4th International Conference on Hydrogen Safety
12-14 September 2011, San Francisco

Introduction to Hydrogen Safety Engineering

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- Basic process of hydrogen safety engineering (HSE)
- Main three steps of HSE:
  - Qualitative design review (QDR)
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  - Assessment against acceptance criteria
- Benefits of HSE
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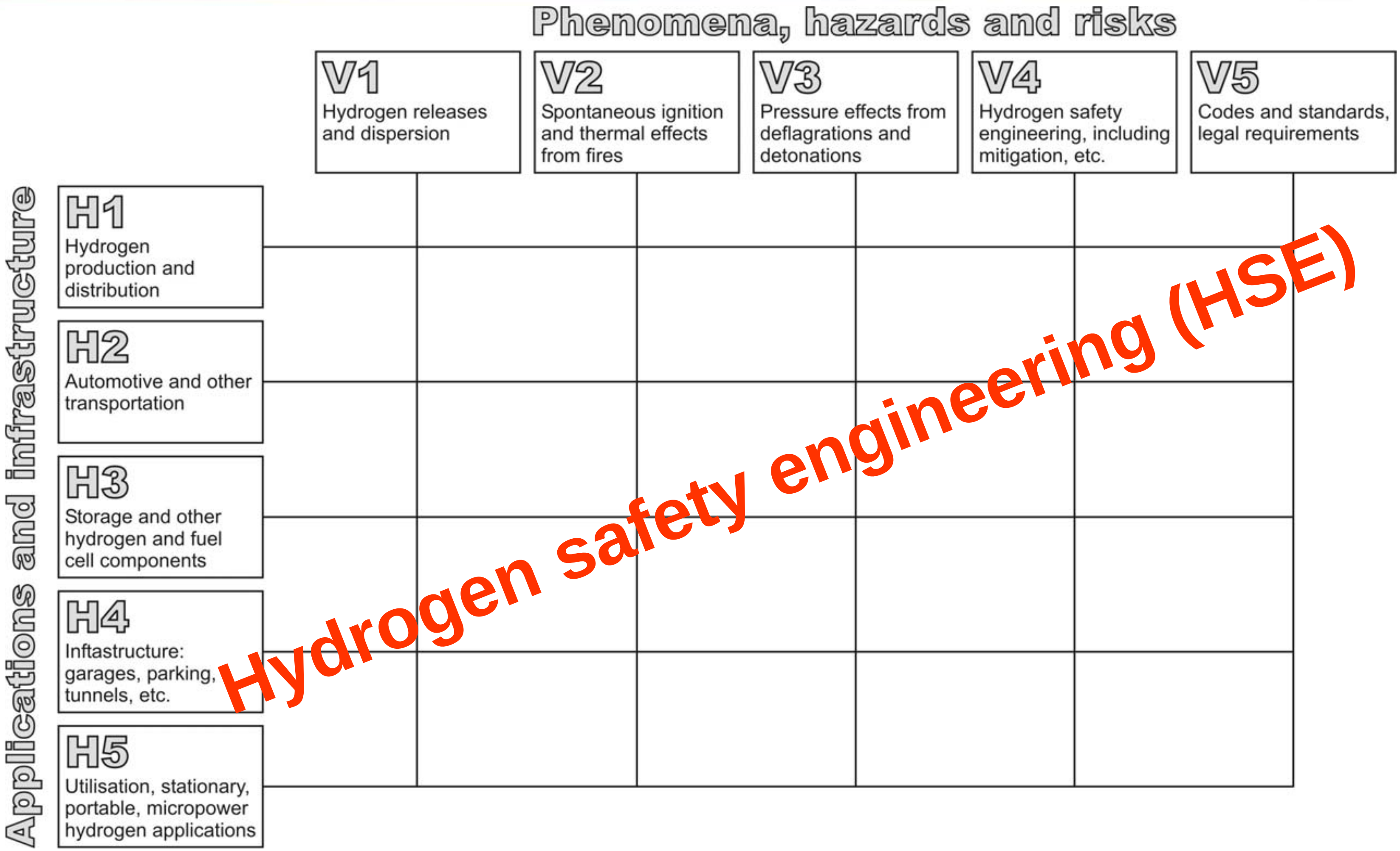
Definition

- The viability and public acceptance of the hydrogen and fuel cell systems depend on their robust safety engineering design, education and training of the workforce (*P* up to 1000 bar and *T* down to -253^{o}C). This can be provided only through **building up and maturity of the hydrogen safety engineering (HSE) profession**.
- Design for hydrogen safety should be treated as an **engineering responsibility rather than as a matter for detailed regulatory control**; designers should develop a greater understanding of hydrogen safety.
- **Hydrogen safety engineering (HSE)** is the application of **scientific and engineering principles** to the protection of life, property and environment from adverse effects of accidents involving hydrogen.

Scope



Phenomena, hazards and risks

V1 Hydrogen releases and dispersion

V2 Spontaneous ignition and thermal effects from fires

V3 Pressure effects from deflagrations and detonations

V4 Hydrogen safety engineering, including mitigation, etc.

V5 Codes and standards, legal requirements

Applications and infrastructure

H1 Hydrogen production and distribution

H2 Automotive and other transportation

H3 Storage and other hydrogen and fuel cell components

H4 Inftastructure: garages, parking, tunnels, etc.

H5 Utilisation, stationary, portable, micropower hydrogen applications

Hydrogen safety engineering (HSE)

The HySafe activity matrix

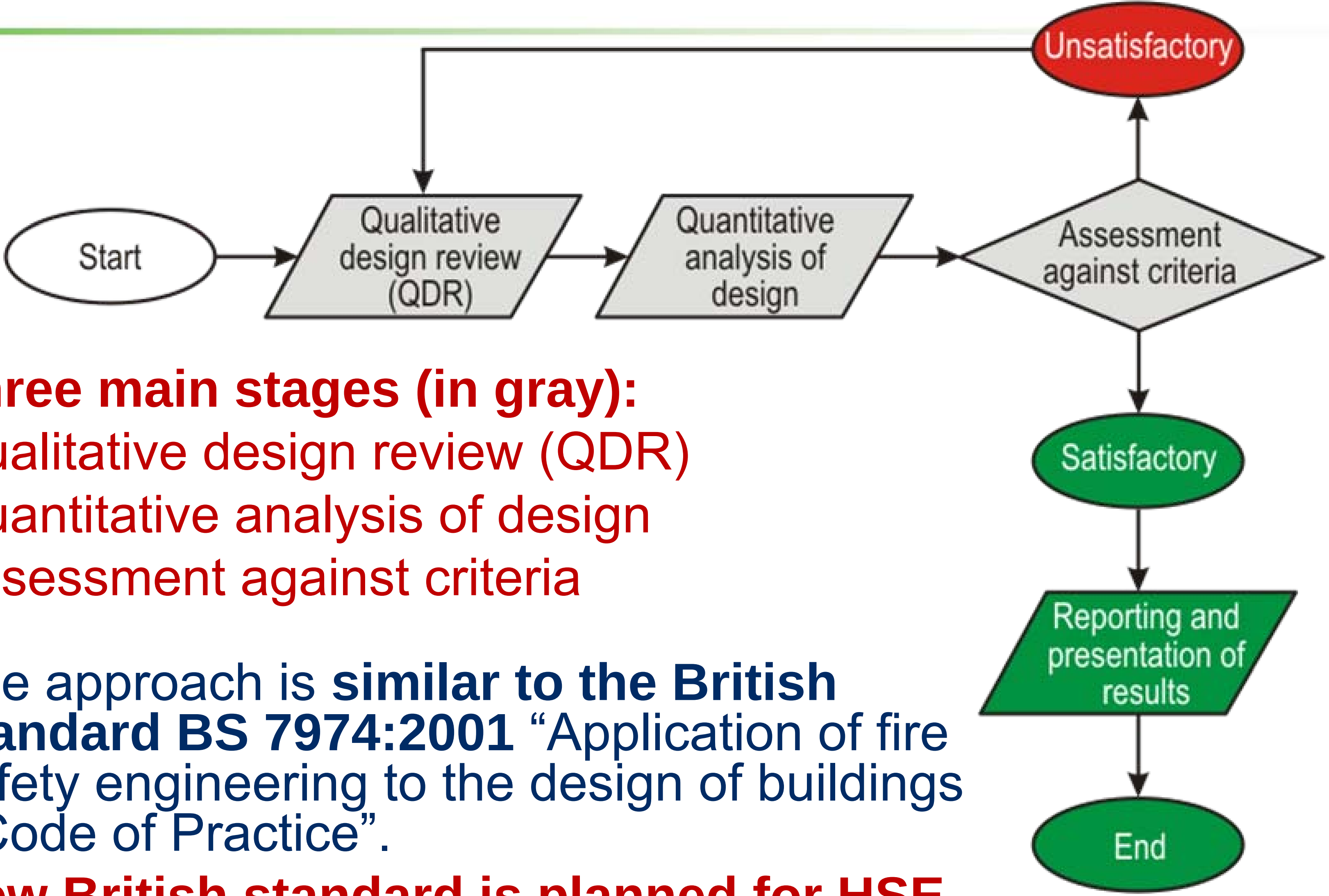
Glossary (extraction)

- **Accident:** an unforeseen and unplanned event or circumstance
- **Hazard:** chemical or physical condition that has the potential for causing damage to people, property and the environment
- **Consequences:** expected effects from the realisation of the hazard and severity, usually measured in terms of life safety exposure, property damage and environmental impact
- **Risk:** combination of the probability of an event and its consequence
- **Deterministic study:** methodology, based on physical relationships derived from scientific theories and empirical results that, for a given set of initial conditions, will always produce the same outcome
- **Probabilistic study:** systematic development of numerical estimates of the expected frequency and/or consequence of potential accidents

Deterministic vs probabilistic

- Probabilistic risk assessment require statistical data. Emerging technologies can hardly be characterised by representative statistical data. Probabilistic methods only complements not substitutes professional safety engineering design.
- Risk-informed methods are not always easy to understand. There are still debates in hydrogen safety community on aspects and interpretations of risk-informed approaches and uncertainty of their predictions.
- The public is keen to know that all possible has been done to make HFC applications safe rather than be simply satisfied that the probability of death is 10^{-4} or 10^{-6} or 10^{-8} (court issue!).
- Potential problem – research resources can be diverted away from solving real engineering problems to development risk theories, whose uncertainties are questionable.

