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Centre for Hydrogen Safety and Codes & Standards ™

Risk-Informed and Science-Based Approach to Hydrogen Codes and Standards

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Acknowledgement

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Special Thanks to

Jeff LaChance for the permission to use text and slides describing Sandia National Labs work in the field of risk-informed separation distances. This work is sponsored by the US DOE. And to Jake DeVaal of Ballard Power Systems for the permission to use slides describing the work in support of FC vehicles safety standard development.

Outline

- EIGA Approach to Safety Distances.
- Examples of Risk-Informed and Science-Based Approach to Hydrogen Codes and Standards:
  - ✓ ISO/TC 197 WG 11 recommendations on safety distances.
  - ✓ CFD-based comparison with IEC 60079-10 requirements for hazardous zones.
  - ✓ Sandia NL work on safety distances.
  - ✓ CFD-based analysis of lower detection limit requirement for ISO/TC 197 WG 13 standard on hydrogen detection apparatus.

EIGA Approach

Determination of Safety Distances, IGC Doc 75/07/E. Basis of Approach

Key Definition

- The safety distance from a piece of equipment is to provide a ***minimum safety*** which will mitigate the effect of any likely event and prevent it from escalating into a larger incident.
  - ✓ Effectively this means that ***safety distance is a distance to acceptable risk***.

Key Limitations and Provisions

- The safety distance is ***not intended*** to provide protection ***against catastrophic events*** or major releases and these should be addressed by other means to reduce the frequency and/or consequences to an acceptable level.
- In most cases the use of safety distance to provide ***protection from all possible events is not practicable***.
- Therefore it is necessary to understand which ***risks*** can be reasonably mitigated by a safety distance.

EIGA Approach

Basis of Approach

Safety distance is the function of:

- **The nature of the hazard (e.g. flammable).**
- **The equipment design and the operating conditions (e.g. pressure, temperature) and/or physical properties of the substance under those conditions.**
- **Any external mitigating measures (e.g. fire barriers).**
- **The "object" which is protected by the safety distance, i.e. the harm potential (e.g. people, environment or equipment).**

Selection of Risk Criteria

- **2×10^{-4} per annum as an average minimum natural individual fatality risk for westernized (European) industrialized population.**
- **It includes all harm exposures in occupational, traffic, and home / leisure segments, with appr. 0.7×10^{-4} per annum for each segment.**
- **Since “traffic” segment contributes 0.7×10^{-4} per annum, then the risk from fuelling should be at least half of that, i.e., *3.5×10^{-5} per annum* or 1/6 of natural individual fatality risk.**

