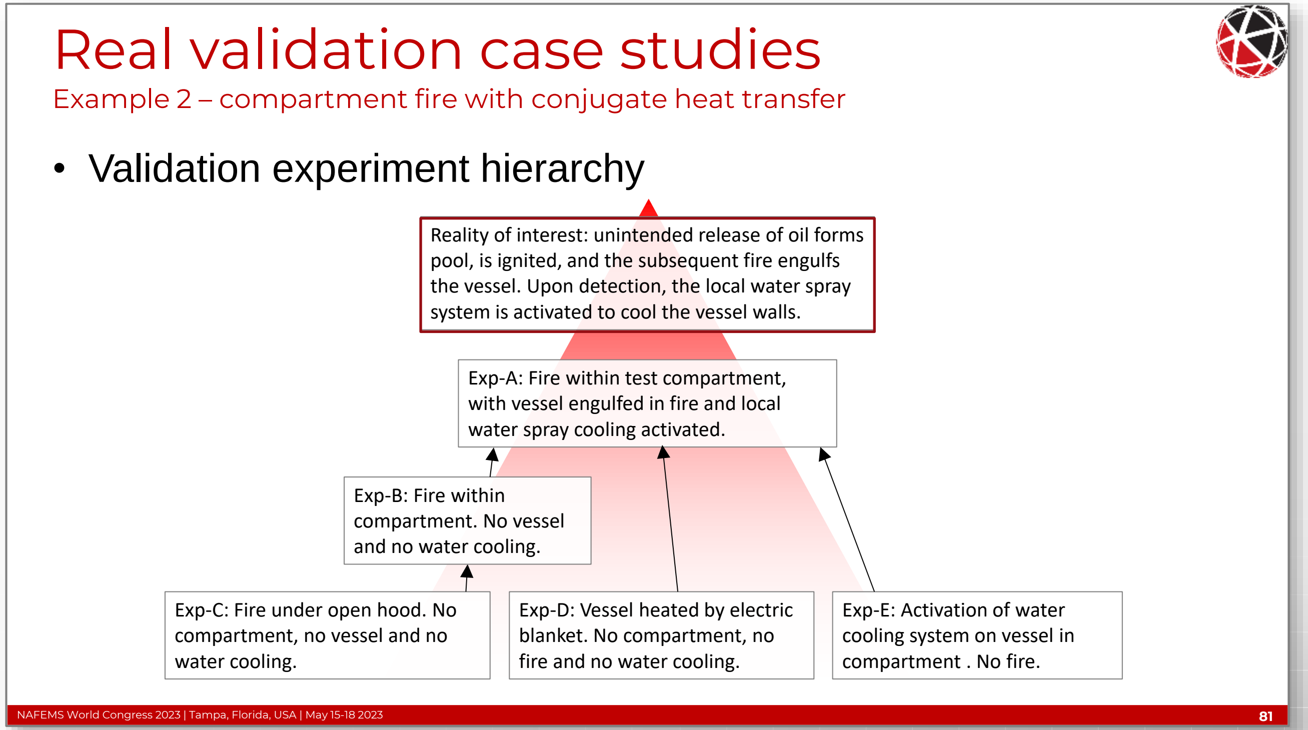

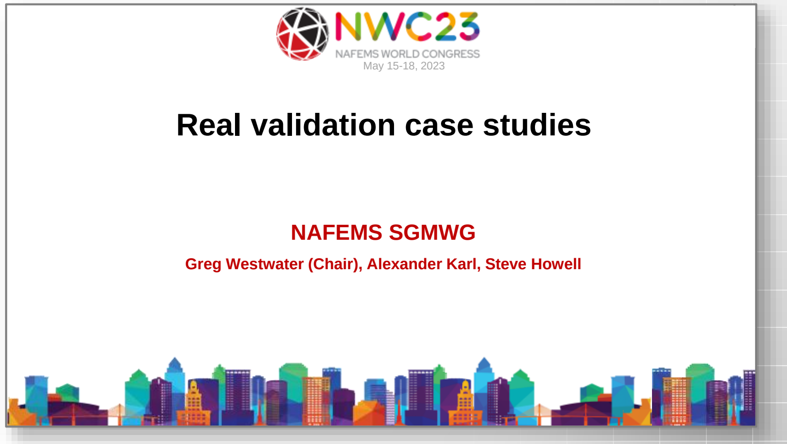

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Understanding the physics

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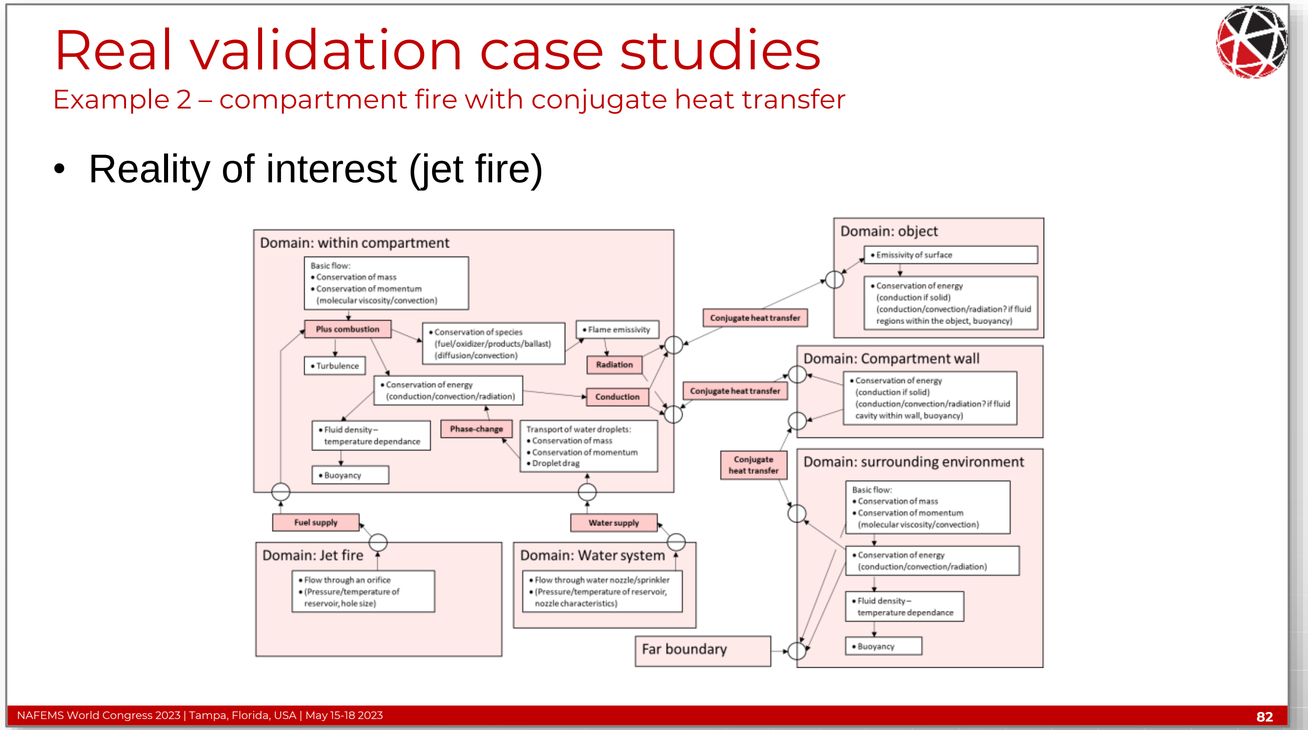

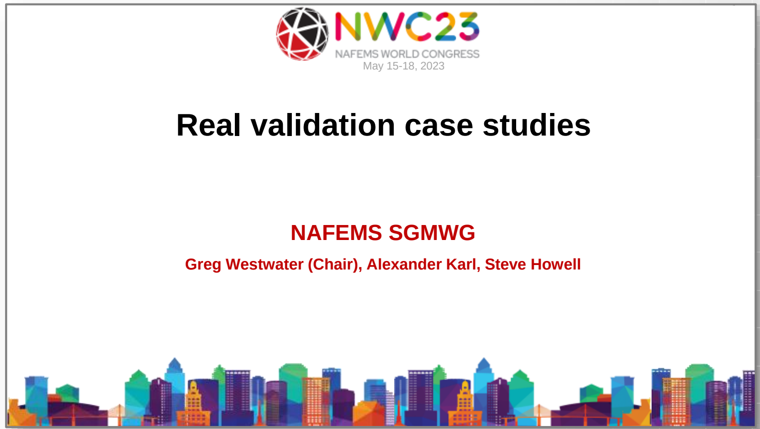

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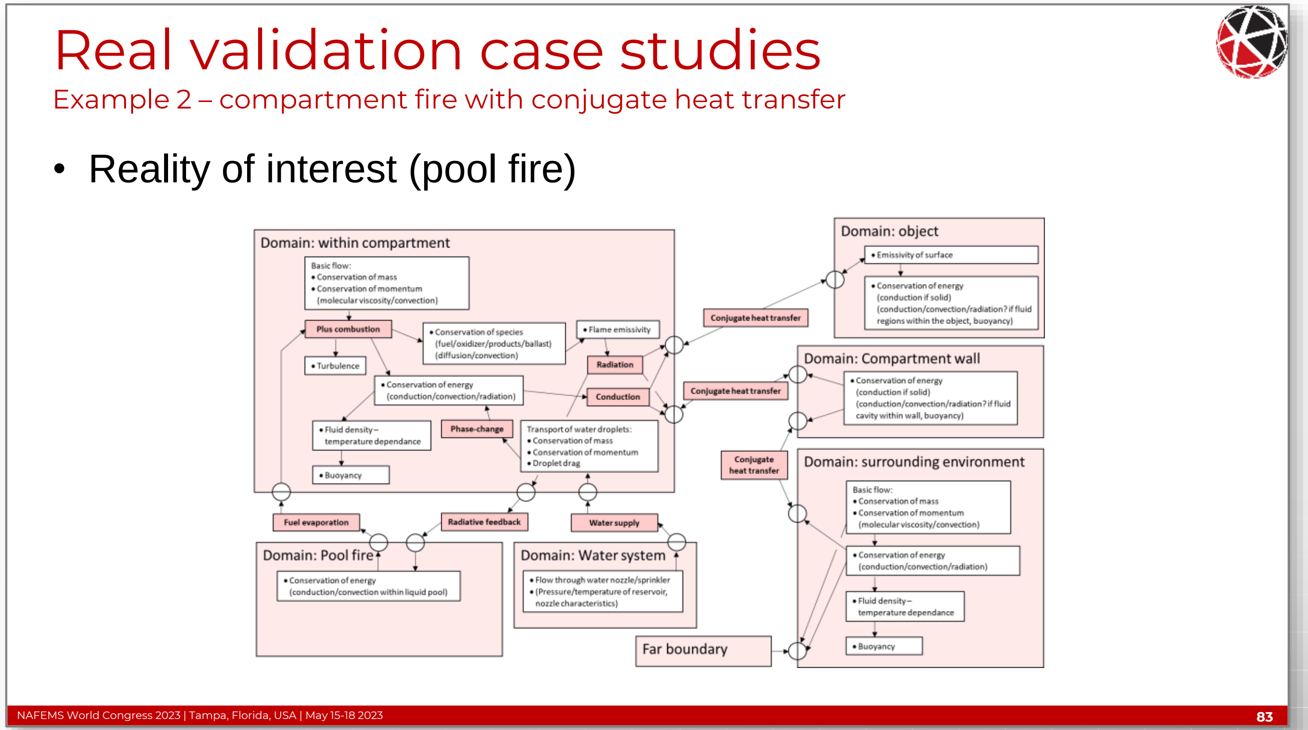

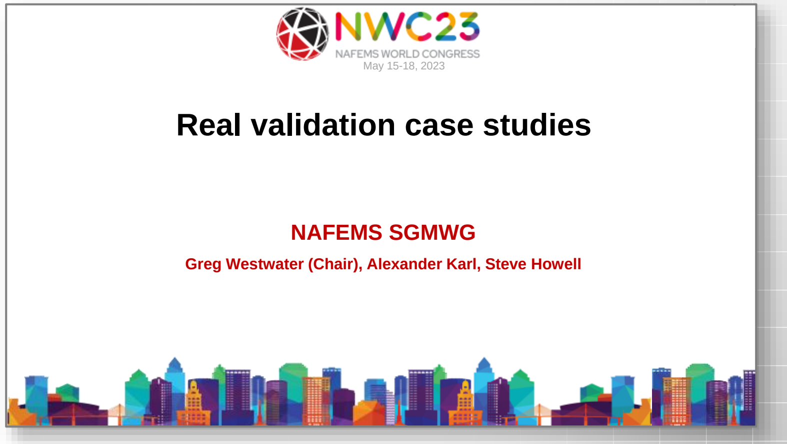

Confidence in simulation for certification

Understanding the physics

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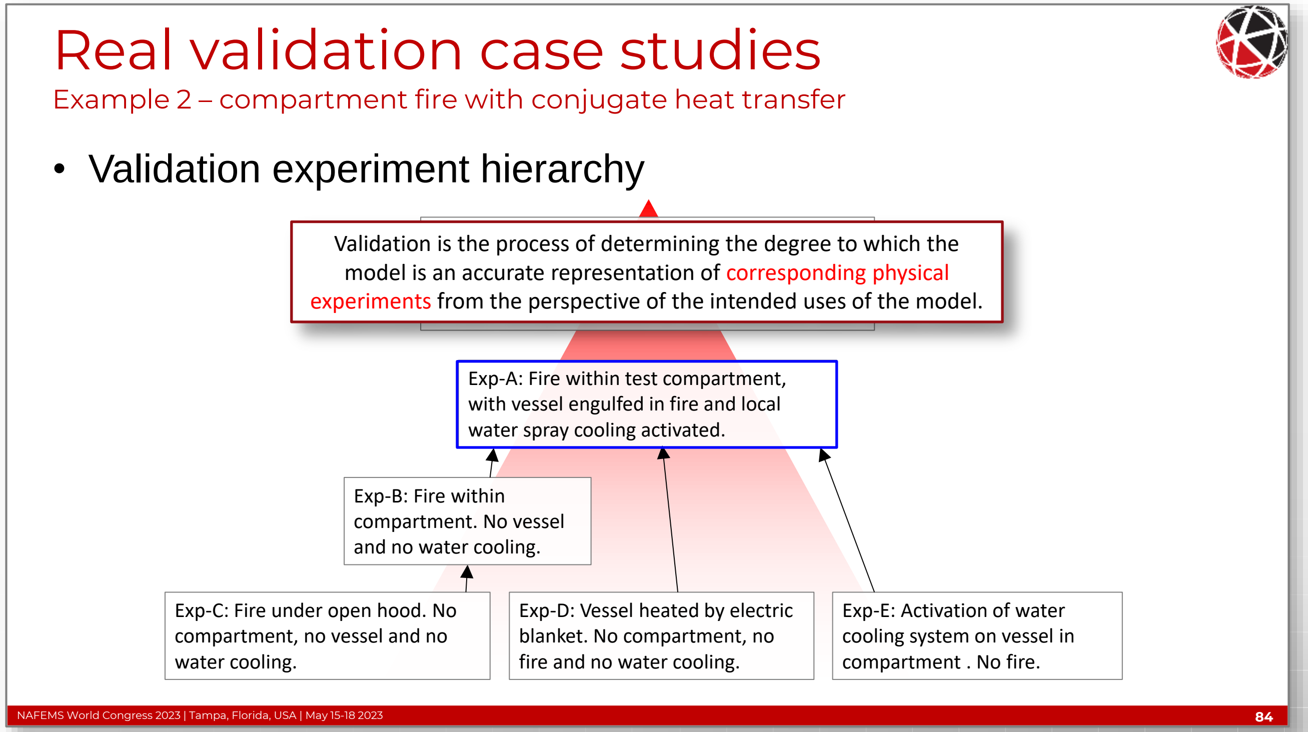