Basic process



Three main stages (in gray):

- Qualitative design review (QDR)
- Quantitative analysis of design
- Assessment against criteria

The approach is **similar to the British standard BS 7974:2001** “Application of fire safety engineering to the design of buildings - Code of Practice”.

New British standard is planned for HSE

Three main stages

- **Qualitative design review (QDR).** A QDR team (see later) carries out: review of design; definition of safety objectives; analysis of hazards and consequences; establishment of ***trial safety designs***; definition of ***acceptance criteria***, ***scenarios*** to study. Key information is compiled to evaluate trial design in the quantitative analysis.
- **Quantitative analysis.** Engineering methods and tools are used to ***evaluate the trial safety designs*** identified in QDR following scenario(s). Quantitative analysis can be time-based analysis using appropriate sub-system guidelines to give numerical values of the impact of accident on people, property and environment.
- **Assessment against acceptance criteria.** The output of the quantitative analysis is ***compared against the acceptance criteria*** identified in QDR. If the safety performance of a hydrogen system does not match acceptance criteria, the design is unsatisfactory and the objectives are not fulfilled it is necessary to restart a new study from QDR stage.

Glossary (continued)

- ***Trial safety design:*** package of hydrogen safety measures which in the context of the system and/or infrastructure *may* meet the specified safety objectives
- ***Acceptance criteria:*** term of reference against which the performance of a design is assessed
- ***Scenario:*** set of circumstances, chosen as an example, that defines the development of accident

- ***Separation distance (to be used later in presentation):*** the minimum separation between a hazard source and an object (human, structure, etc.) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident

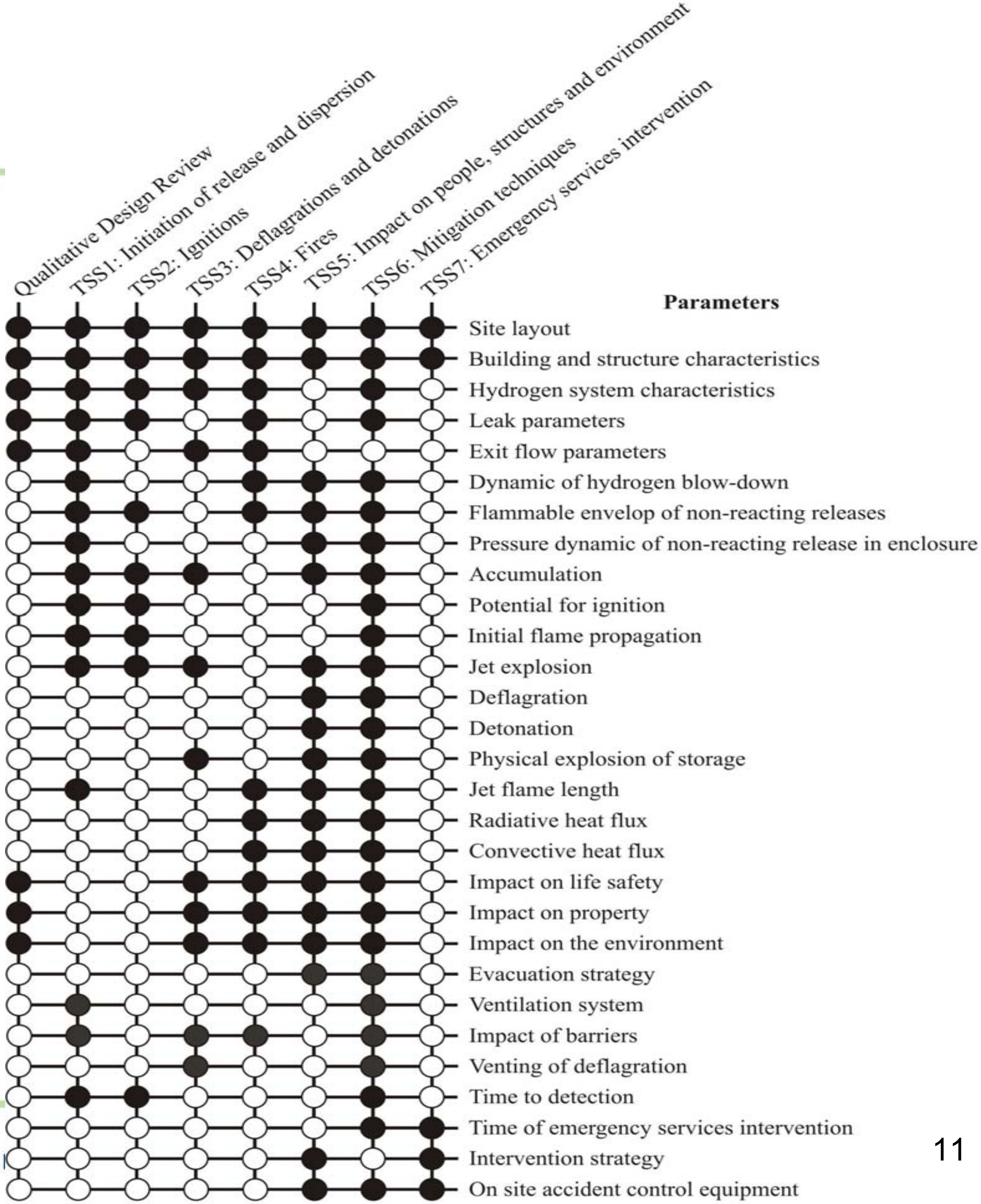
Sub-systems and guides

To simplify the evaluation of hydrogen safety design, the process is broken down into Technical Sub-Systems (TSS):

- TSS1: Initiation of release and dispersion
- TSS2: Ignitions
- TSS3: Deflagrations, detonations, blast waves
- TSS4: Fires
- TSS5: Impact on people, structures and environment
- TSS6: Mitigation techniques
- TSS7: Emergency service intervention
- Plus "*Guide to* design framework and hydrogen safety engineering procedures"
- Plus "*Guide on* probabilistic hydrogen risk assessment"

Description of TSS is out of the scope of this presentation (examples)

Interaction of TSS (example)



Parameters	Qualitative Design Review	TSS1: Initiation of release and dispersion	TSS2: Ignitions	TSS3: Deflagrations and detonations	TSS4: Fires	TSS5: Impact on people, structures and environment	TSS6: Mitigation techniques	TSS7: Emergency services intervention
Site layout	●	●	●	●	●	●	●	●
Building and structure characteristics	●	●	●	●	●	●	●	●
Hydrogen system characteristics	●	●	●	●	●	○	●	○
Leak parameters	●	●	●	○	●	○	●	○
Exit flow parameters	●	●	○	●	●	○	○	○
Dynamic of hydrogen blow-down	○	●	○	○	●	●	●	○
Flammable envelop of non-reacting releases	○	●	●	○	●	●	●	○
Pressure dynamic of non-reacting release in enclosure	○	●	○	○	○	●	●	○
Accumulation	○	●	●	●	○	●	●	○
Potential for ignition	○	●	●	○	○	○	●	○
Initial flame propagation	○	●	●	○	○	○	●	○
Jet explosion	○	●	●	●	○	●	●	○
Deflagration	○	○	○	○	○	●	●	○
Detonation	○	○	○	○	○	●	●	○
Physical explosion of storage	○	○	○	●	○	●	●	○
Jet flame length	○	●	○	○	●	●	●	○
Radiative heat flux	○	○	○	○	●	●	●	○
Convective heat flux	○	○	○	○	●	●	●	○
Impact on life safety	●	○	○	●	●	●	●	○
Impact on property	●	○	○	●	●	●	●	○
Impact on the environment	●	○	○	●	●	●	●	○
Evacuation strategy	○	○	○	○	○	●	●	○
Ventilation system	○	●	○	○	○	○	●	○
Impact of barriers	○	●	○	●	●	○	●	○
Venting of deflagration	○	○	○	●	○	○	●	○
Time to detection	○	●	●	○	○	○	●	○
Time of emergency services intervention	○	○	○	○	○	○	●	●
Intervention strategy	○	○	○	○	○	●	○	●
On site accident control equipment	○	○	○	○	○	●	●	●

QDR: steps

- The Qualitative Design Review (QDR), a ***qualitative process*** that draws upon the ***experience and knowledge*** of ***the team members*** *(owner, approval bodies, insurer, emergency services, and owners of any occupancy in the vicinity of the infrastructure, etc.)*.
- Ideally, the QDR should be carried out ***early in the design*** process.
- ***The following steps*** should be taken during QDR:
  a) review technical characteristics of the system or infrastructure, site layout and management;
  b) establish safety objectives;
  c) identify hazards and possible consequences;
  d) establish trial safety designs;
  e) identify acceptance criteria and methods of analysis;
  f) establish accident scenarios for analysis.