EIGA Approach

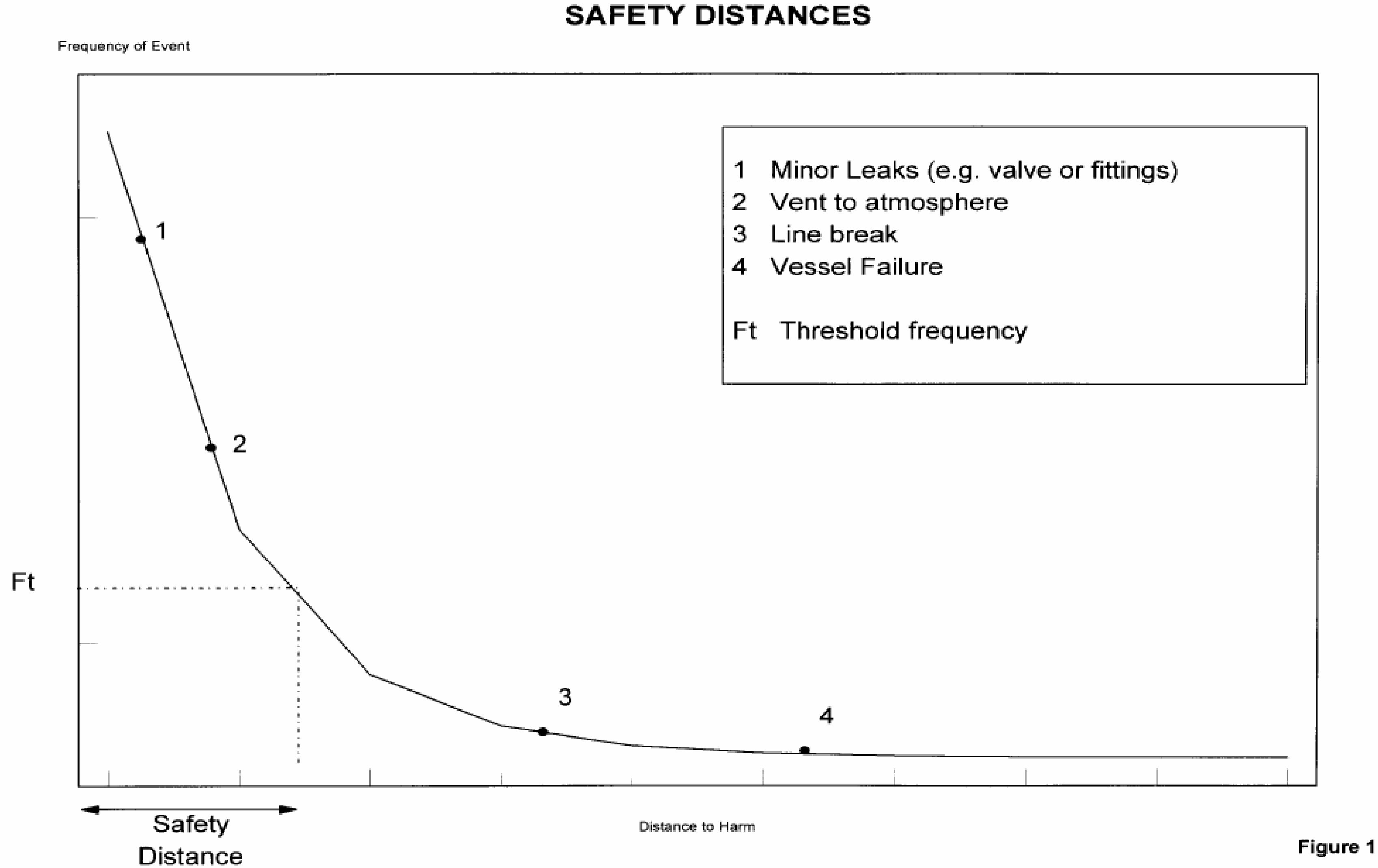


Figure 1

EIGA Approach

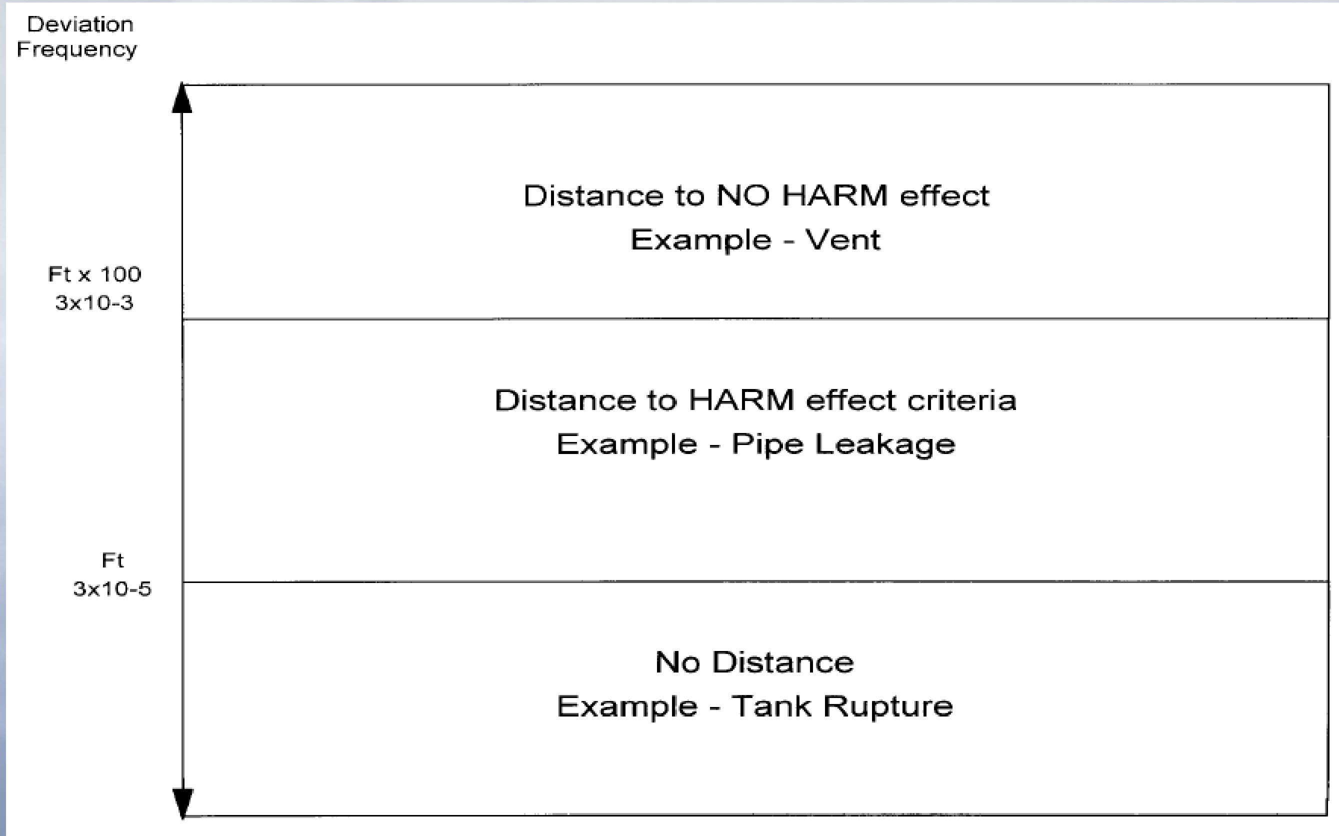
Summary of the method

- ***Identify*** **the** ***hazard*** **sources and events (e.g. release of gas) taking into account the likelihood.**
- ***Calculate*** **the** ***effects*** **on neighbouring objects taking into account mitigating factors.**
- ***Determine*** **the** ***safety distance*** **to each object to meet the minimum hazard criteria.**