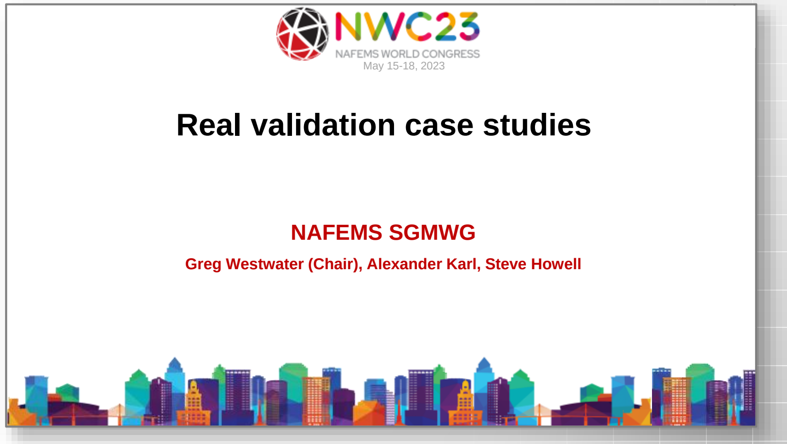

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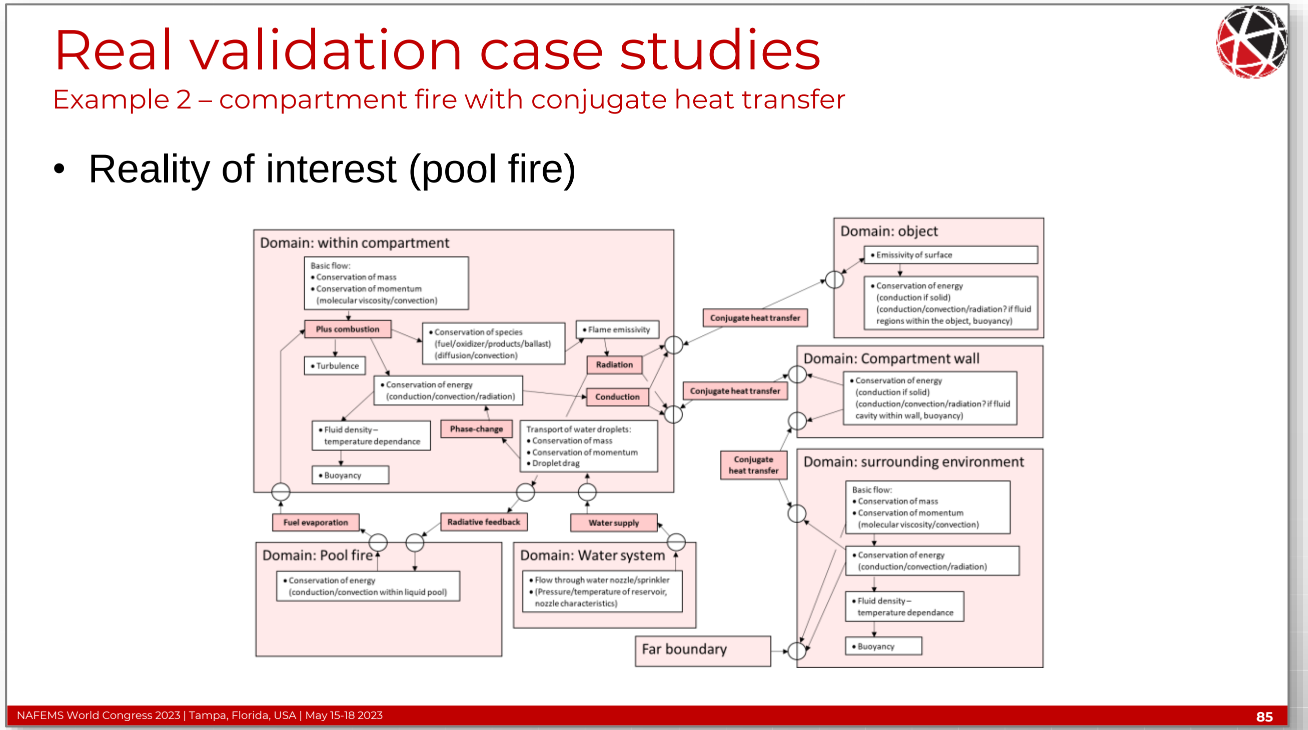

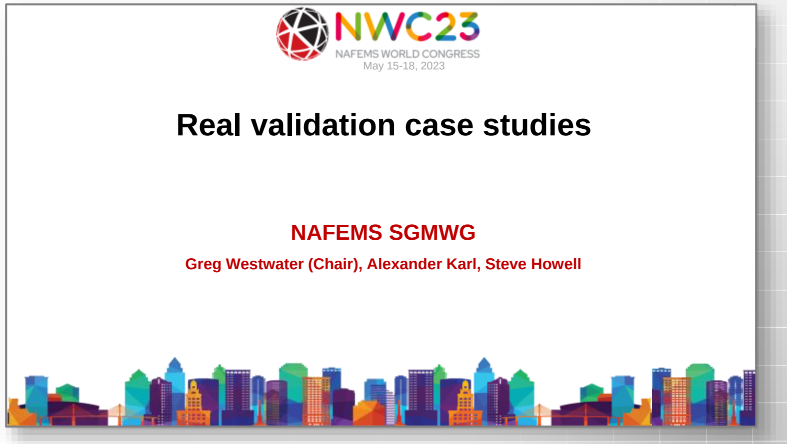

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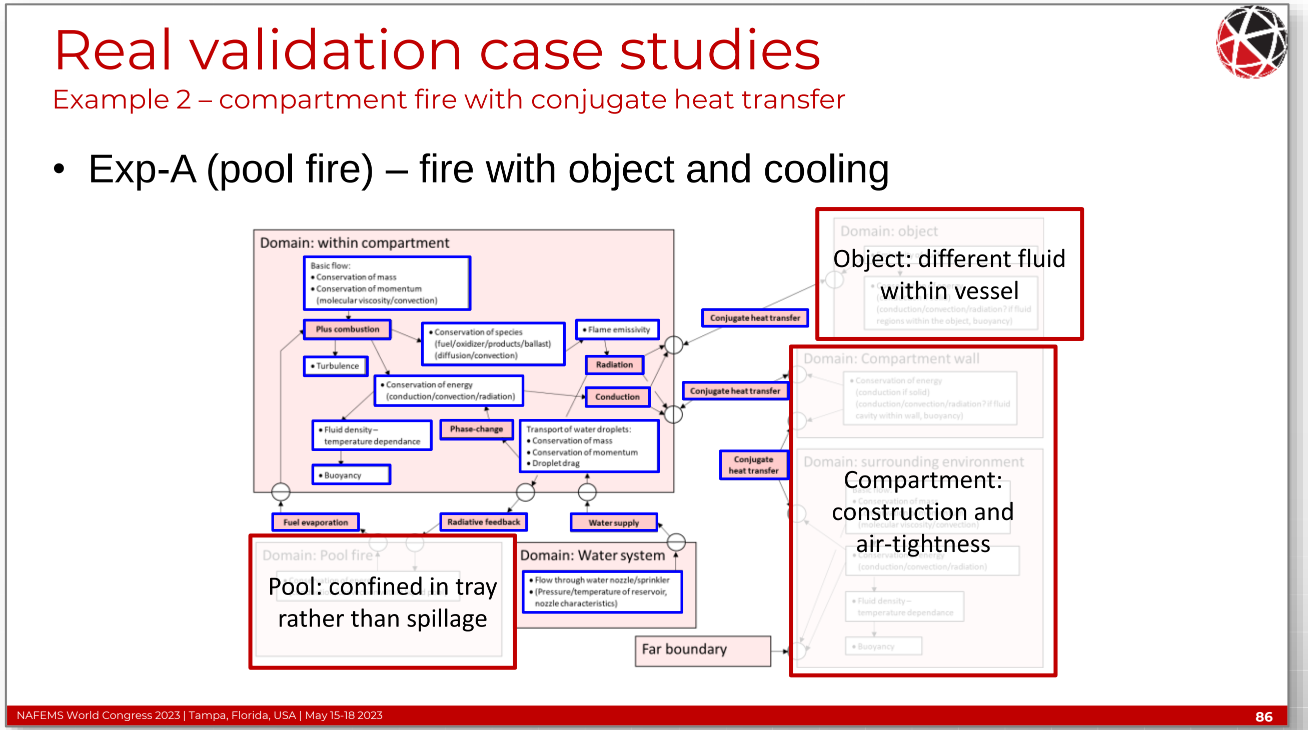

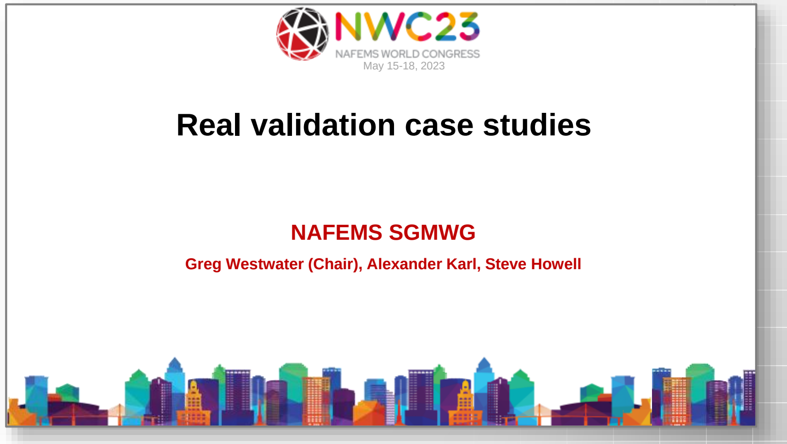

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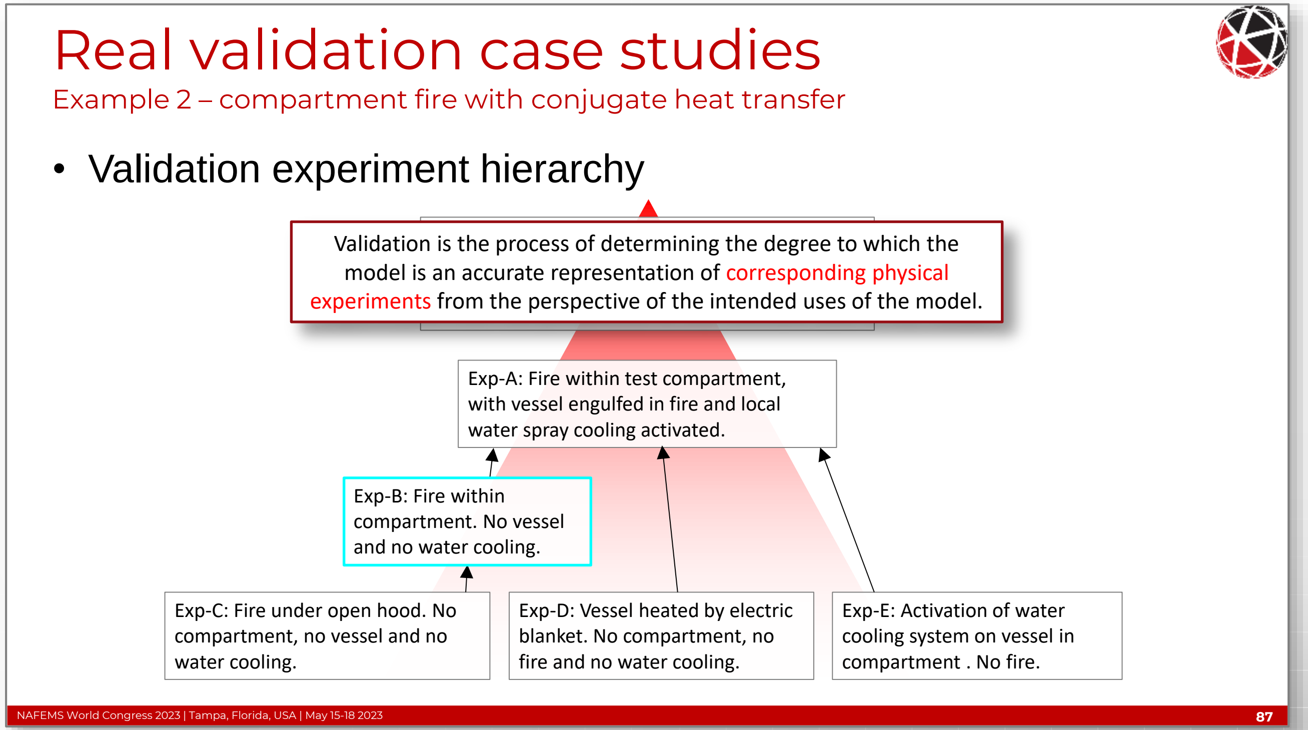

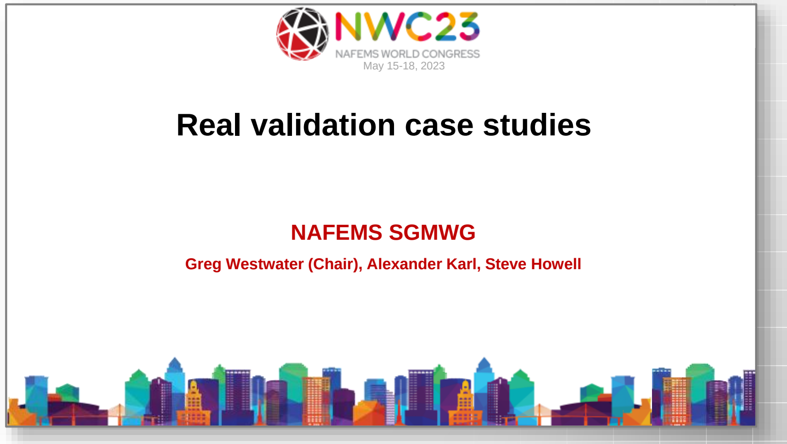

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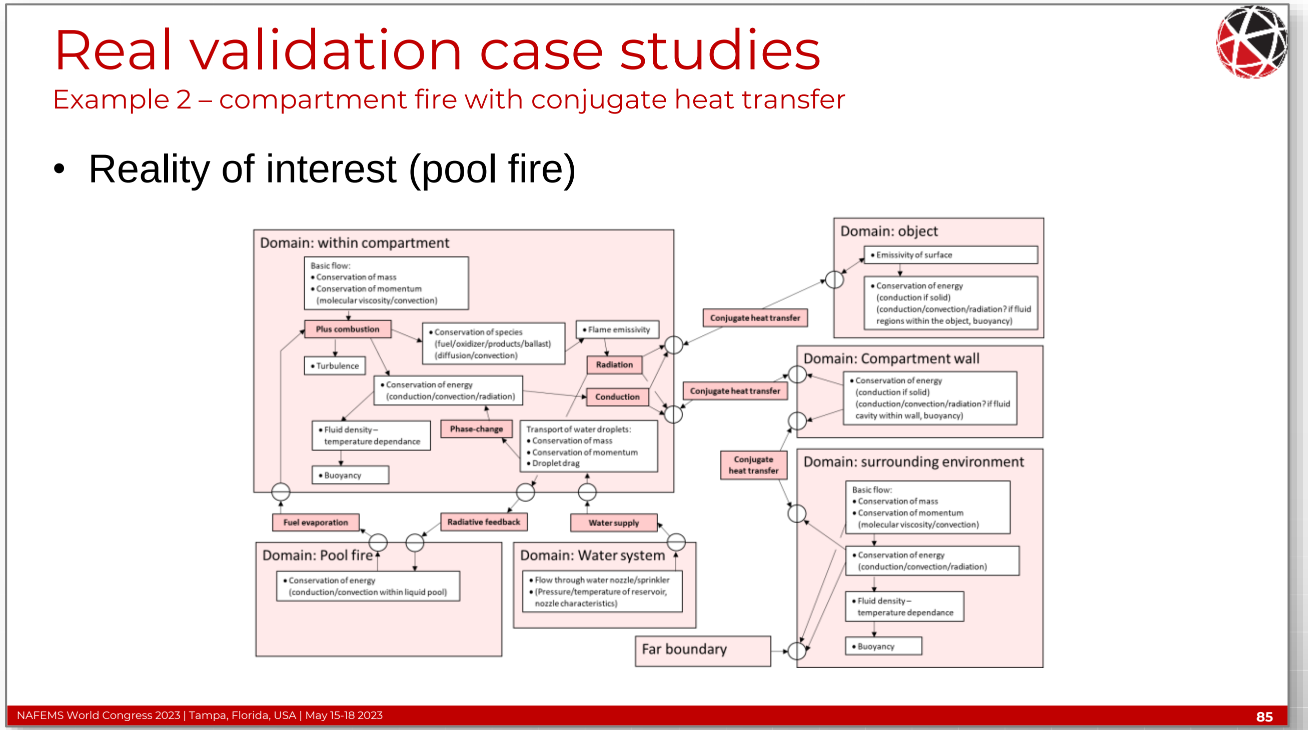