QDR: safety objectives

The main ***hydrogen safety objectives*** that may be addressed are (list is not exhaustive; not all items may be appropriate to a particular study):

a) life safety;
b) loss control; and
c) environmental protection.

The main ***life safety objectives*** may include provisions to ensure that:

- The occupants are able ultimately to leave the scene of the accident in reasonable safety *or the risk* to occupants is acceptably low;
- Emergency service are able to operate in reasonable safety;
- Structure collapse does not endanger people (including first responders) who are likely to be near the scene.

QDR: acceptance criteria[1]

- **Acceptance criteria**: term of reference against which the performance of a design is assessed (BS 7974:2001)
- Acceptance criteria may include the definition of value for: number of specific valuable objects that are acceptable to damage; maximum zone of direct damage due to hydrogen release, fire and/or explosion; maximum time periods for recovery from an accident, etc.
- Damages caused by hydrogen accident can be evaluated by taking into account critical values that causes irreversible damages (overpressure, impulse, radiative heat flux, etc.). These acceptance criteria should be adequately chosen by the QDR team and hydrogen safety engineer, depending on particularities of a case.

QDR: acceptance criteria^2

- ***Criteria*** should be identified which can be used to assess that ***the requirements of legislation have been satisfied***. The quality of hydrogen safety provisions will directly depend on availability of overall performance-based HSE methodology rather than a group of codes and standards. The HSE design has to be in compliance with legislation.
- ***The following methods*** (one or more) can be used to determine compliance to acceptance criteria against which established designs will be assessed:
  a) deterministic, b) probabilistic, c) comparative, d) financial

For deterministic study the objective is to show that on the basis of the initial assumptions (scenarios), a ***defined set of conditions will not occur***. Generally, ***life safety criteria*** should be set to ensure that a safety solution offers at least the same level of safety as similar exiting technologies.

QDR: acceptance criteria[3]

- ***For probabilistic studies*** the objective is usually to show that ***the likelihood of a given event occurring*** (e.g. injury, death, large life loss, large property loss and environmental damage) is acceptably or tolerably small. ***A full probabilistic study*** is only likely to be justified when a ***substantially new approach*** to infrastructure design or hydrogen safety practice is being adopted.
- ***For comparative studies*** the objective is to demonstrate that the infrastructure, as designed, presents ***no greater safety issues*** to the occupants than a similar infrastructure complying with a ***well established RCS***. In many projects it is likely that the provisions of existing codes of practice and other guidance will be largely followed and that hydrogen safety engineering techniques will not be necessary, or may be used ***only to justify limited departures*** from the codes.

QDR: methods of analysis

- ***The QDR team*** should determine the ***depth and scope of quantification*** required and identify appropriate ***methods of analysis***.
- The ***QDR study may remove the need*** for further detailed analysis where, for instance, the qualitative study has shown a level of safety which is equal to that in prescriptive codes and guidance documents.
- ***The following types of methods of analysis*** can be recommended by the ***QDR team***:
  - *a) simple calculations;*
  - *b) a computer-based deterministic analysis;*
  - *c) a simple probabilistic study* ***(example - risk of hydrogen-fuelled car in a garage: about 5k garage fires annually, different consequences).***

QDR: scenarios

- The detailed analysis and quantification of accident scenarios should be ***limited to the most significant*** or ***worst-credible*** scenarios.
- ***The QDR team*** should establish the ***important scenarios to analyze*** and those that ***do not require analysis***. Events with a very low probability of occurrence should not be analyzed ***unless their outcome is potentially catastrophic*** and a ***reasonably practicable remedy is available***.
- The identified scenarios should be described ***in a manner suitable for the quantification process***.

Document outputs of QDR

- The QDR team should provide ***a document*** with a set of qualitative outputs to be used in the quantitative analysis:
  - *results of the architectural and system review;*
  - *hydrogen safety objectives;*
  - *significant hazards and associated phenomena;*
  - *one or more trial designs;*
  - *acceptance criteria; and*
  - *specifications of the accident scenarios for analysis;*
  - *suggested methods of quantitative analysis*.
- Following QDR the team should decide ***which trial design(s) is likely to be optimum***.

The team should then ***decide whether quantitative analysis is necessary*** to demonstrate that the design meets the hydrogen safety objective(s).

- Data and assumptions of QDR should be ***transparent.***

Quantitative analysis (1/3)

- Following the QDR a ***quantitative analysis*** should be carried out, which ***should be split into a number of separate parts***, referred to as technical sub-systems (TSS).
- ***The technical sub-systems*** are intended to provide ***guidance on the type of calculations*** that may be carried out in support of a study.
- The technical sub-systems ***may each be used in isolation*** when analyzing a particular aspect of design ***or all may be used together*** as part of an overall hydrogen safety engineering evaluation of a system and/or infrastructure.

Quantitative analysis (2/3)

- The various aspects of the analysis (or in effect each TSS) ***may be quantified by either***:
  - deterministic studies; or
  - probabilistic risk assessment.

<u>Deterministic procedures</u>

- It quantifies ***accident development***, including dispersion of released hydrogen and its combustion when appropriate, ***and the consequences*** of these for the system and its occupants. A deterministic analysis involves the evaluation of a set of circumstances that will ***provide a single outcome***, i.e. the ***design will either be successful or not***.
- The interaction with people can give rise to ***a very complex system***. To evaluate safety by deterministic calculations some ***conservative simplifications should be made.***

Quantitative analysis (3/3)

Probabilistic design procedures

- The desired level of safety can be determined by making ***comparative judgments*** using currently ***available statistics as a reference point***.
- The risk associated with hydrogen accident takes into account the ***likelihood*** of unwanted release occurring and their ***potential consequences***, e.g. the potential number of deaths and extent of property loss.
- The probabilistic risk assessment ***should be preceded by the QDR*** for two main reasons:

  a) to ensure that the problem is fully understood and that the analysis addresses the relevant aspects of the safety system;

  b) to simplify the problem and reduce as far as possible the calculational effort required (applicable to deterministic procedures too).

Assessment against criteria[1]

- ***The results*** of the quantitative analysis ***should be compared with the acceptance criteria identified during the QDR***. Three types of methods of analysis:
  - *a) deterministic;*
  - *b) probabilistic;*
  - *c) comparative.*
- If, following the quantitative analysis, it is demonstrated that ***none of the trial designs satisfies*** the specified acceptance criteria, the ***QDR and quantification process should be repeated*** until a hydrogen safety strategy has been found that satisfies acceptance safety criteria and other design requirements.

Assessment against criteria^2

- ***In a deterministic study*** the objective is to show that on the basis of the initial assumptions (usually "credible worst-case") a defined set of conditions will not occur. It should be assessed that all persons ***can leave*** a threatened part of an infrastructure in reasonable safety without assistance (***life safety***). Where the ***failure of the structure*** will threaten the life, adequate ***fire and explosion resistance*** should be provided.
- ***In a probabilistic study***, such criteria are set that the probability of a given event occurring is acceptably low.
- ***For comparative study*** the acceptance criteria may simply be defined in terms of compliance with existing code requirements

Reporting

The report on HSE could contain the following information:

- a) Objectives of the study;
- b) Full description of the HFC system/infrastructure;
- c) Results of the QDR;
- d) Quantitative analysis: 1) Assumptions; 2) Engineering judgments; 3) Calculation procedures; 4) Validation of methodologies; 5) Sensitivity analysis;
- e) Assessment of analysis results against criteria;
- f) Conclusions: 1) Hydrogen safety strategy; 2) Management requirements; 3) Any limitations on use;
- g) References, e.g. drawings, design documentation, technical literature, etc.