- ***Consider*** **additional prevention or** ***mitigating factors*** **and re-calculate safety distance.**

EIGA Approach

Harm and No Harm Criteria of Severity

- "Harm" criterion – 1% probability of fatality for general population.
- "No Harm" criterion – 0.1% probability of fatality for general population.



What Are Risk-Informed Codes & Standards?

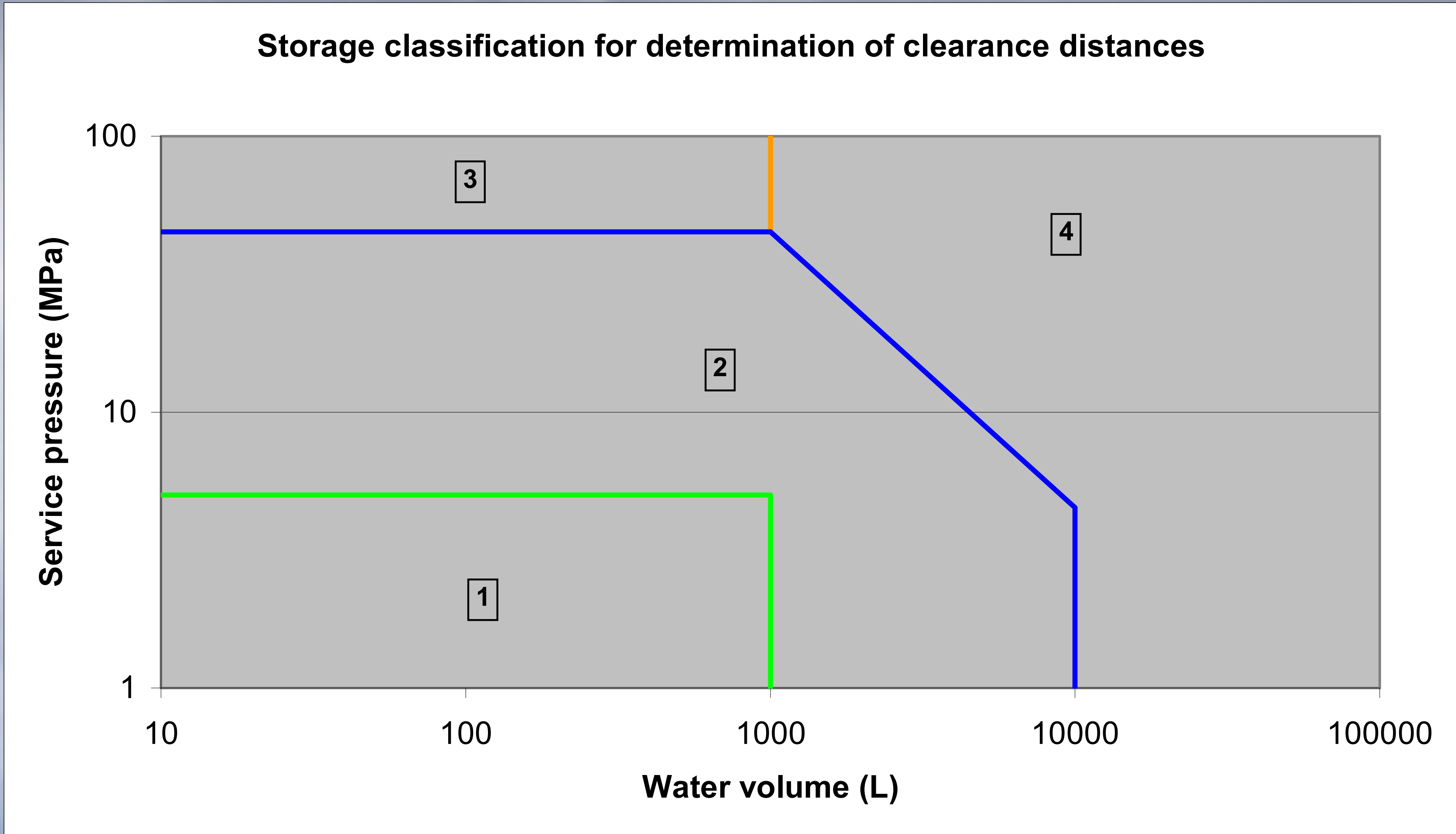
Traditional approach – *"from outside in"*