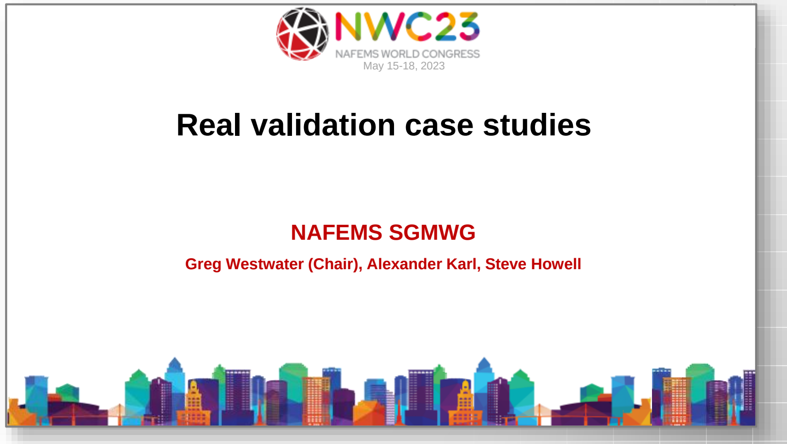

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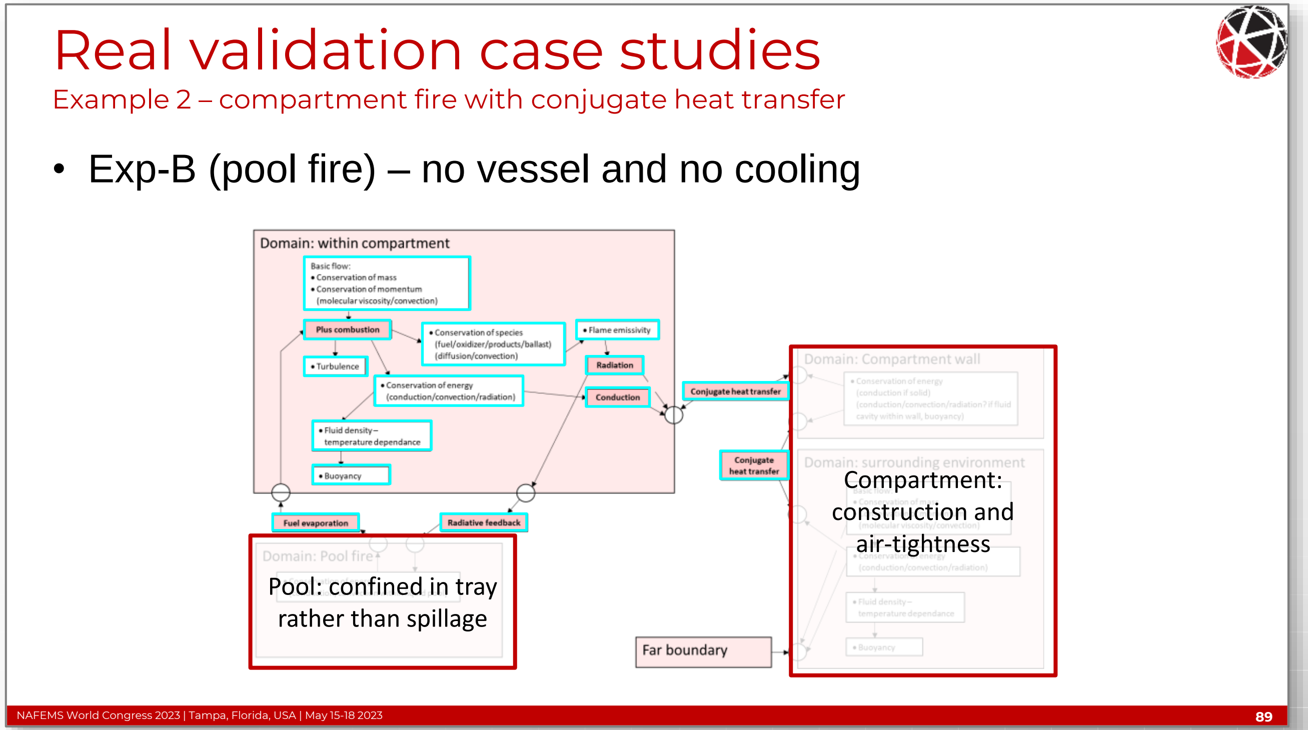

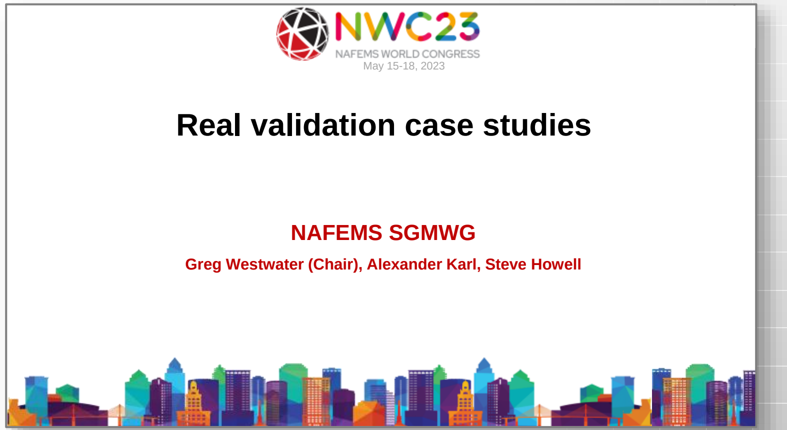

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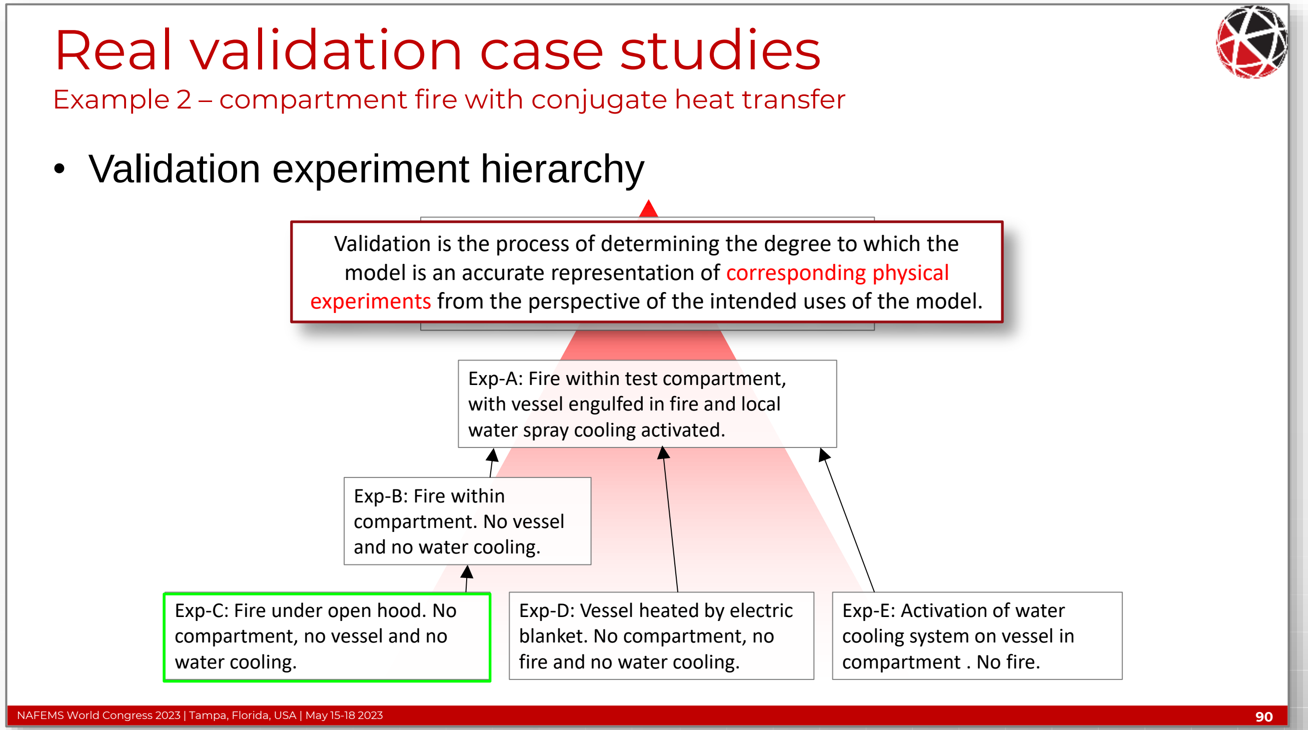
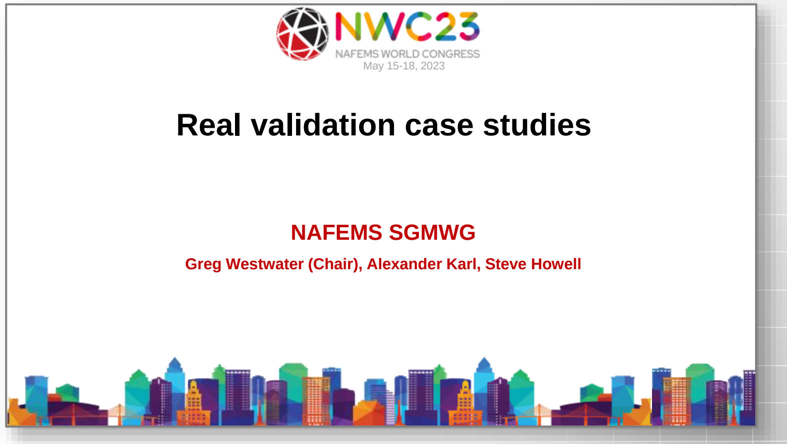




Confidence in simulation for certification

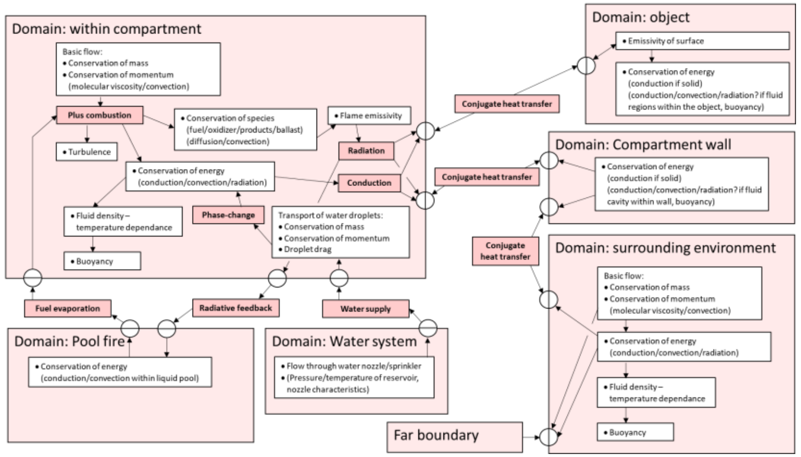
Understanding the physics

- Conceptual model

Real validation case studies

Example 2 – compartment fire with conjugate heat transfer

- Reality of interest (pool fire)



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Real validation case studies

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Understanding the physics

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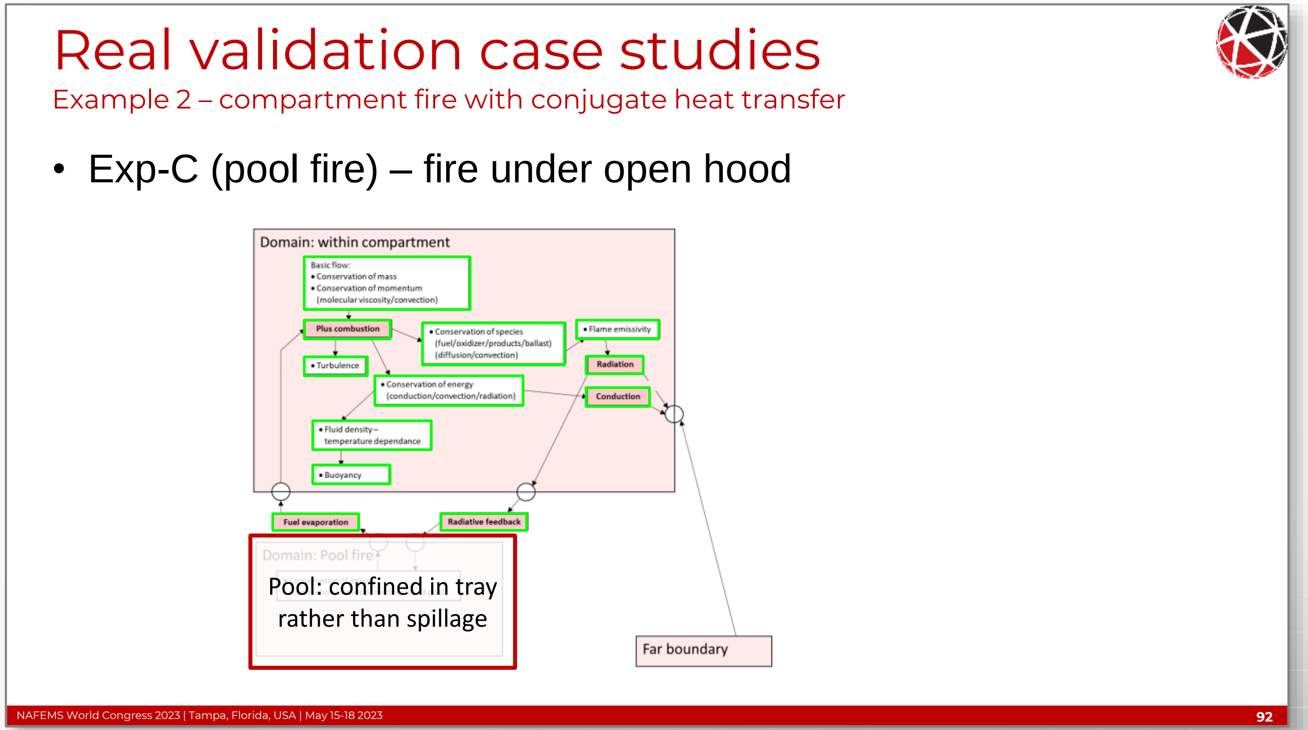