Benefits

Hydrogen safety engineering:

- Provides an engineer with a disciplined approach to hydrogen safety design
- Allows safety levels for alternative designs to be compared
- Provides a basis for selection of the most appropriate hydrogen safety systems
- Provides opportunities for innovative design, including new engineering tools (not yet in RCS)
- Provides information on the management of hydrogen safety

RCS and HSE

There is an overestimation to some extent of expectations and the role of RCS in safety design. Indeed:

- RCS by definition are at least three years old to current level of knowledge in the field.
- RCS are often naturally quite narrowed by a particular topic and cannot account ahead for all possible situations, especially for developing technologies; or too general (ISO/PDTR 15916).
- RCS are written and reflect interests of mainly industry rather than all stakeholders.
- Safety information is “naturally” fragmented throughout the growing with time number of RCS.
- **Thus, a separate overarching safety oriented standard, giving the methodology to carry out HSE and maintain available knowledge in the field in one place is needed.**

HSE tools and examples

1. **Technological and safety requirements:** *Inherently safer design*
2. **The similarity law for unignited releases:** *PRD diameter for a forklift in warehouse*
3. **The universal flame length correlation:** *Effect of restrictor in a pipeline*
4. **Separation for unignited and ignited leak:** *Which separation distance is longer?*
5. **Momentum- and buoyancy-controlled leaks:** *Decrease of separation distances*
6. **CFD and simple engineering models:** *Pressure peaking effect in vented enclosure*

7 8 9 10 11 12 13 14 15 … **>>> MSc HSE**

HSE tool:
Matching of technological and safety requirements

Example:
Inherently safer design of fuel cell system

1

Inherently safer design ①

- Current fuel cell (FC) systems are often designed that piping diameter is **d=5-15 mm** and pressure is **p=5-15 bar**.
- **Minimum mass flow rate (d=5 mm, p=5 bar)** calculated using the under-expanded jet theory is about **6 g/s**.
- **Maximum mass flow rate (d=15 mm, p=15 bar)** is **170 g/s**.
- Let us consider 50 kW FC system (multi-family dwellings, etc.):
  - Assuming electrical efficiency of FC is 45%, heat of reaction of hydrogen with air 132.5 kJ/g, the mass flow rate for functioning of FC can be calculated as only (50 kW)/0.45/(132.5 kJ/g)=**0.84 g/s**.
  - This mass flow rate (**0.84 g/s**) can be provided at **p=5 bar and d=1.8 mm** restrictor (or at **p=2 bar, d=2.9 mm**)
- **Result: essential decrease of separation distance and improvement of hydrogen safety of FC system**

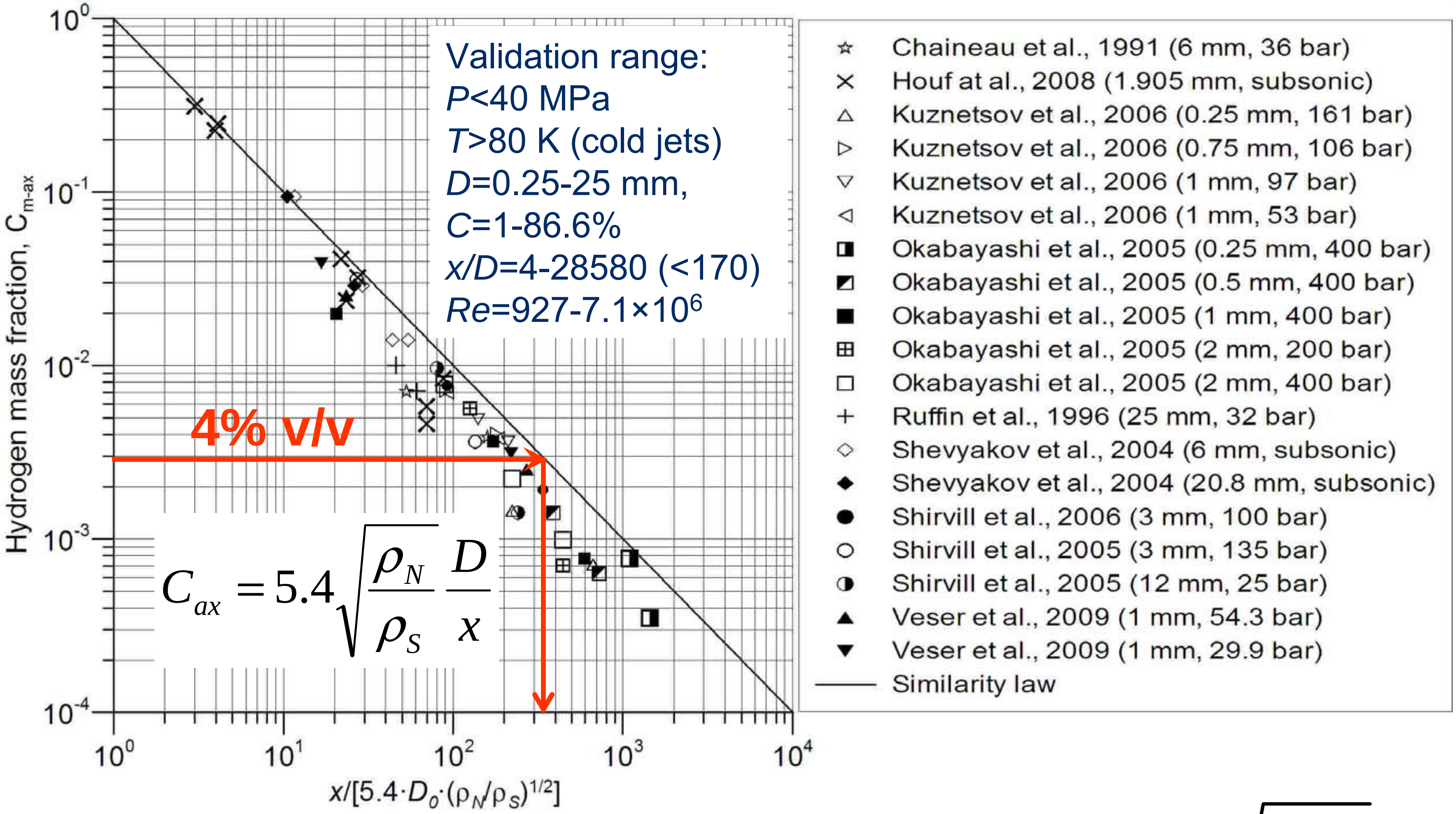
HSE tool:
The similarity law for unignited releases

Example:
PRD diameter for a forklift in warehouse

2

The similarity law

2



Validation range:
P<40 MPa
T>80 K (cold jets)
D=0.25-25 mm,
C=1-86.6%
x/D=4-28580 (<170)
Re=927-7.1×10^6

$$C_{ax} = 5.4\sqrt{\frac{\rho_N}{\rho_S}\frac{D}{x}}$$

Distance to 4% by volume: $x_{4\%} = 1574 \cdot \sqrt{\rho_N} \cdot D$

PRD diameter for forklift ②

- **Safety strategy:** in a case of upward release from the forklift onboard storage at **35 MPa** we would like to exclude formation of a flammable layer under a ceiling (**10 m** above the PRD).
- To realize this strategy the concentration on the jet axis at distance 10 m should be equal or below 4% v/v (mass fraction C_{ax}=0.00288).
- The under-expanded jet theory gives $\boldsymbol{\rho_N}$**=14.6 kg/m^3** for storage pressure 35 MPa. Thus, the **PRD diameter** can be calculated straight forward from the similarity law as **1.5 mm**

$$D = \frac{C_{ax}}{5.4}\sqrt{\frac{\rho_S}{\rho_N}}x = \frac{0.00288}{5.4}\sqrt{\frac{1.204}{14.6}}10 = 0.0015$$

Separation prescription ②

- Usefulness of prescriptive codes for separation distances, e.g. International Fire Code (edition 2006) is questionable. For example, IFC provides separation distance from non-reacting leaks in Tables without any reference to the original source of information or reasoning.
- In particular, it is impossible to calculate separation distance using real parameters of hydrogen or fuel cell system such as:
    - Leak diameter,
    - Storage pressure,
    - The axial hydrogen concentration.
- Without science-informed approach such kind of RCS should be avoided for safe introduction of HFC systems and infrastructure.