- Main goal: protect hydrocarbon containing equipment and storage from outside environment
- Based on limited industrial experience and guess work
- C&S do not incorporate risk considerations into requirements

New approach taken to hydrogen – *"from inside out"*

- Main goal: protect surrounding environment and people from hydrogen containing equipment and storage
- Based on science (experimental and numerical modeling)
- C&S requirements are risk-based to address risk acceptance criteria

ISO/TC 197 WG 11
Recommendations on Safety Distances



Developed by Frederic Barth, Air Liquide, France

ISO/TC 197 WG 11
Recommendations on Safety Distances

Storage category		1 V <= 1000 L & P <= 5 Mpa	2 V <= 1000 L & 5 < P <= 45 MPa OR 1000 < V <= 10000 L & Q <= 30 kg	3 V <= 1000 L & P > 45 Mpa	4 V > 1000 L & Q > 30 kg OR V > 10 000 L	Main risk addressed / comments
Exposures	Building of non-combustible material (2 hr resistant)	0	0	0	1,5	H2 fire impingement / access for cooling to be provided for larger tanks ?
	Building of combustible material	1	3	4	4	H2 fire impingement radiation / to avoid extension to buildings Building fire radiation on large storage / to avoid escalation
	Wall opening not above hydrogen system	1	2	3	3	Explosive atmosphere in building in case of H2 leak
	Wall opening above hydrogen system	1,5	3	4	4	Explosive atmosphere in building in case of H2 leak
	Flammable liquids above ground < 4000 L	1,5	3	4	6	H2 fire impingement / where this results in escalation, depending on relative storage sizes
	Flammable liquids above ground > 4000 L	3	6	8	8	Flammable liquid fire radiation effects on H2 storage / where this results in escalation
	Flammable liquids below ground - Vent and Fill openi	1,5	3	3	3	Flammable liquid fire
	Flammable gas storage > 500 m3	1,5	3	4	5	H2 fire impingement / where this results in escalation, depending on relative storage sizes
	Stocks of combustible material, e.g. timber	1,5	3	4	4	Flammable gas fire radiation effects on H2 storage / where this results in escalation
	Ground level sources of ignition	1,5	3	4	4	Delayed ignition of explosive atmosphere in case of leak
	Air conditioning & air compressor intake	3	6	8	8	Intake of explosive atmosphere in building or air-system / flow field created by air system can lead to rapid H2 concentration in building or air system
	Public assembly	3	6	8	8	H2 fire or explosion / possible extension of harmful effects before maximum time needed to evacuate - prevention of major accident involving public
	Public sidewalks and parked vehicles, lot line	1,5	3	4	4	Explosive atmosphere/flame impigement/radiation potential in case of leak
	Trolley, train power line vertical plane	1,5	8	8	8	Ignition of explosive atmosphere in case of large leak / prevention of major accident involving public
	Overhead electrical line	1,5	1,5	1,5	1,5	Line falling on H2 system