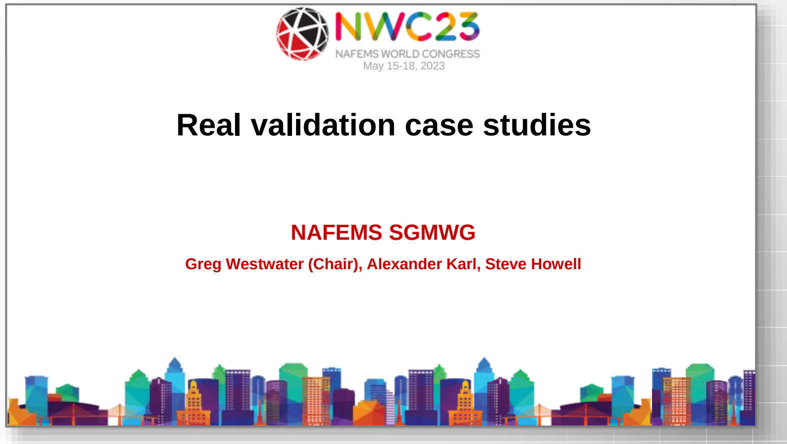

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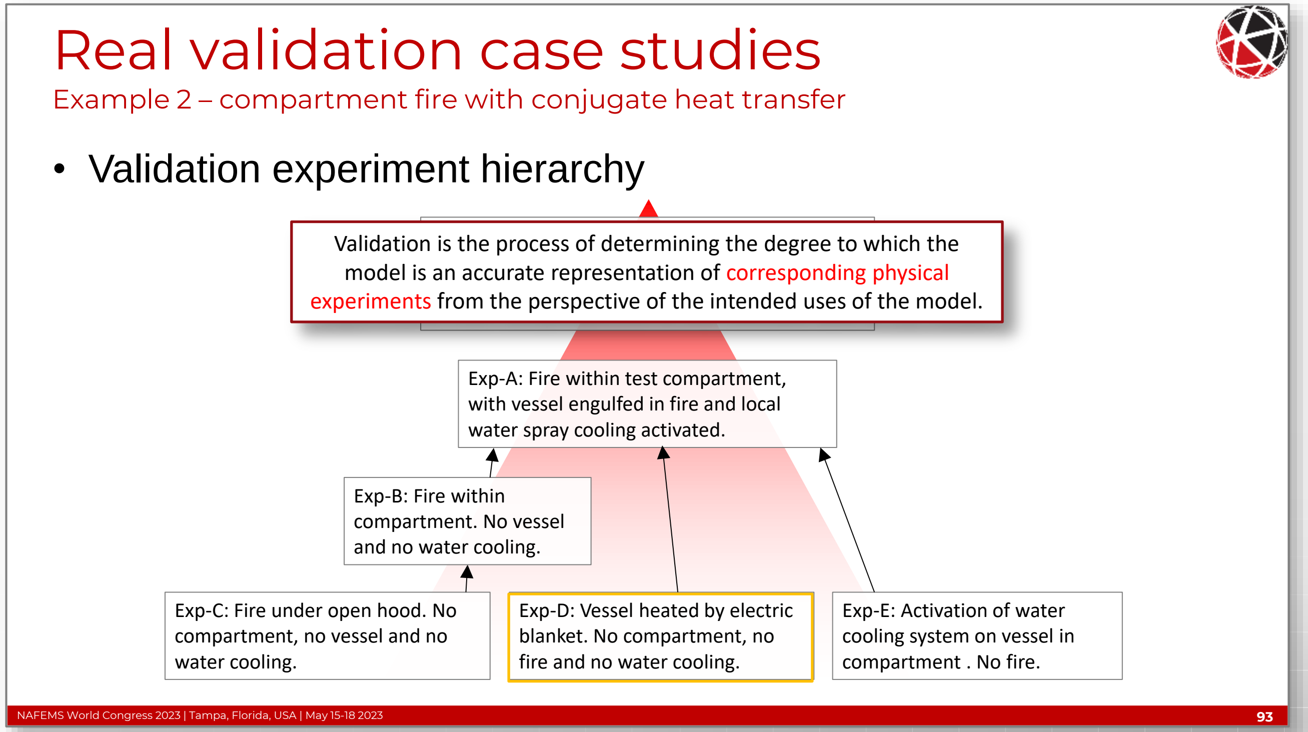

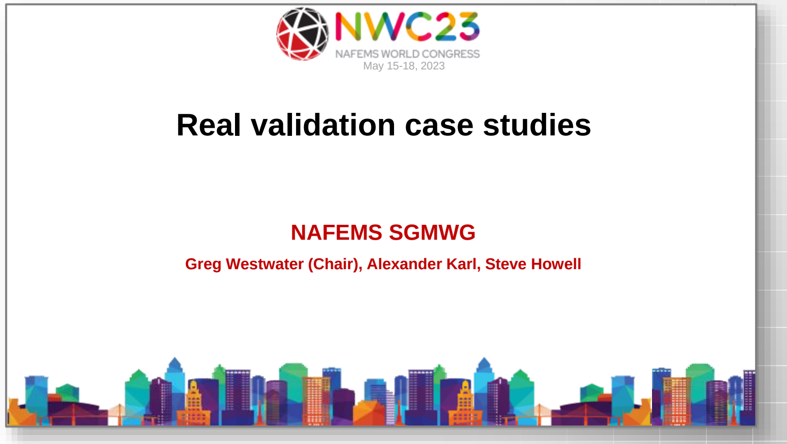

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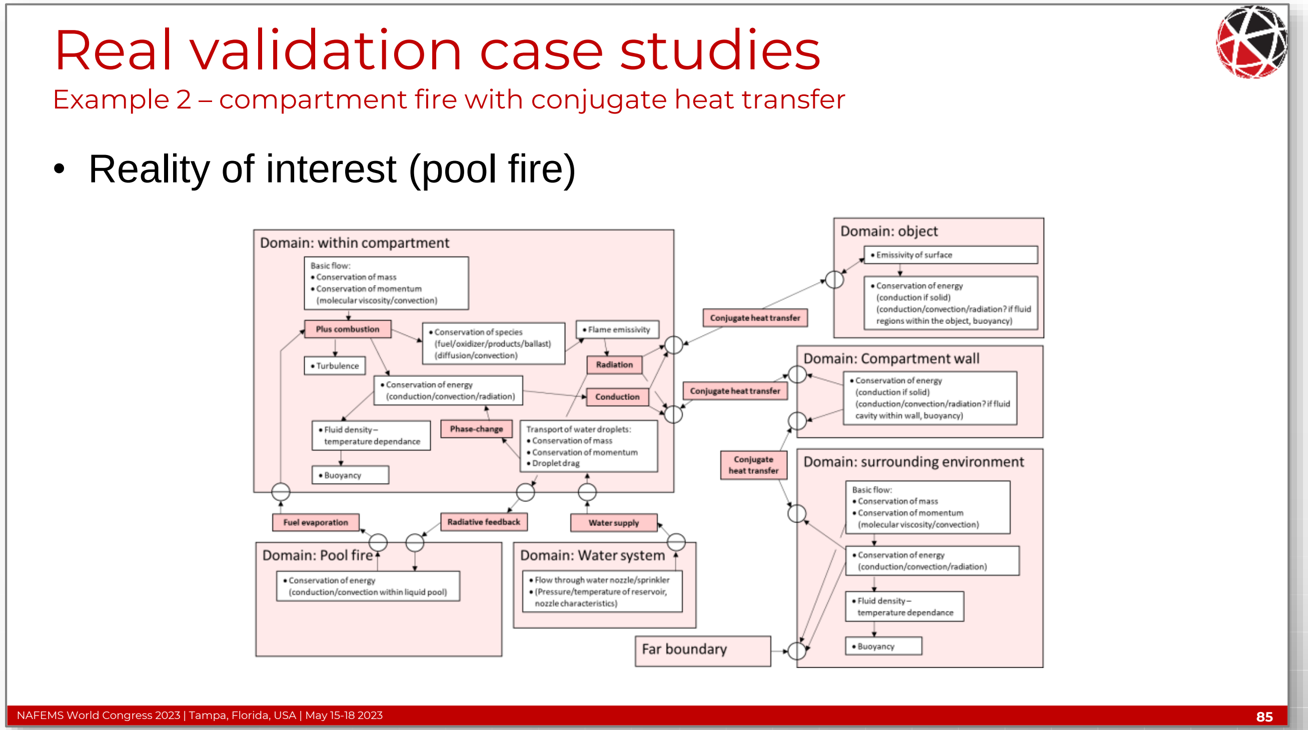

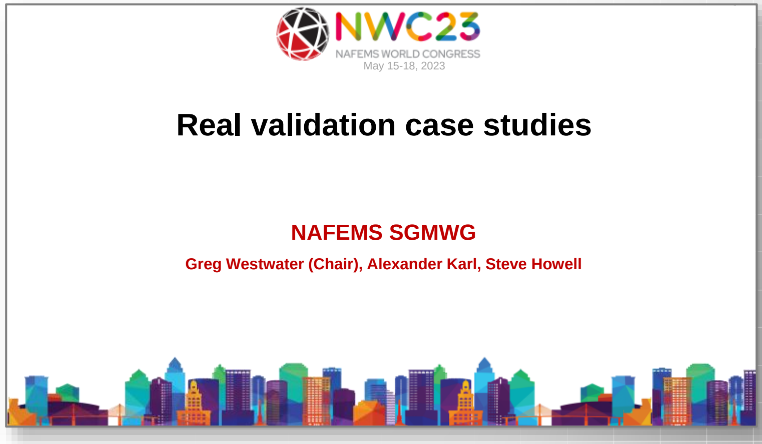

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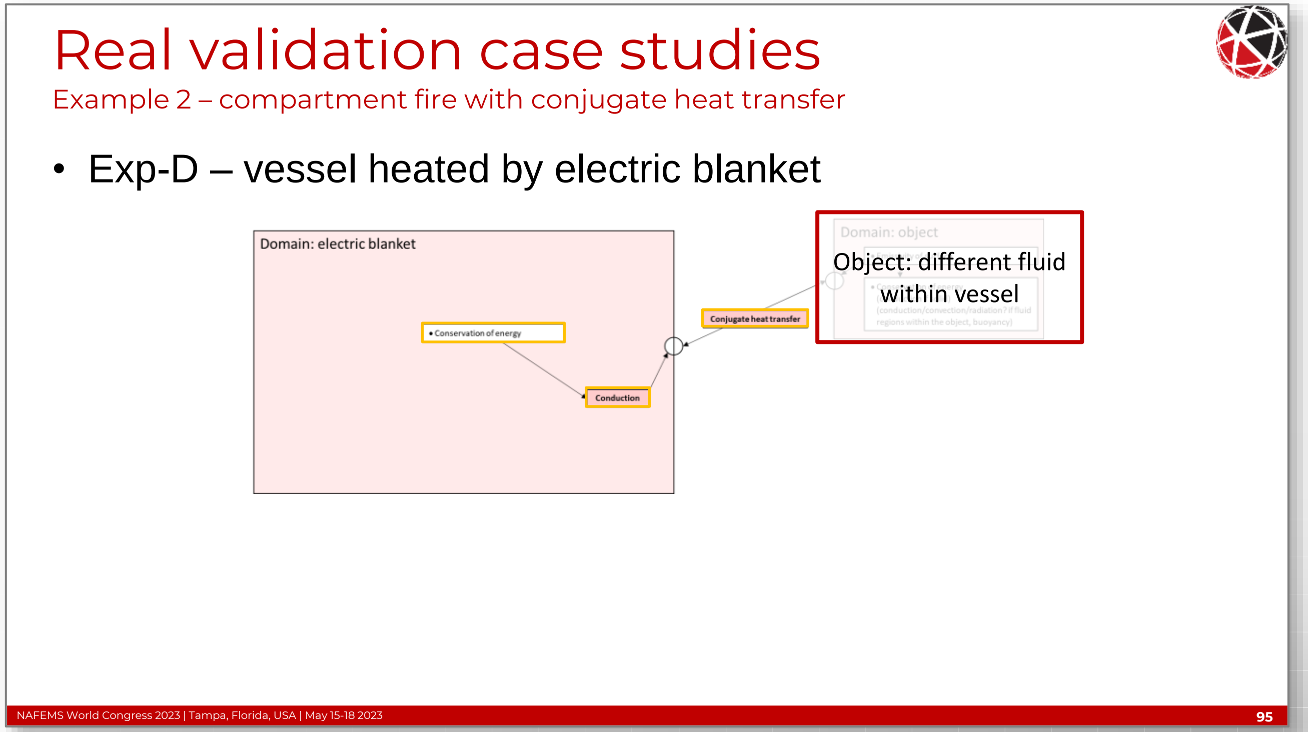

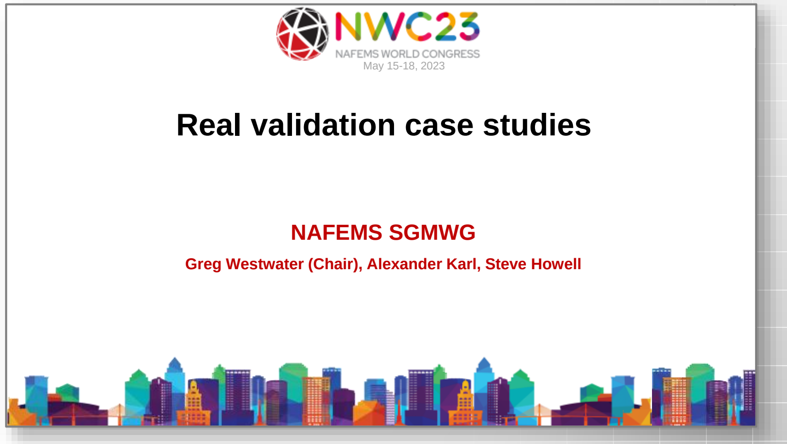

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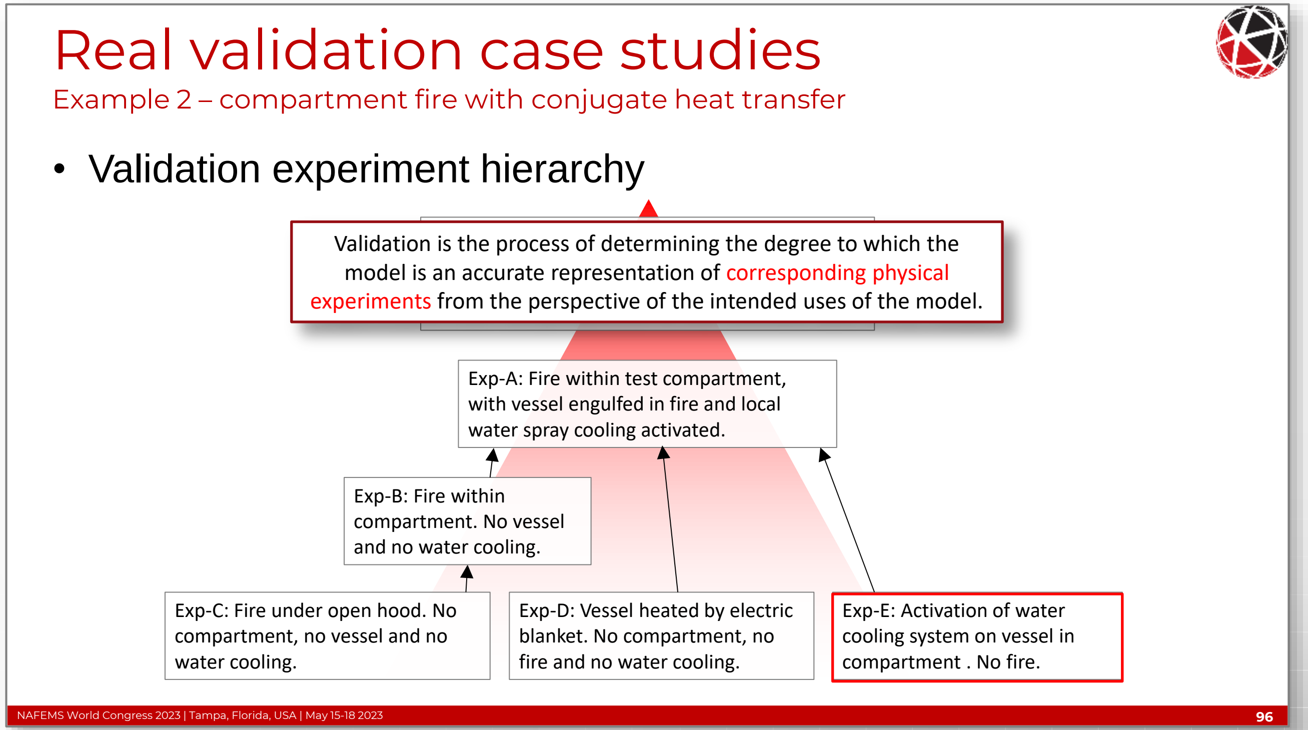