HSE tool:
The universal flame length correlation

Example:
Effect of restrictor in a pipeline

③

Hydrogen flame length ③

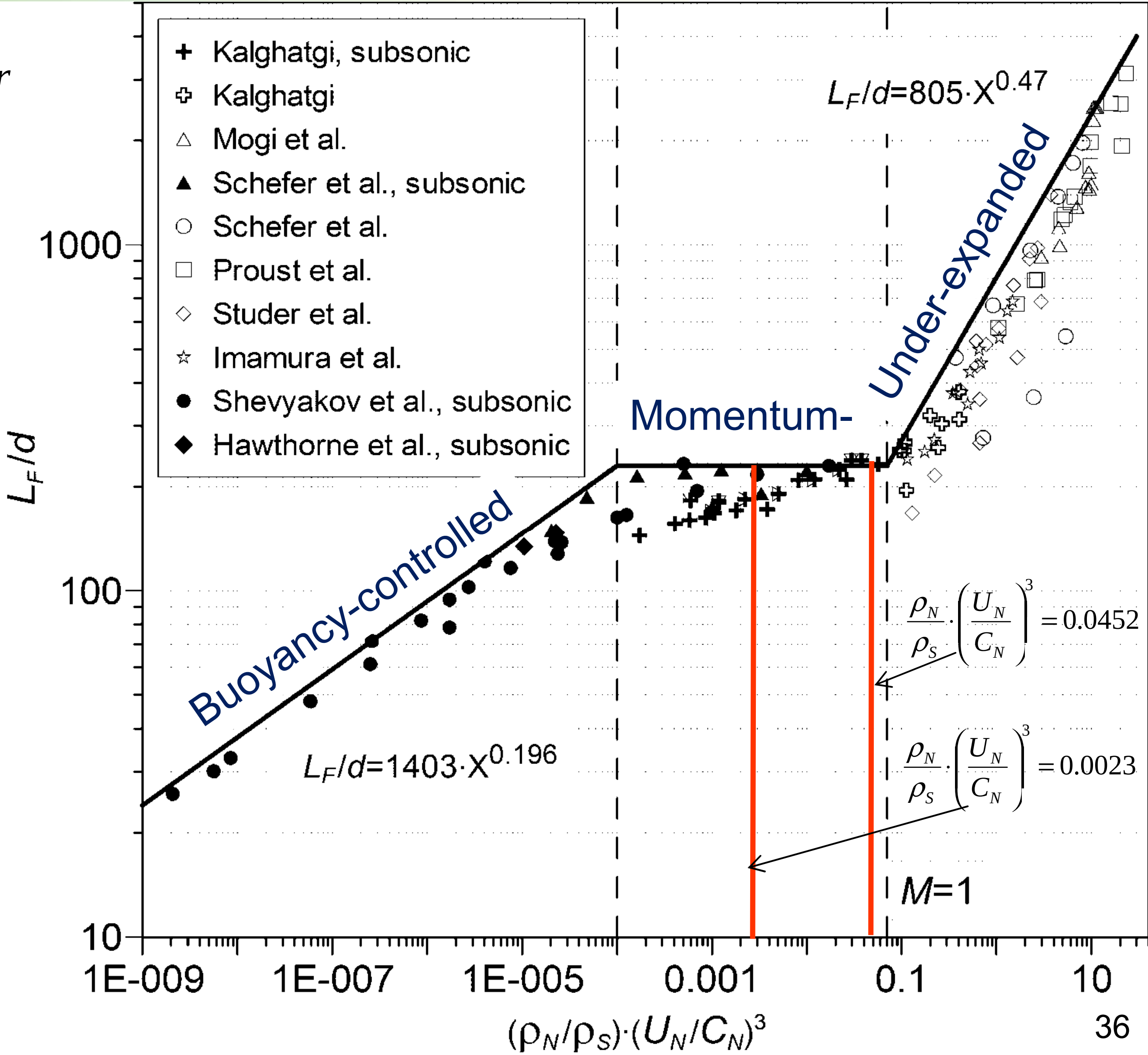
$$\frac{\rho_N}{\rho_S}\cdot\left(\frac{U_N}{C_N}\right)^3=\frac{g\cdot\mu_N}{\rho_S\cdot C_N^3}\cdot \mathrm{Re}\cdot Fr$$

Validation:

P =0.1-90 MPa

D=0.4-51.7 mm

L/T; SS/S/SS



Effect of flow restrictor ③

- For 45 kW FC (efficiency 45%) we need power supply of 45/0.45 = 100 kW. The mass flow rate needed is 100kW/152.34kJ/kg = **0.66 g/s** (H_c=152.34 kJ/g).
- If pipeline pressure is **1.5 bar**, then flow is sub-sonic, jet is expanded and density of H2 can be taken as **$_N$=0.0838 kg/m^3**. Velocity is $U_N = \sqrt{2\Delta P / \rho_N}$ =1092.4 m/s. Thus, **restrictor diameter** should be ***D*=3 mm**.
- Value of abscissa is $(\rho_N / \rho_S) \cdot (U_N / C_N)^3 = 0.0452$. Thus, we are in momentum regime with L_F/D=230 and flame length from restrictor would be **L_F=69 cm (3 mm)**.
- Let us have restrictor D=3 mm in a pipeline ***D*=6 mm**. Then, $(\rho_N / \rho_S) \cdot (U_N / C_N)^3 = 0.0023$. With L_F/D=230 the **flame length is increased to L_F=138 cm (by 100%)**.

HSE tool:
Comparison separation distances for unignited and ignited leak

Example:

Answering the question - which separation distance is longer?

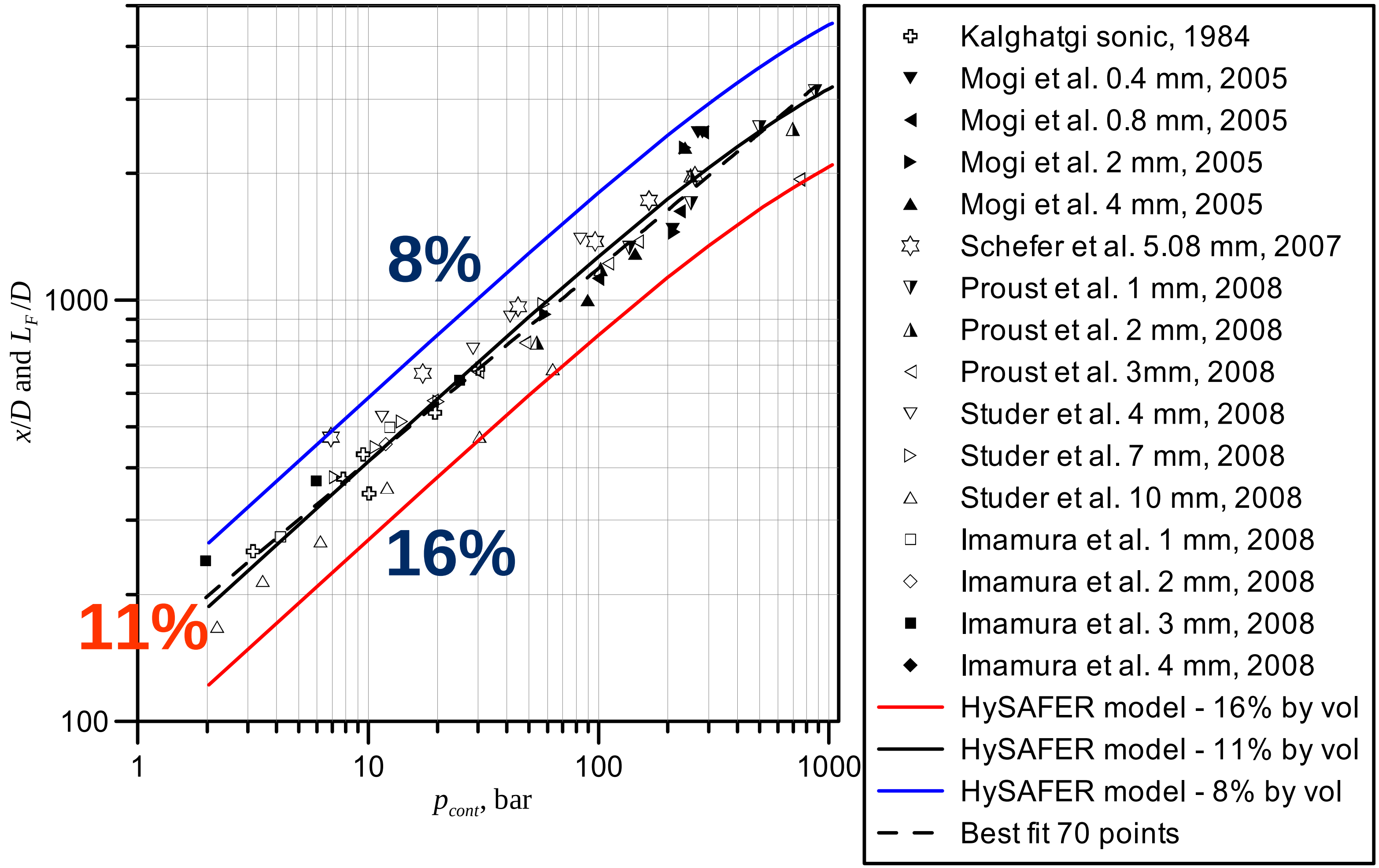
④

“Unsafe” (misleading) statements

- **(-) Sunavala, Hulse, Thring, 1957**: “Calculated flame length may be obtained by substitution the concentration corresponding to the **stoichiometric** mixture (29.5% of H2 in air) in equation of axial concentration decay for non-reacting jet”
- **(-) Bilger and Beck, 1975:** flame length is defined “for convenience” as the length on the axis to the point having a mean composition which is **stoichiometric** (H2 concentration is twice of O2).
- **(-) Bilger, 1976:** the calculated flame length may be obtained by substitution the concentration corresponding to the **stoichiometric** mixture in the equation of axial concentration decay for a non-reacting jet.

Where is a jet flame tip location?

- **Flammable envelope** = 4% v/v (LFL)
- **Flame tip location** = 11% v/v in **unignited jet** (8-16%)



11% is not stoichiometry (29.5%) – 33 times longer!!!