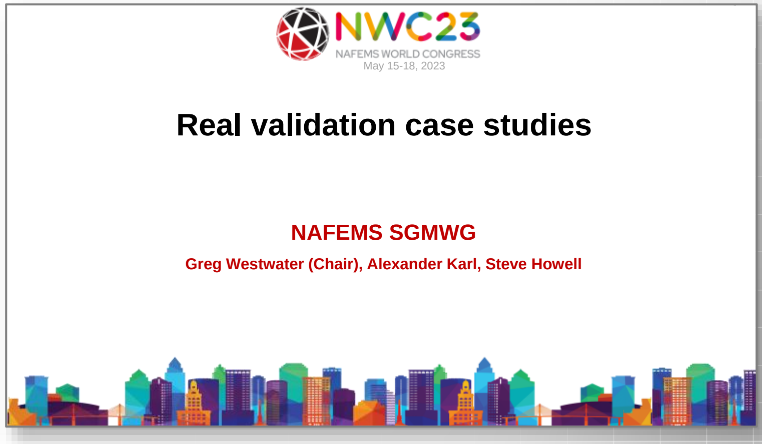

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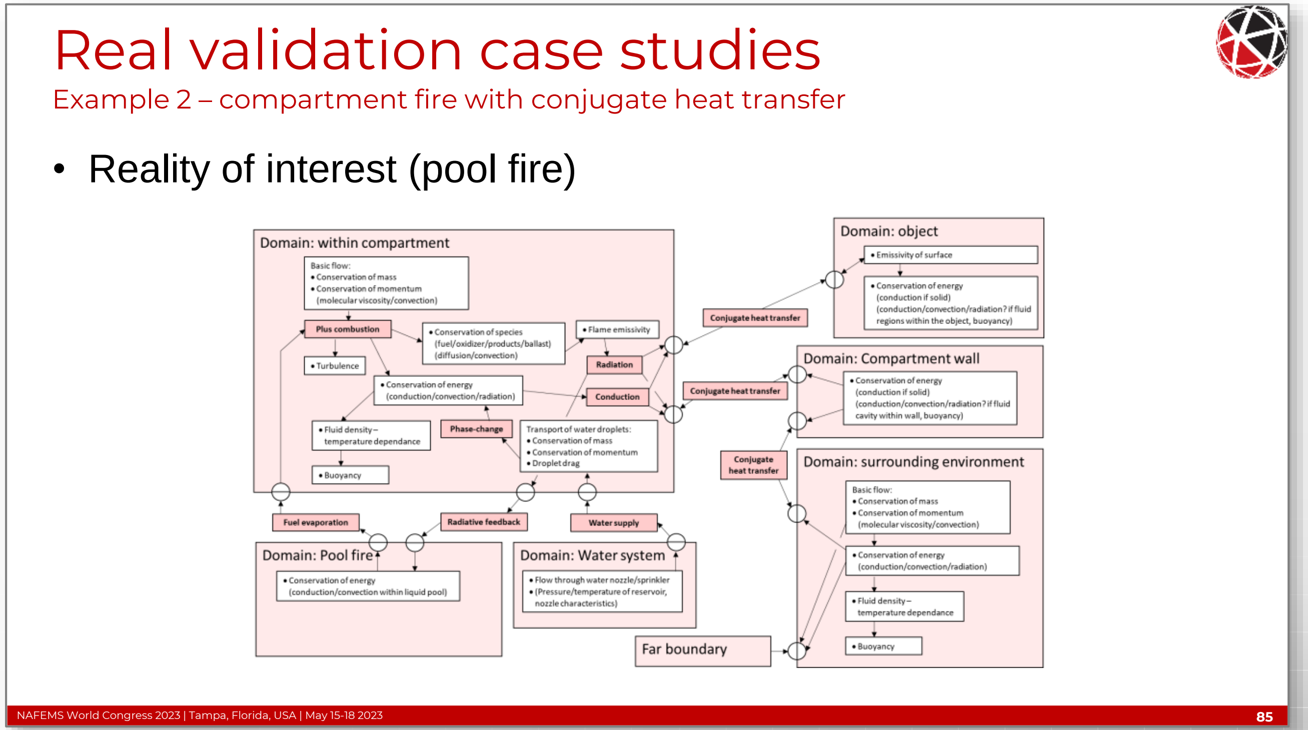

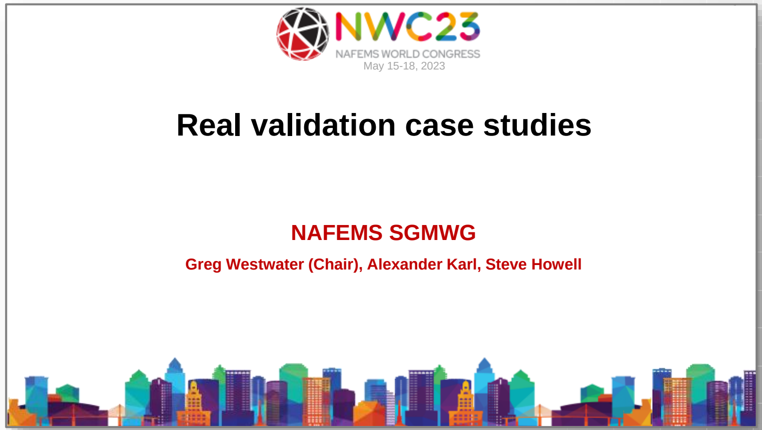

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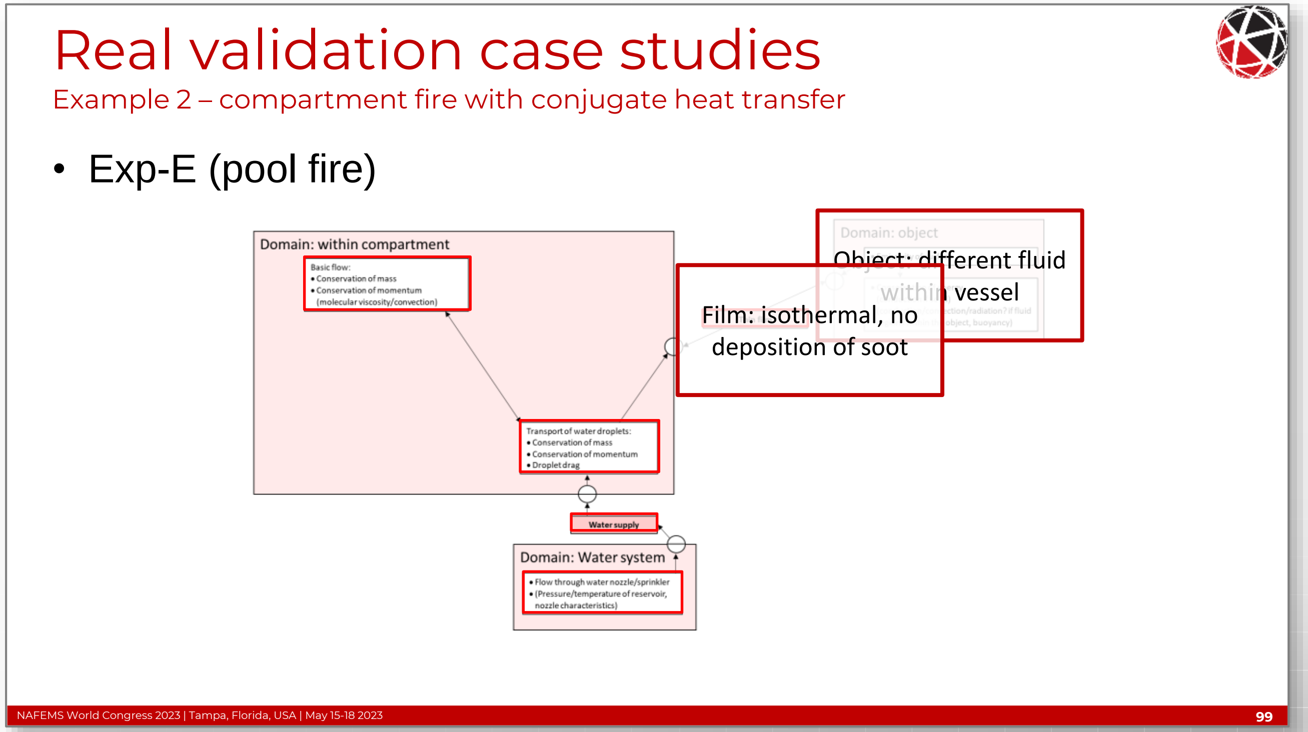

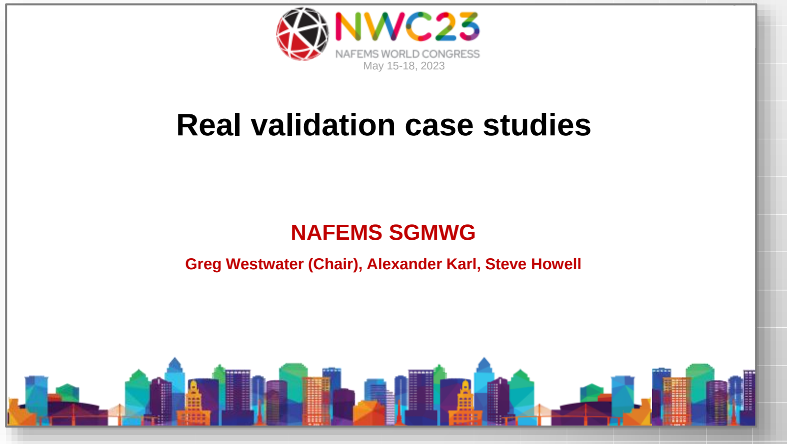

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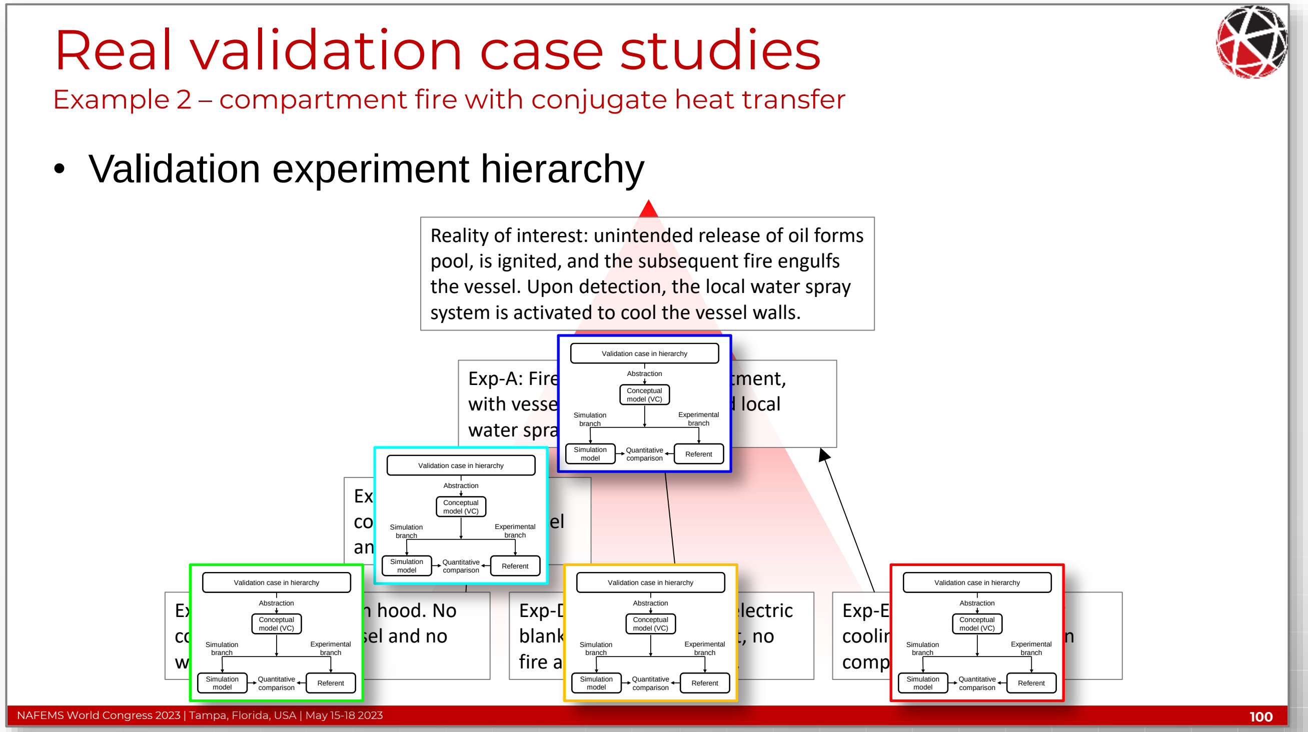

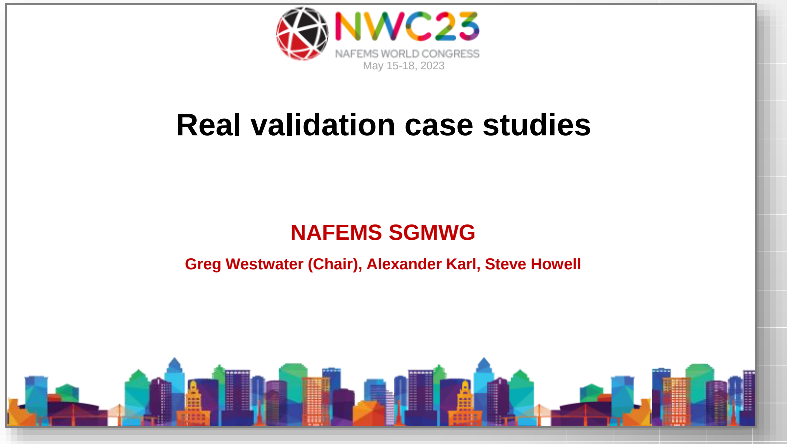

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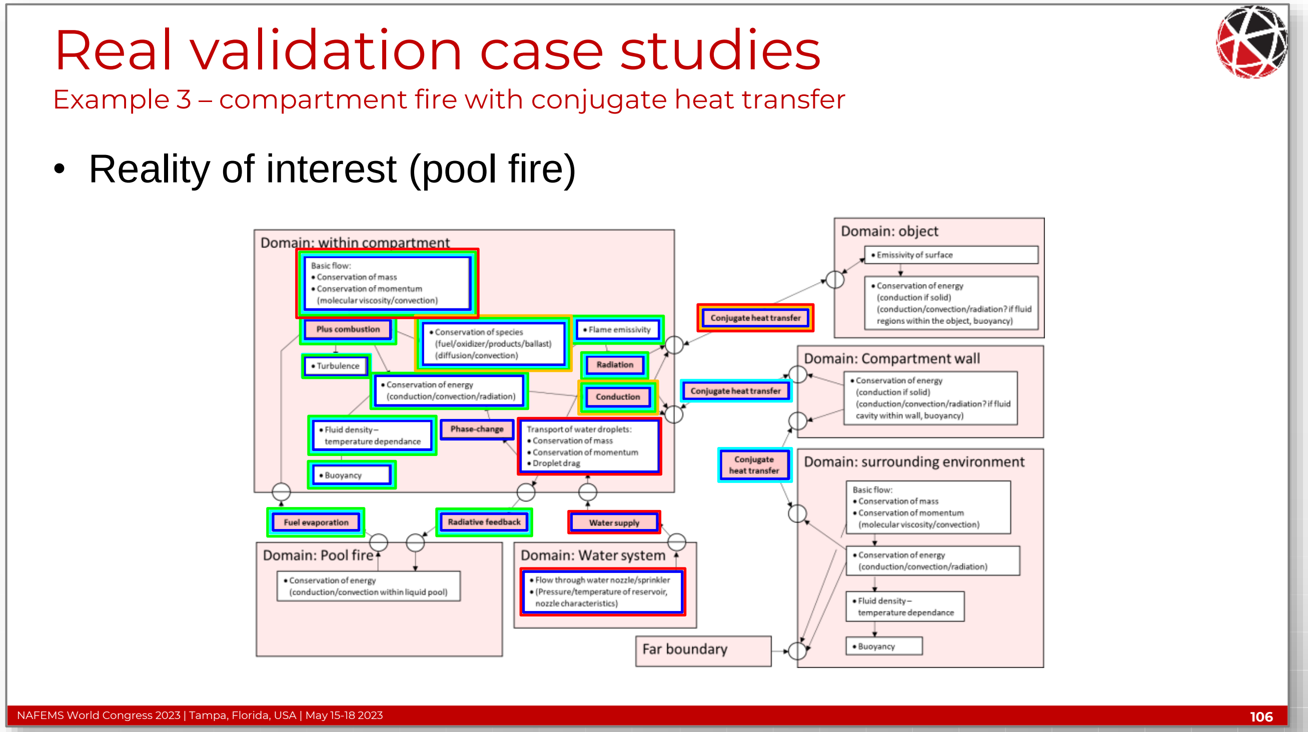
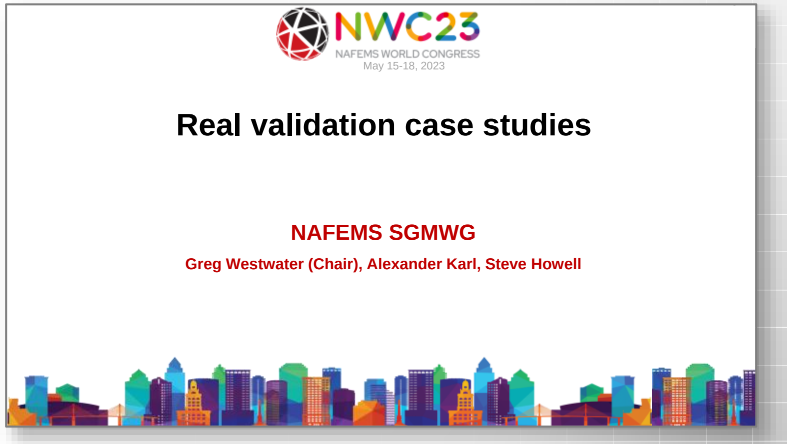
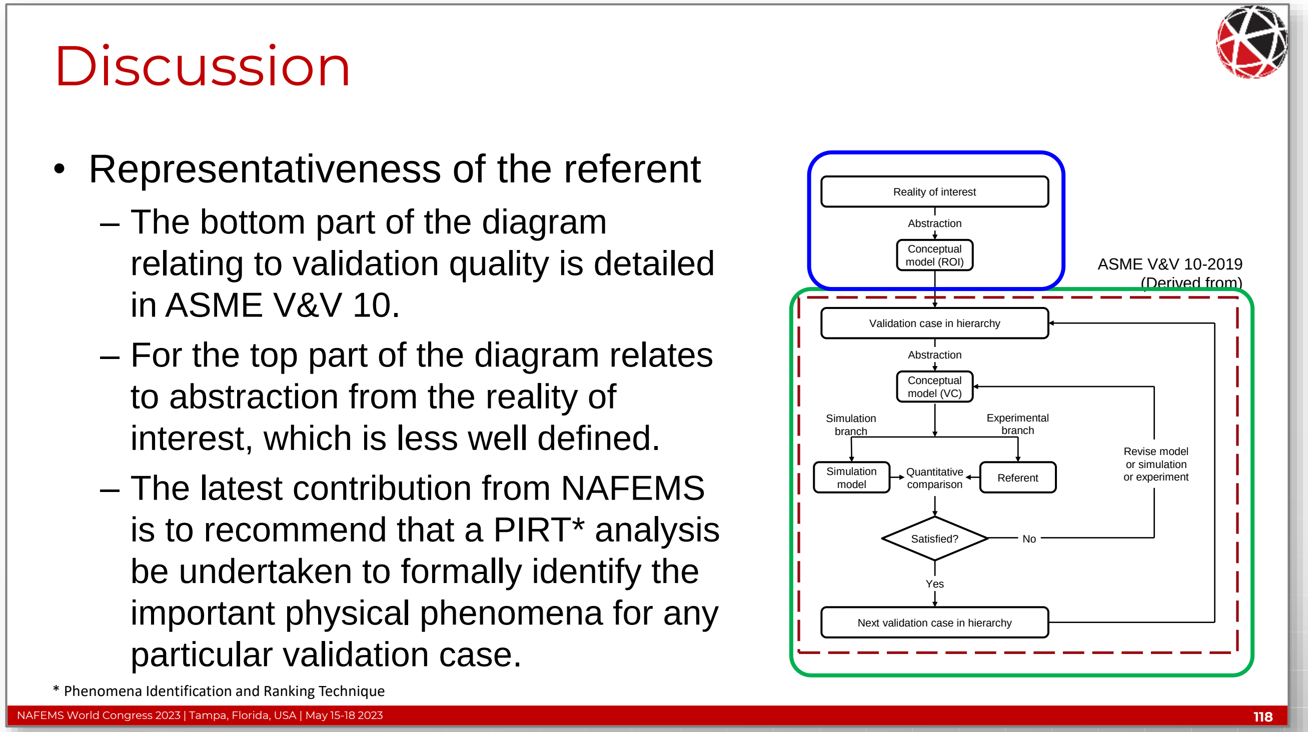


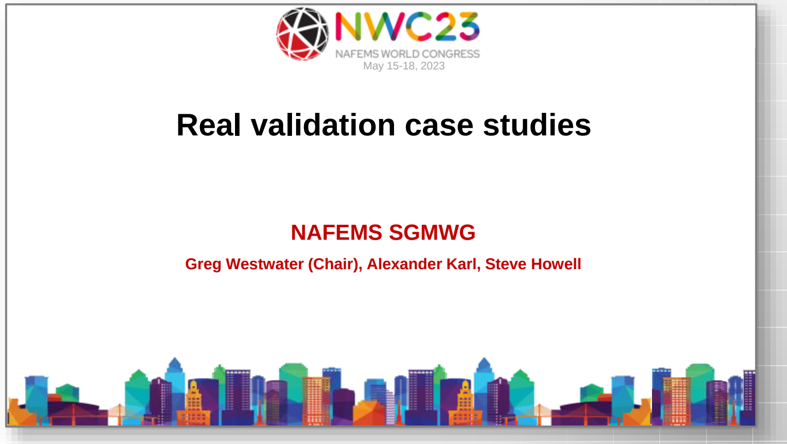


Confidence in simulation for certification

Understanding the physics

- Representativeness of the referent





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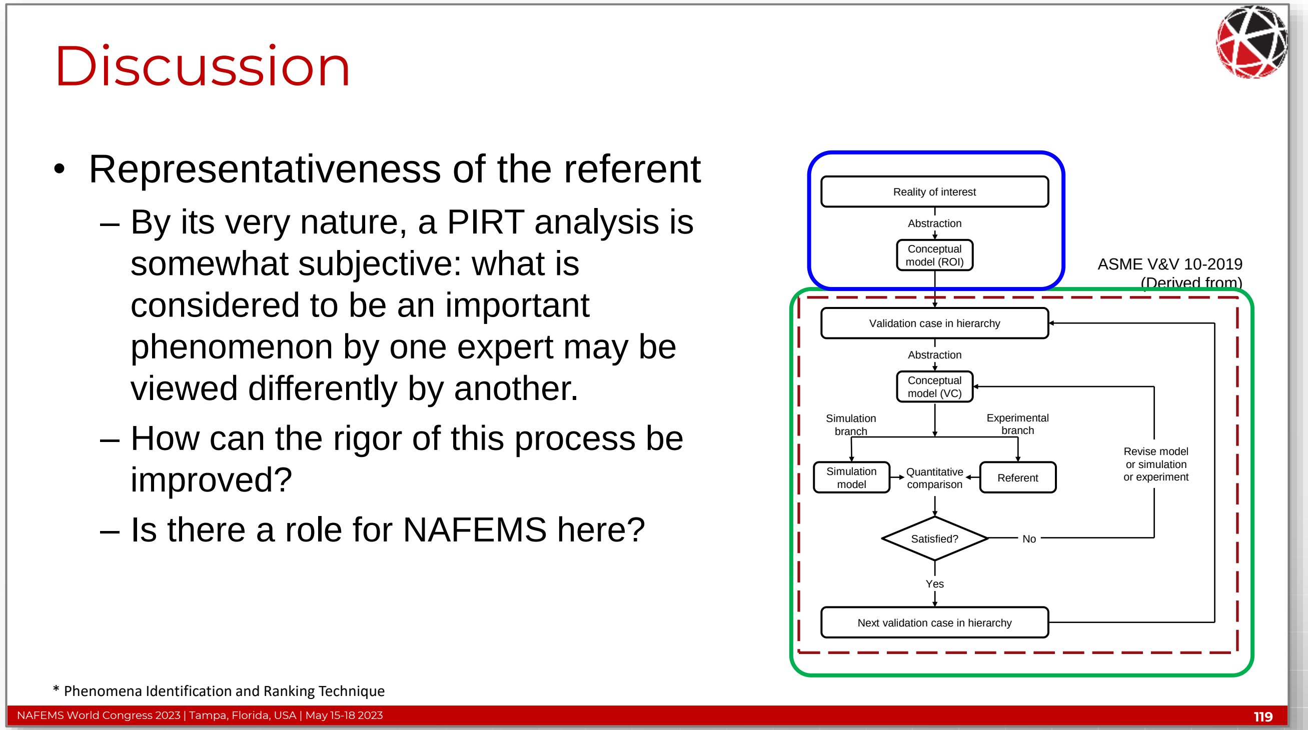

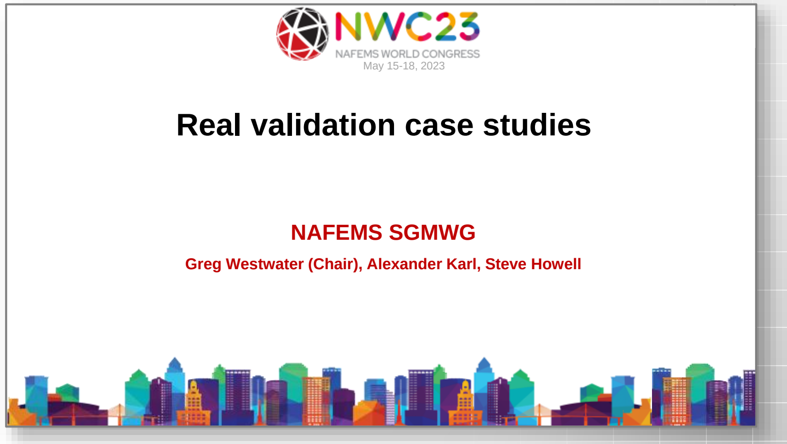

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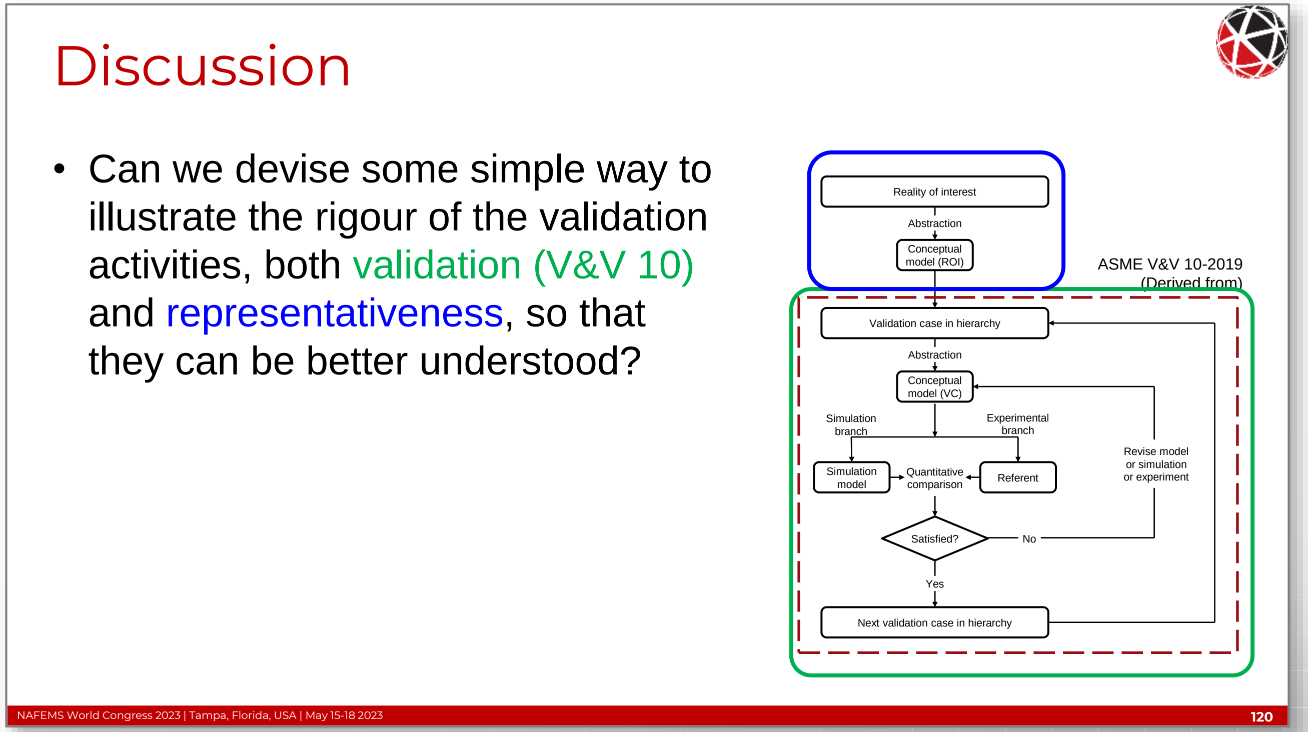