Unignited VS jet fire

4

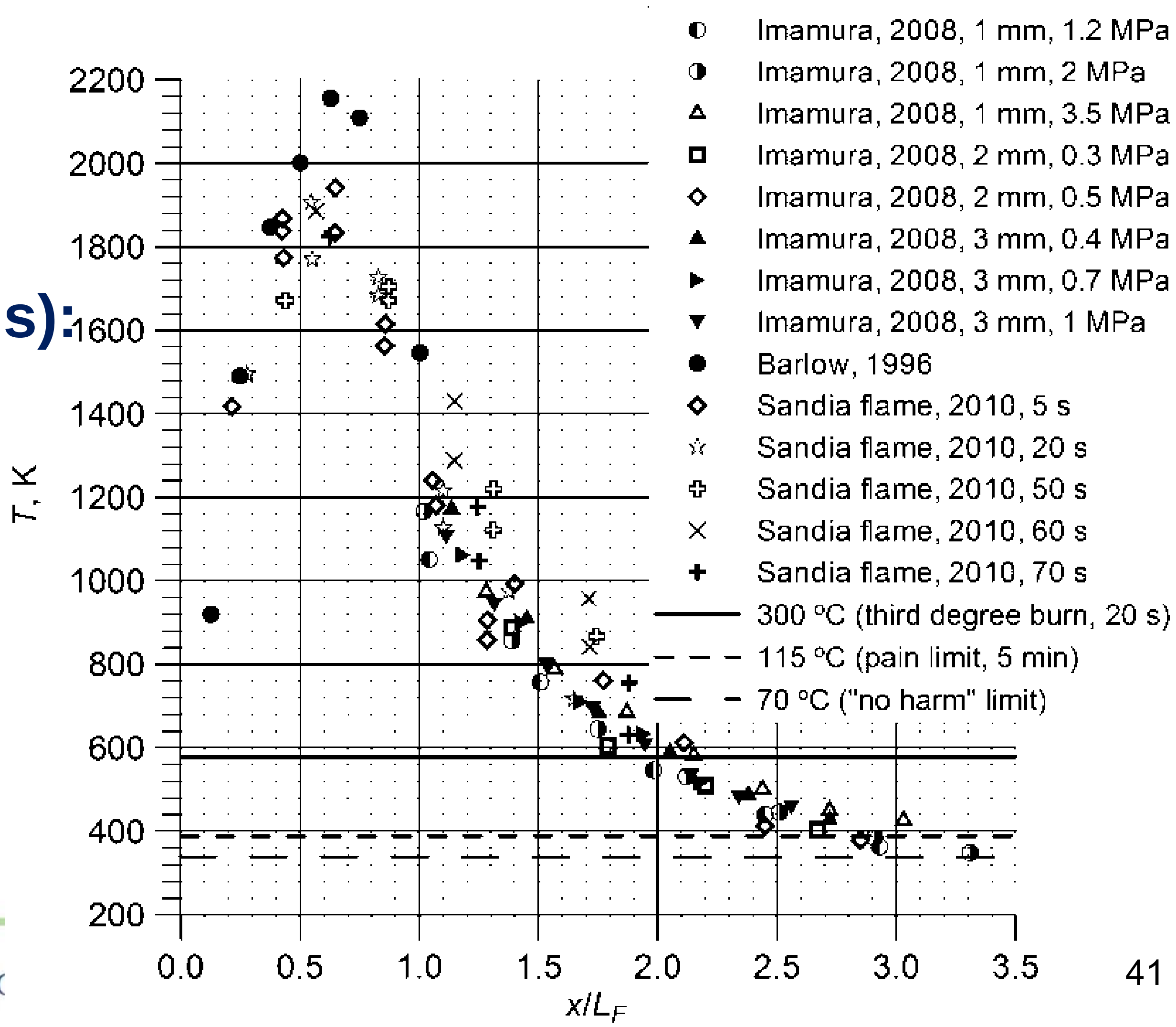
Separation distances (momentum-dominated leak)

Unignited jet:

$$x_{4\%} = 1574 \cdot \sqrt{\rho_N} \cdot D$$

Jet fires (3 separations):

- $x=3.5L_F$ for “no harm” separation (70°C)
- $x=3L_F$ for pain limit (115°C, 5 min)
- $x=2L_F$ for third degree burns (309°C, 20 s)



Unignited VS jet fire ④

The ratios of a separation distance to *LFL* (non-reacting jet) to three separation distances based on the choice of harm criteria for jet fire are (flame tip location is 11% v/v in non-reacting jet):

$x_{4\%}/x_{T=70C}=x_{4\%}/(3.5 \cdot x_{11\%})=2.95/3.5=0.84$ (“no harm”);

$x_{4\%}/x_{T=115C}= 2.95/3=0.98$ (“pain limit”);

$x_{4\%}/x_{T=309C} =2.95/2=1.48$ (“death limit” – unprotected).

In the conservative case (flame tip location is 8% v/v) these ratios:

$x_{4\%}/x_{T=70C(8\%)}=2.08/3.5=0.59$ (“no harm”);

$x_{4\%}/x_{T=115C(8\%)}=2.08/3=0.69$ (“pain limit”);

$x_{4\%}/x_{T=309C(8\%)} =2.08/2=1.04$ (“death limit” – unprotected).

“Unexpected” conclusion - in the conservative case all three separation distance for jet fire are longer or equal to the separation distance based on LFL (non-reacting release).

HSE tool:

Transition from momentum- to buoyancy-controlled leak graph

Example:

Decrease of separation distances

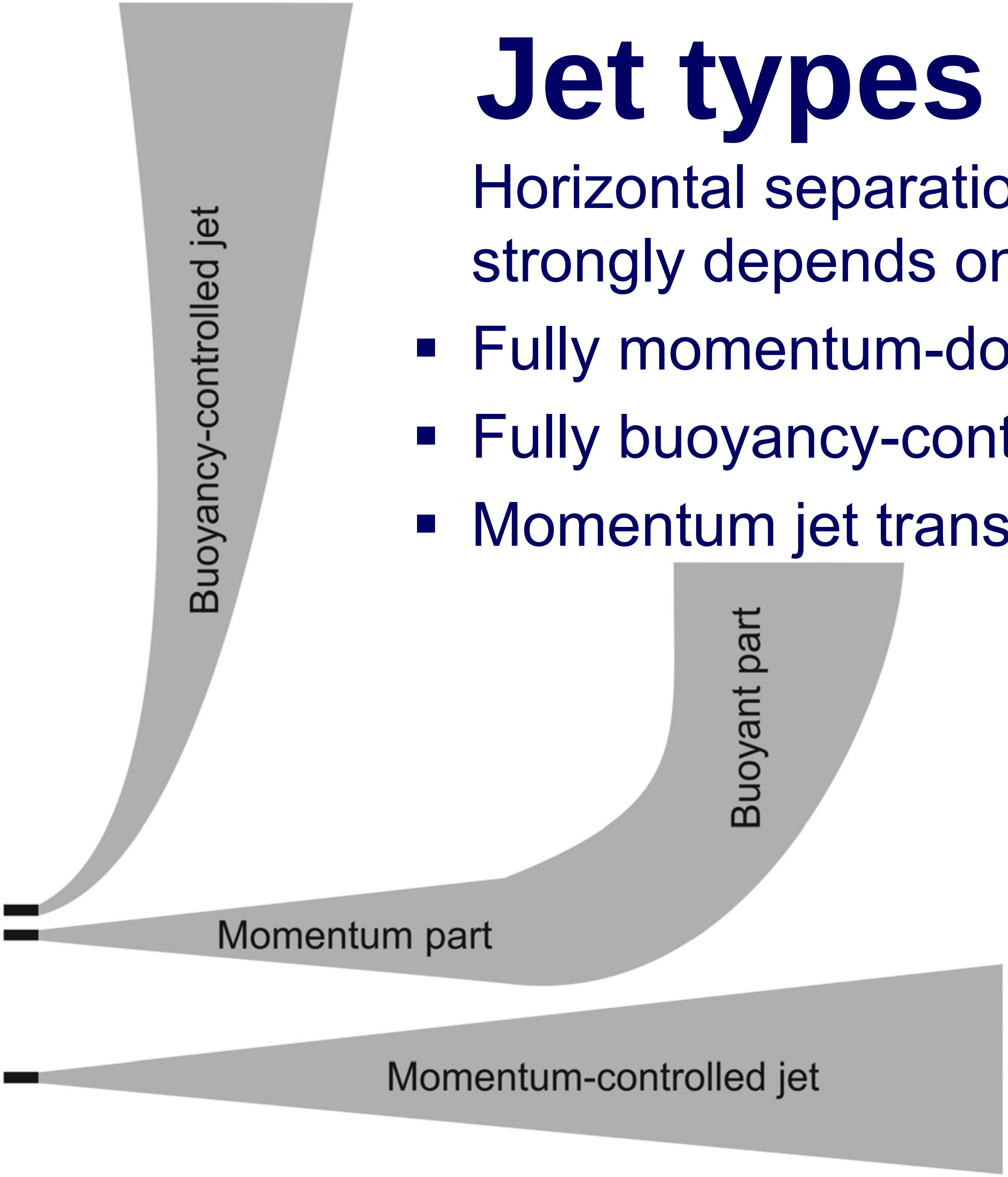
5

Jet types

5

Horizontal separation distance strongly depends on jet type:

- Fully momentum-dominated jet
- Fully buoyancy-controlled jet
- Momentum jet transits to buoyant