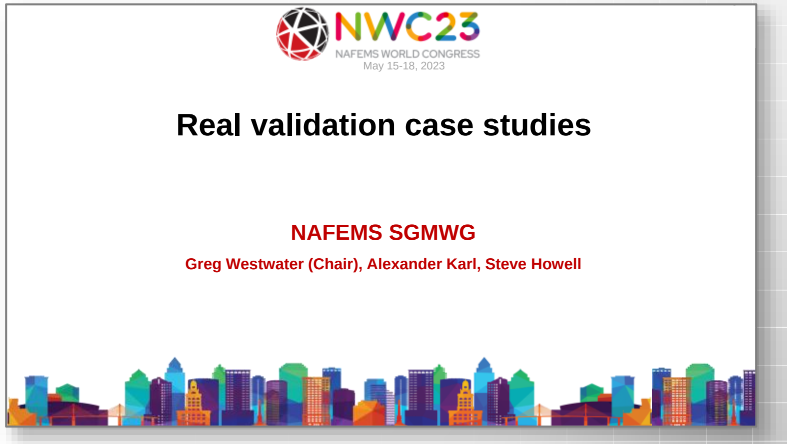

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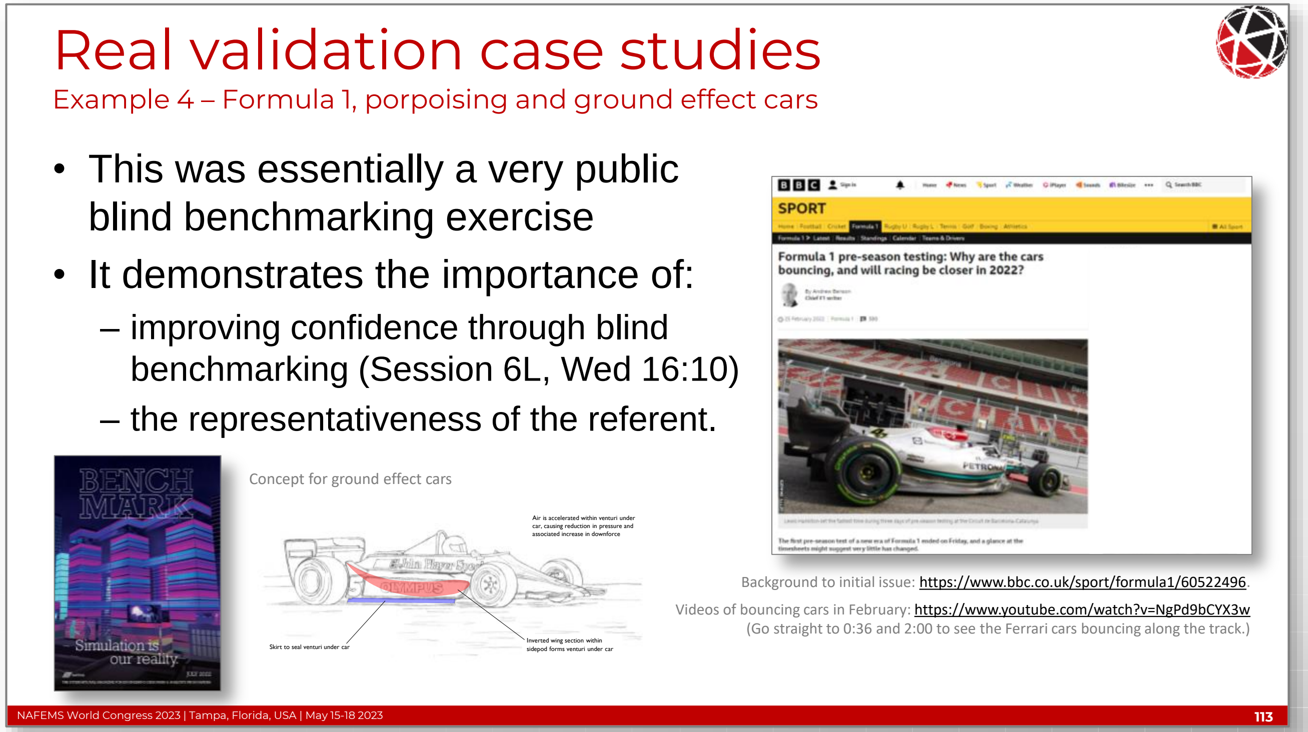

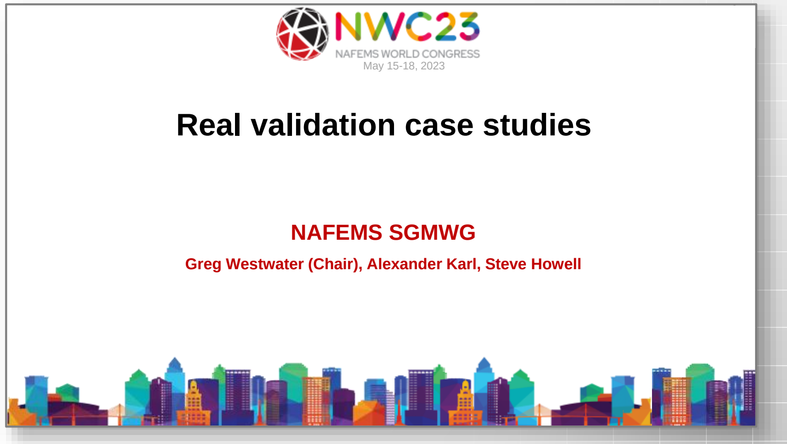

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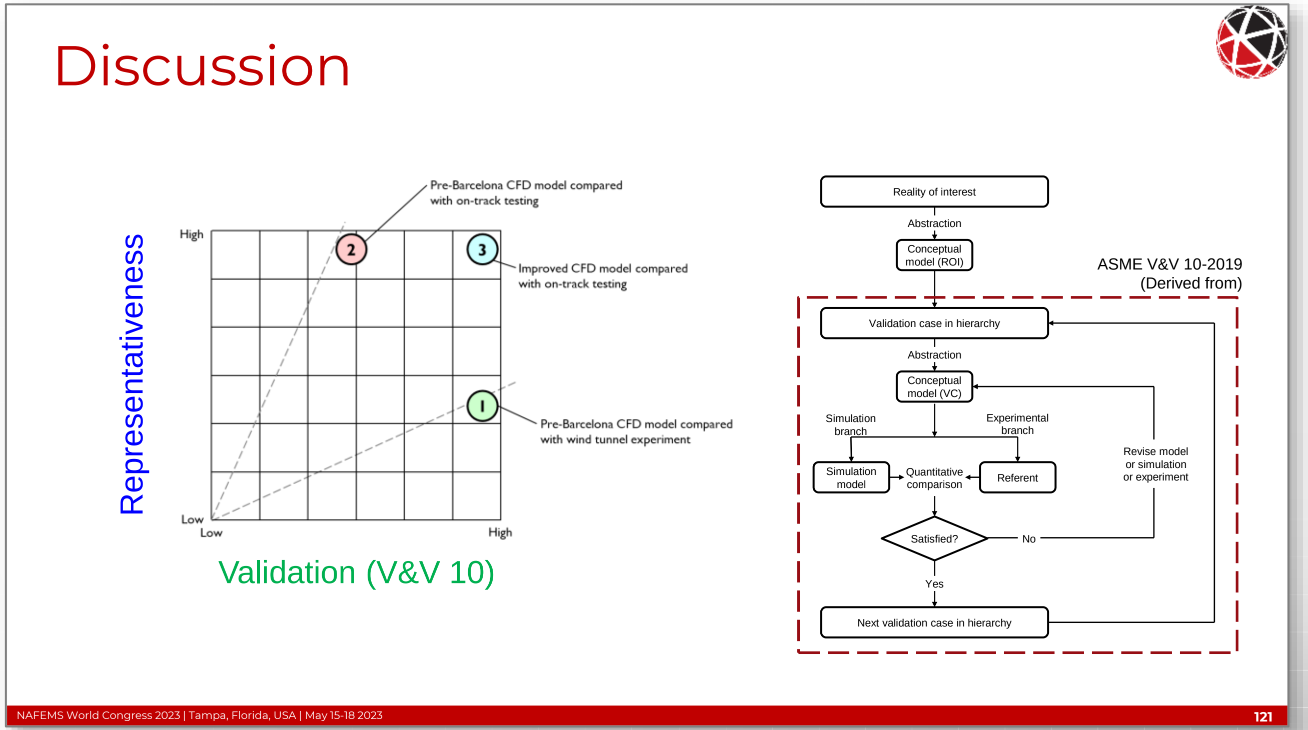

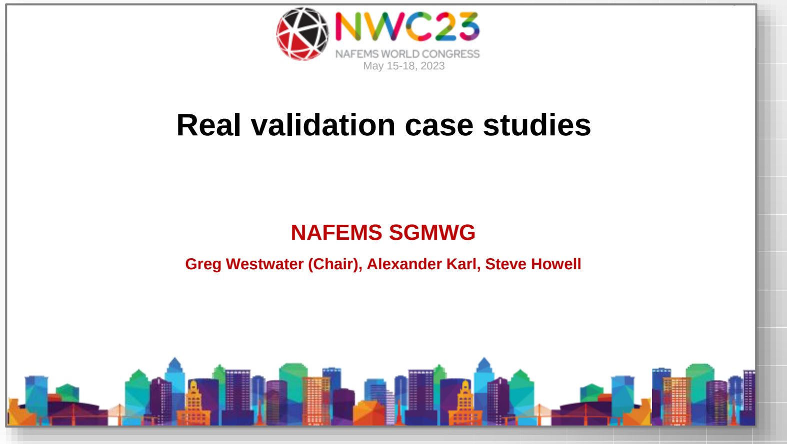

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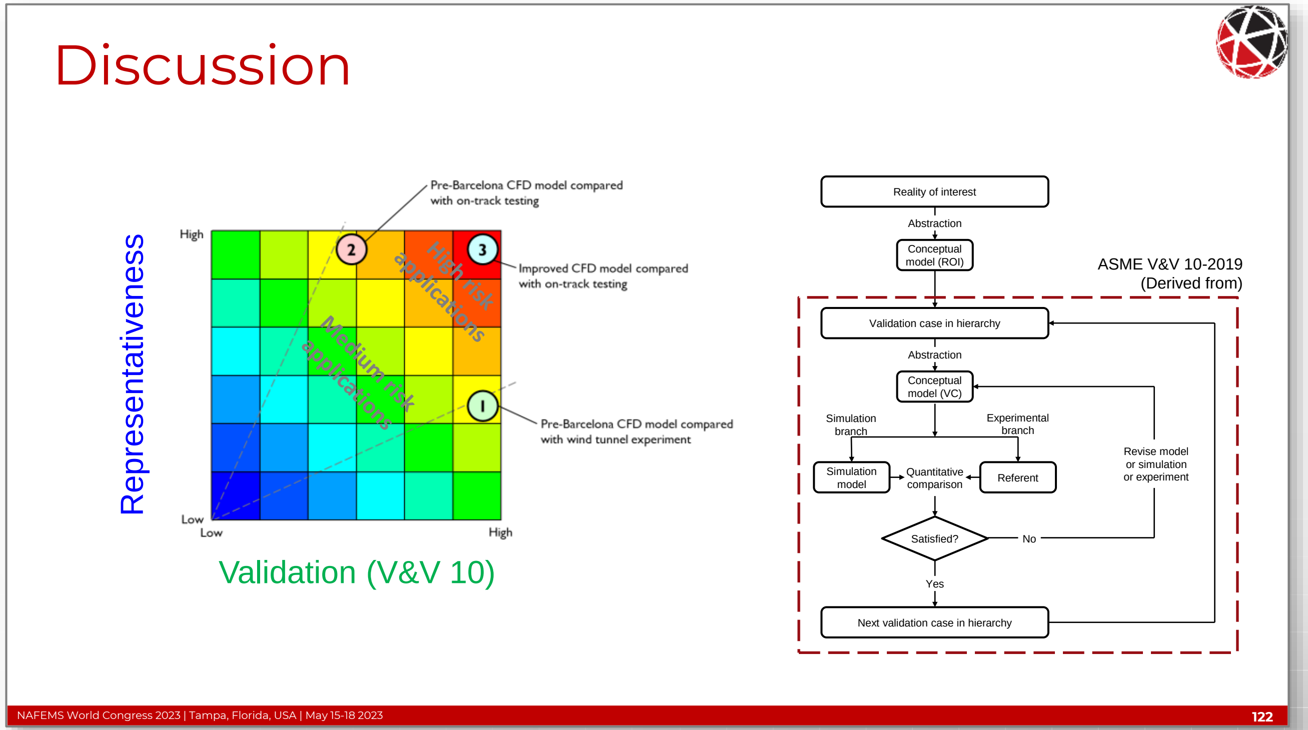

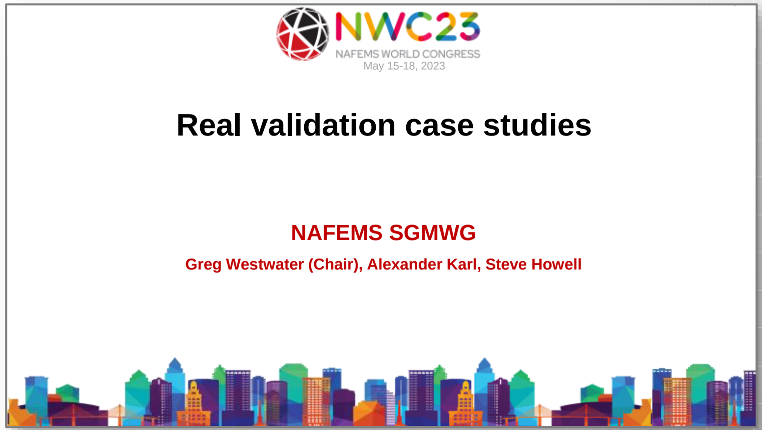

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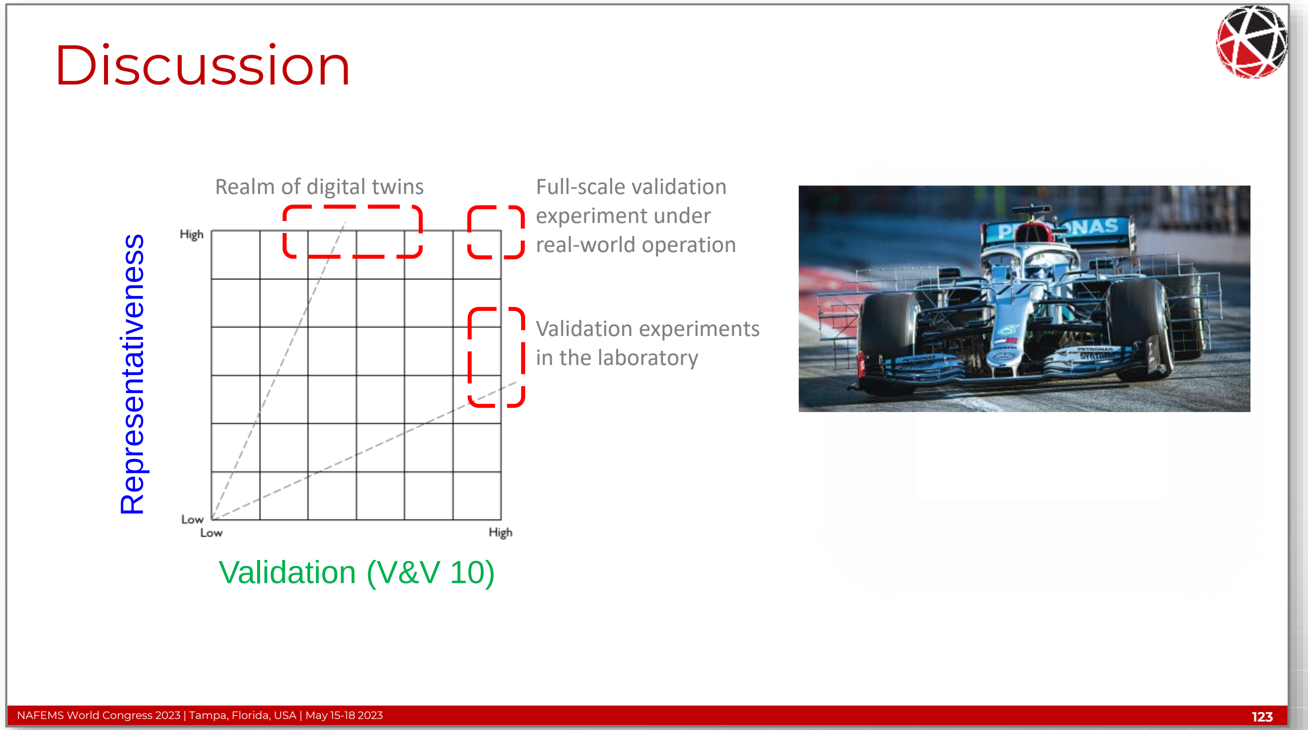
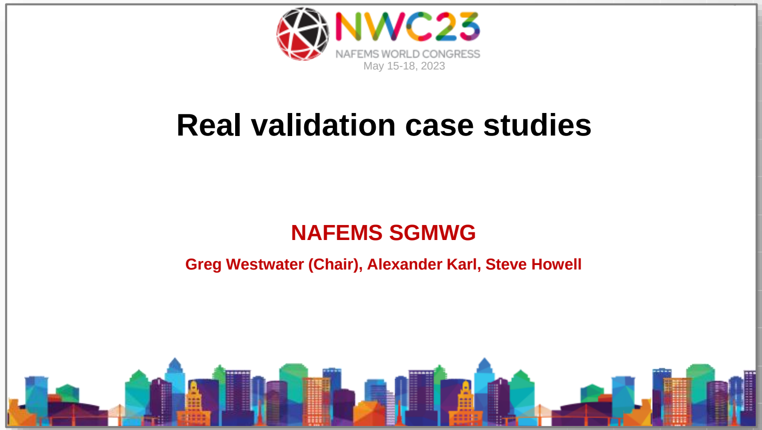




Confidence in simulation for certification

How can we achieve confidence in simulation for certification?

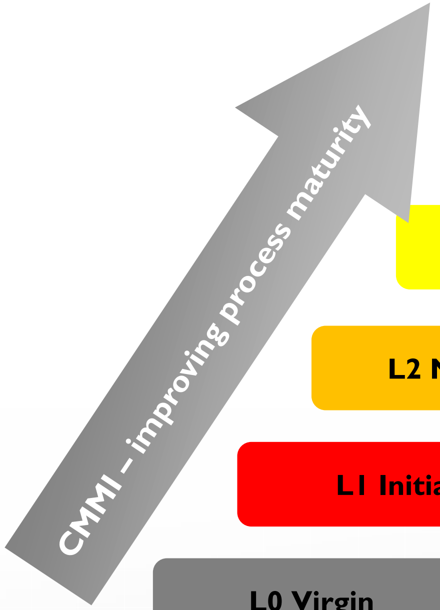
- Through rigorous verification and validation, capturing all relevant physics
  - This requires significant effort that should not be underestimated.

- For widespread adoption in industry:
  - Develop mature processes – embed best practice within a workflow approach.
  - Competence – training and accreditation for both CFD users and CFD codes/workflows.
  - Improve confidence in the CFD process through blind benchmarking.
  - How to interpret the CFD predictions – absolute or relative criteria.
  - Standard templates for certification using CFD.

Confidence in simulation for certification

How can we achieve confidence in simulation for certification?

Develop mature processes – embed best practice within a workflow approach



L5 Optimisation — Processes are continually improved through innovative and incremental technological improvements

L4 Quantitatively managed — Processes are measured and controlled, timing is predictable, quantitative quality goals are set and met

L3 Defined — Processes are well characterised and understood – specifications, peer-review, version control.

L2 Managed — Processes are planned, documented, performed, monitored and controlled at the project level. Often reactive.

L1 Initial — Processes are ad-hoc, success depends upon competencies and heroics of individual people. The person is responsible for the result.

L0 Virgin — Simulation deployed for the first time. Competencies, methods and processes need to be developed.

Capability maturity model integration (CMMI)

Confidence in simulation for certification

How can we achieve confidence in simulation for certification?

Blind benchmarking – NAFEMS SGMWG database of blind benchmarks

Examples of past blind benchmarking

[Jimwd-25] *Round-Robin Study of a-priori Modelling Prediction of the Dalmarnock Fire Test One*, G. Rein et al, Fire Safety Journal 44 (4), 590-602, 2009.
(Presentation to SGMWG/CFDWG, 27 February 2023)

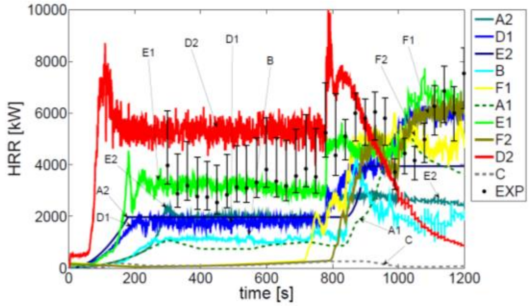


Figure 6: Evolution of the global heat release rate within the compartment. Legend for the different curves: continuous line for CFD simulations; dashed line for zone model simulations; and dotted for the experimental data with error bars.

Table 2: Comparison of simulated time to flashover and maximum average temperature in the smoke layer of the main compartment with experimental data.

Simulation	Time to Flashover[s]	Maximum Average Smoke Layer Temperature [°C]
A1	850	790
A2	290	500
B	840	690
C	no flashover	200
D1	200	720
D2	80	1150
E1	180	900
E2	180	610
F1	720	590
F2	850	720
Experimental	300	750

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The importance of blind benchmarking

NAFEMS SGMWG

Greg Westwater (Chair), Alexander Karl, Steve Howell, Jim Wood

Confidence in simulation for certification

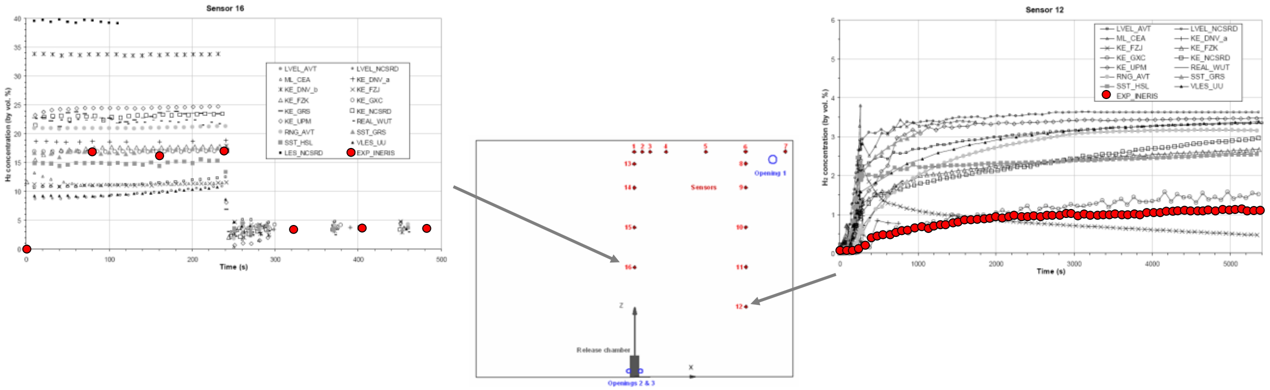
How can we achieve confidence in simulation for certification?

Blind benchmarking – NAFEMS SGMWG database of blind benchmarks

Examples of past blind benchmarking

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, (INERIS Garage release experiments)

Venetsanos AG et al, Intl J Hyd Ener, 34(14), 5912-23, 2009.



Hydrogen release, 1 g/s (4 minutes) in a 80 m^3 room

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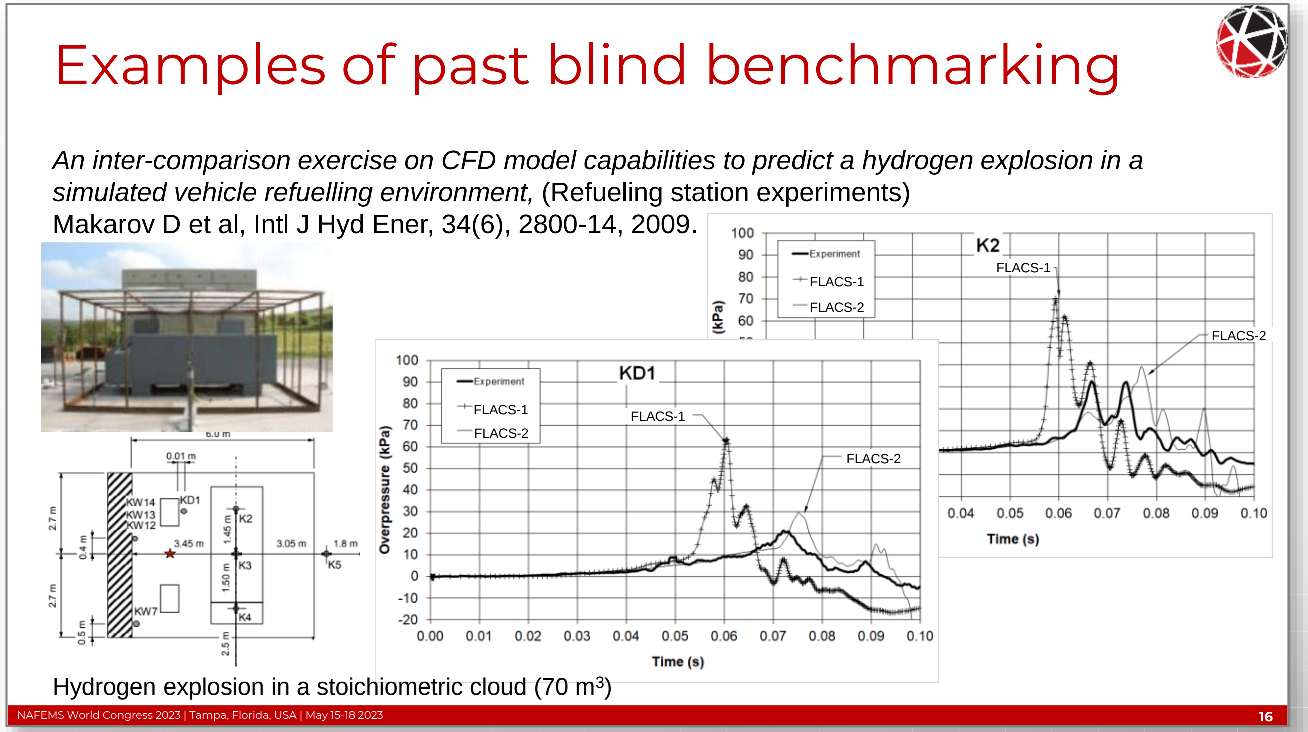

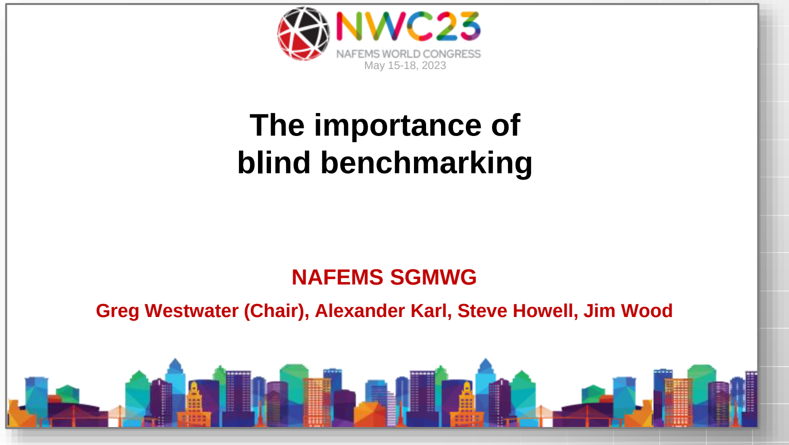

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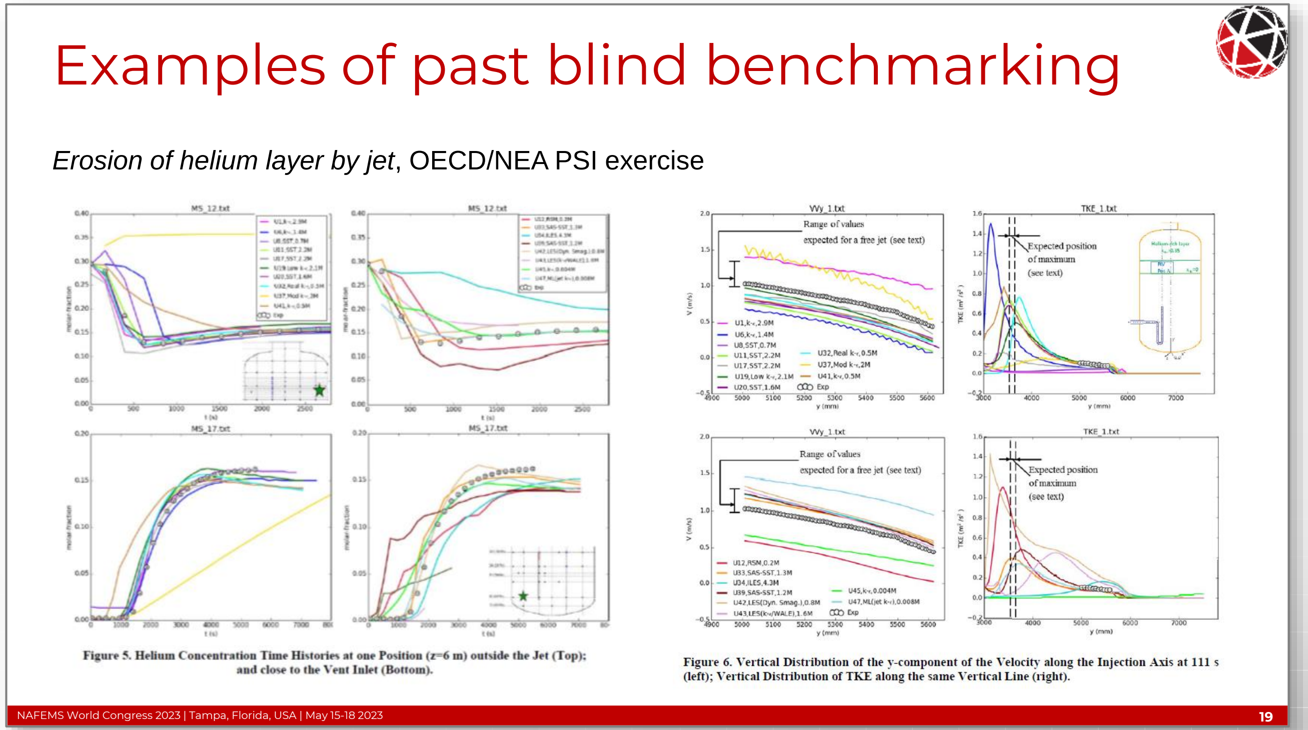

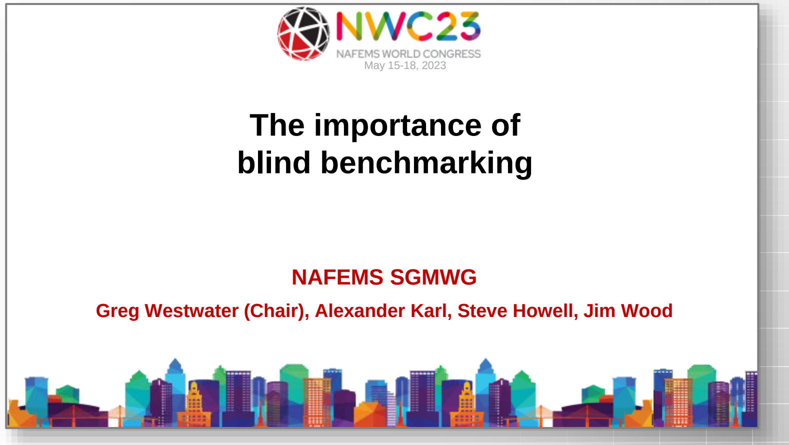

Summary

- The use of engineering simulation is becoming ever more popular:
  - Digital twins
  - Machine learning
  - Simulation for certification.
- We need to remember that a simulation prediction is only as good as the verification and validation activities that underpin it.
- In the offshore industry, CFD has been widely used to support the safety case approach since the 1990s, and there are clear lessons to be learned…
- … **confidence in simulation can be eroded if there is inconsistency between parties – in some regions, this has precipitated a shift away from engineering simulation for certification**

Summary

- How can we achieve confidence in simulation for certification?
  - Through rigorous verification and validation, capturing all relevant physics
  - This requires significant effort that should not be underestimated.

- The following recommendations should be considered:
  - Develop mature processes – embed best practice within a workflow approach.
  - Competence – training and accreditation for both CFD users and CFD codes/workflows.
  - Improve confidence in the CFD process through blind benchmarking.
  - How to interpret the CFD predictions – absolute or relative criteria.
  - Standard templates for certification using CFD.

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Summary

- A simulation prediction is only as good as the verification and validation activities that underpin it:
  - This is becoming more important than ever with the emergence of machine learning tools where predictions may not depend upon physics-based models.
  - If there are important physics missing from the physical experiment, the outcomes of a simulation model and physical validation experiment can agree very well with each other, but not necessarily with the reality of interest.
  - Simulation tools should not be used as *out-of-the-box* solutions. It is not possible to validate a simulation code alone, it is the combination of code plus user, or code plus workflow that must be validated.
  - To have confidence in simulation predictions requires the V&V 10 diagram to be considered in its entirety – **this is the responsibility of the user of the simulation code, not the code developer, and it represents a significant investment of effort**.

Contact us

Enquiries can be directed to:
steve.howell@abercus.com
www.abercus.com