Buoyant VS momentum jets

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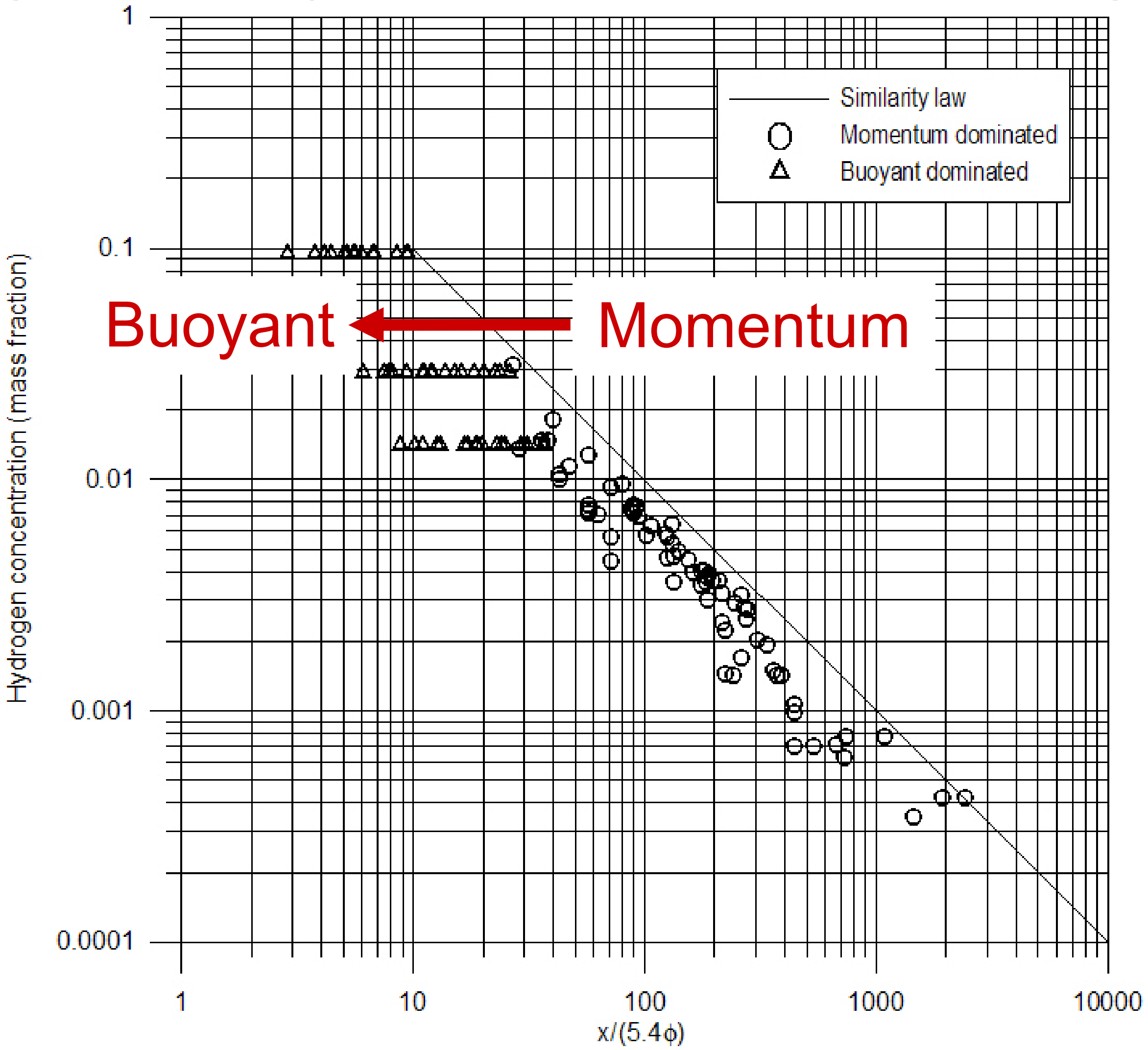
Buoyant jets decay faster than momentum jets (vertical)



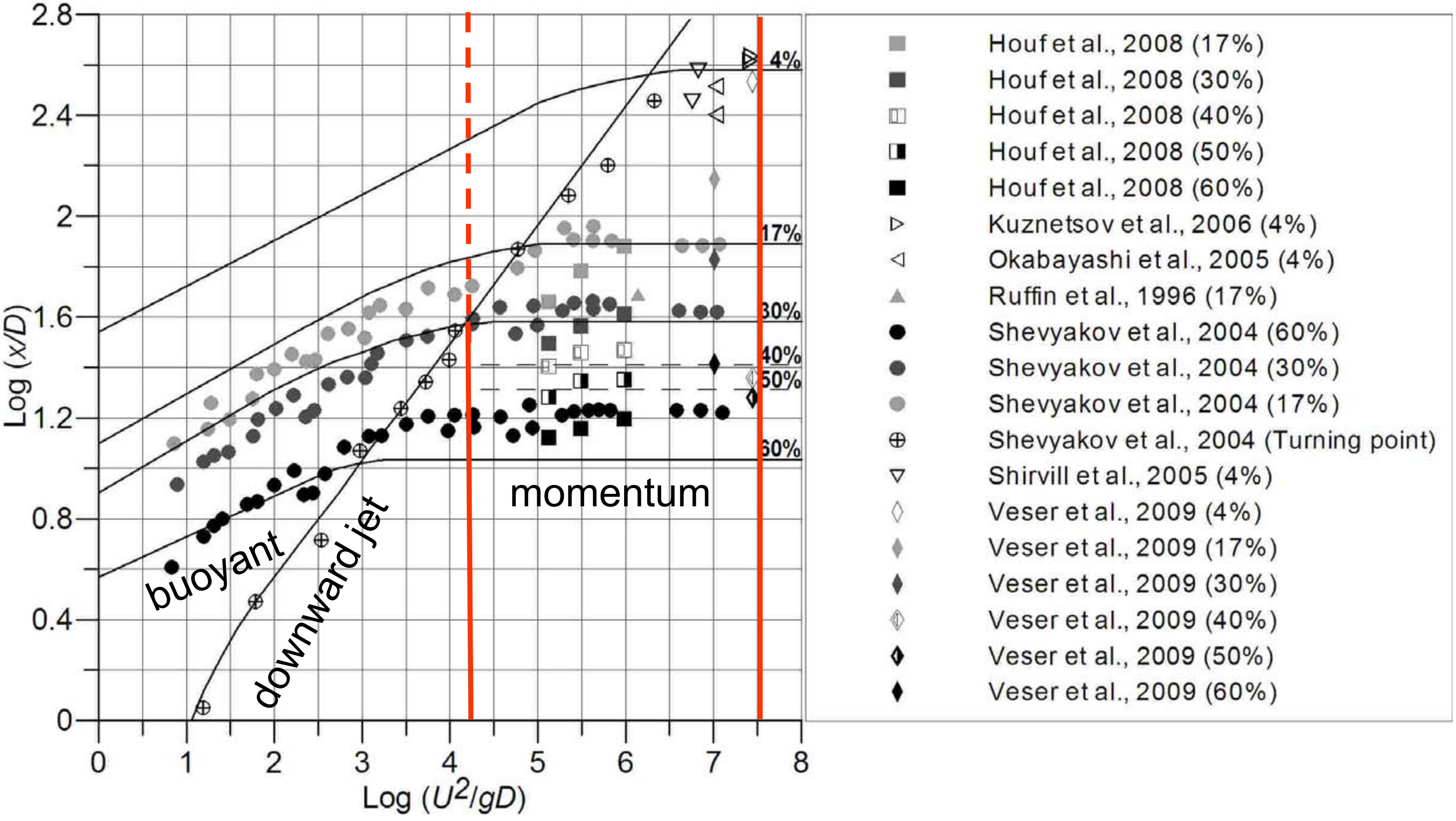
Buoyant ← Momentum

Use of the similarity law – conservative approach

When a jet becomes buoyant?

5

Start from the *Fr*=U^2/gD (*U* and *D* real or notional nozzle)



Buoyant part of jet

Momentum part of jet

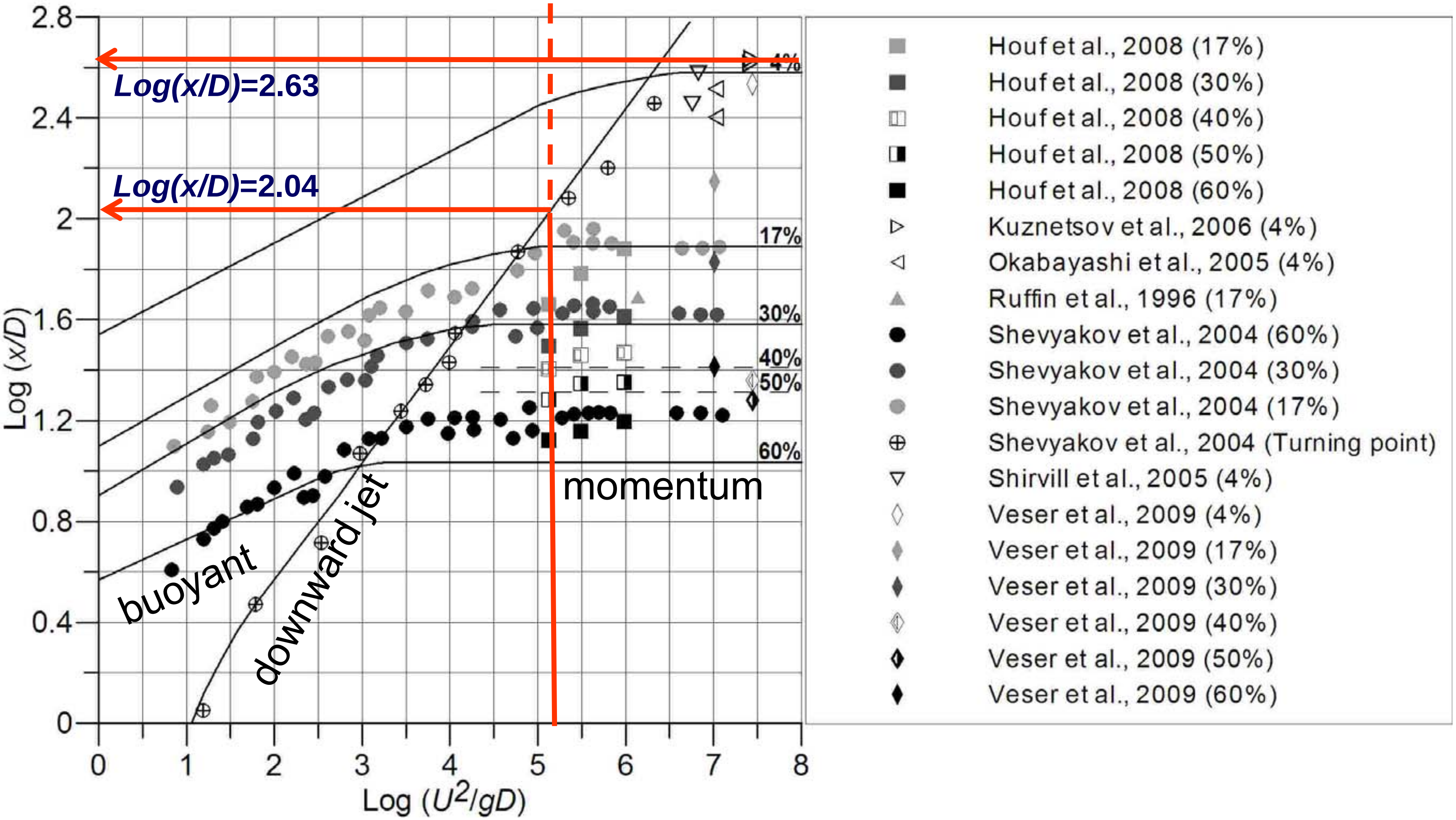
Hydrogen pipeline (1/2)

5

- Since 1938 the chemical industries in Hüls, Ruhr area (Germany): 215 km, maximum pressure *P*=**25 bar**, inner diameter *D*=16.8-**27.3 cm (*D*$_{eff}$=98 cm)**, full bore rupture mass flow rate m=90 kg/s: 15 cars/s (6 kg/fill), 3000 cars/3 min (time of fill), 1.4M cars/day, 10M cars/week (this pipeline would service 10M population), ***Log(Fr=U*^{2}*/gD*$_{eff}$*)*=5.2**.
- If **the similarity law** is applied (assumption of momentum-controlled jet – conservative estimate) then horizontal distance to 4% by volume is **($_N$=1.267) 465 m.**
- If the Schevyakov's graph (previous slide) is applied in assumption of momentum-controlled jet at 4% then separation distance is (***Log(x/D)*=2.63**) **418 m** (close to the similarity law result).

Hydrogen pipeline (2/2)

⑤



$$Log\,(x/D) = 2.63 = \quad Log\,(x/D) = 2.04$$

Separation distance: **465 m reduces to 107 m (>4 times)**

HSE tool:
CFD and simple engineering models

Example:

a) Closed garage

b) Pressure peaking effect in vented garage

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Overlooked safety issue ⑥

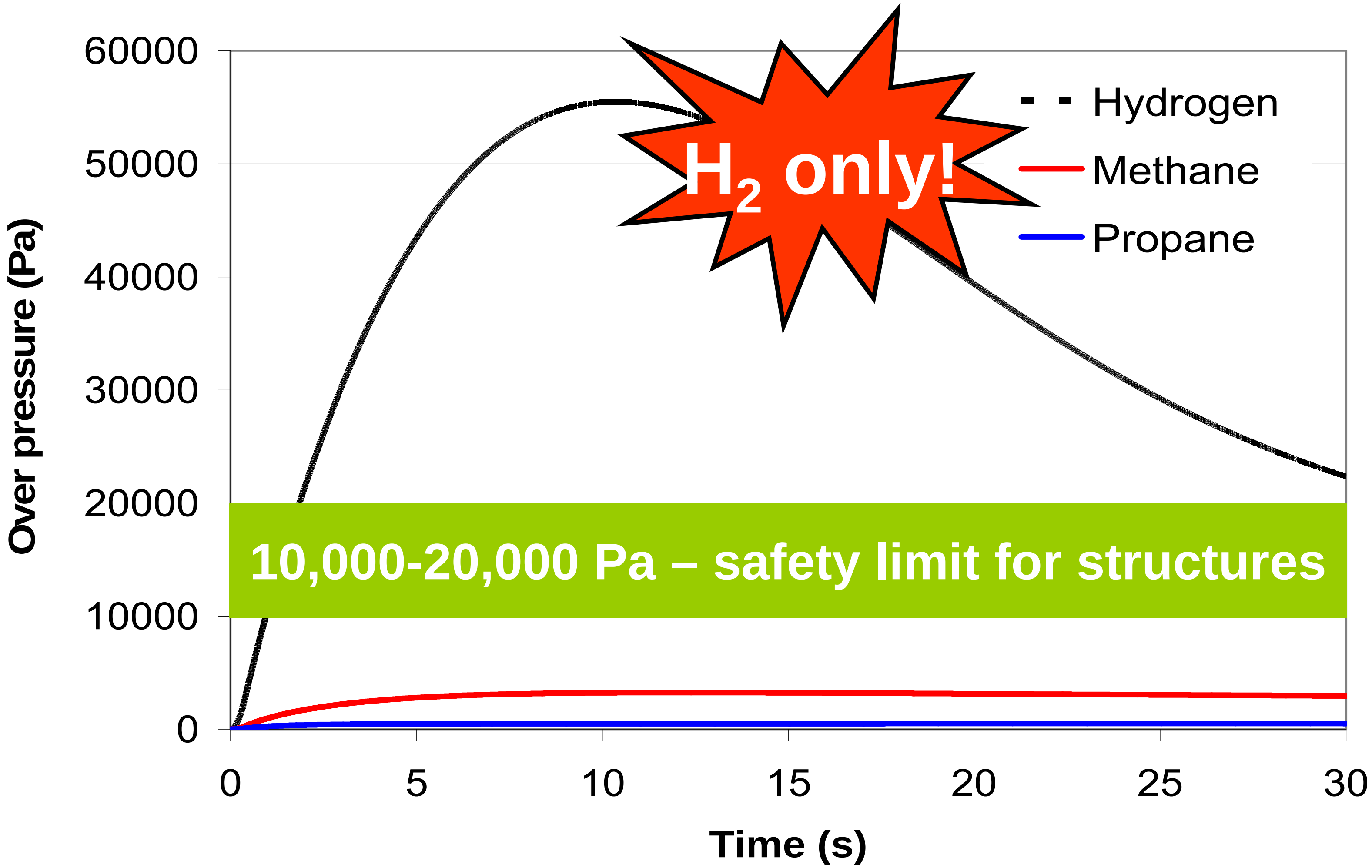
- **Problem**: Hydrogen-powered car is in a **closed garage** of 44 m^3 free volume. Release from an onboard storage through PRD of 5.08 mm diameter at pressure 350 bar gives mass flow rate 390 g/s (volumetric flow rate is 390/2*0.0224=**4.4 m^3/s**).
- **Consequences**: Every second of non-reacting release pressure in the garage will increase by (44+4.4)/44=1.1 times, i.e. on 10 kPa. Civil building structures can withstand 10-20 kPa. **Thus, in 1-2 s the garage "is gone"**.

Commercialisation in 2015…

Pressure peaking phenomenon!

6

Small garage LxWxH=4.5x2.6x2.6 m (“brick” vent).
Mass flow rate 390 g/s (H2: 350 bar, 5.08 mm orifice).



Solution: new onboard storage and PRDs

Acknowledgements

Contributions and support of:

- Colleagues from the HySAFER Centre at the University of Ulster
- Partners from the European Network of Excellence HySafe and International Association for Hydrogen Safety, other European and International projects
- The European Commission and Fuel Cell and Joint Undertaking

are gratefully appreciated.

THANK YOU

Learn more!

MSc in Hydrogen Safety Engineering (distance learning course):

http://campusone.ulster.ac.uk/potential/postgraduate.php?ppid=24