Comparison with IEC 60079-10 Requirements for Hazardous Zones

IEC 60079-10 Electrical Apparatus for Explosive Gas Atmospheres – Classification of Hazardous Atmospheres:

- **Sets out the essential criteria against which the risk of ignition can be assessed, and**
- **Provides the design and control parameters that can be used in order to reduce such a risk. The important criteria are:**
  - ✓ **Release rate and class, LFL of the gas, release concentration, degree and quality of ventilation,**
- **Outlines main steps to calculate a hazardous zone: determine the number of air changes, calculate the resulting volumetric air flow rate (dV/dt_{min}), then calculate the hypothetical ignitible mixture volume V_z**

Key Deficiencies of IEC 60079-10

- **Linear and directly proportional correlation between hydrogen concentration and sizes of corresponding clouds:**

$$(dV/dt)_{min} = \frac{(dG/dt)_{max}}{k \times LEL_m} \times \frac{T}{293}$$

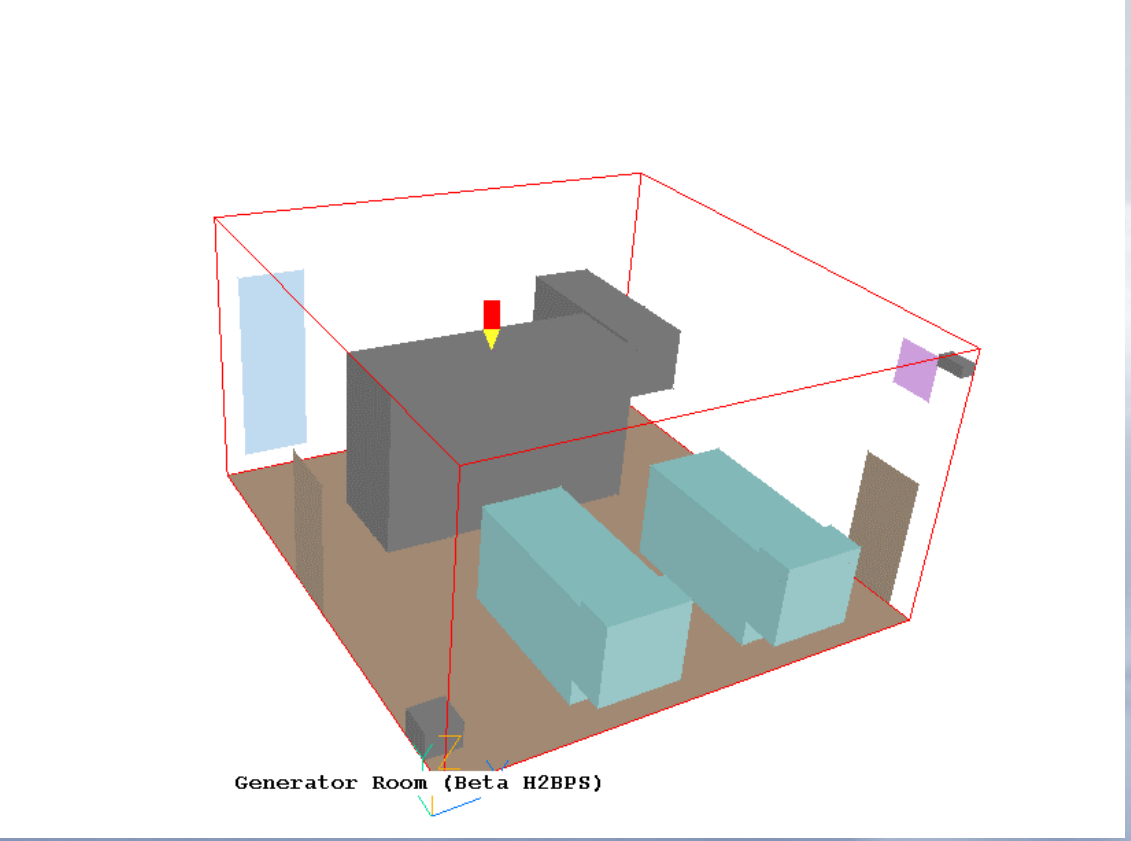
where

$(dV/dt)_{min}$	is the minimum volumetric flow rate of fresh air (volume per time, m^3/s);
$(dG/dt)_{max}$	is the maximum rate of release at source (mass per time, kg/s);
LEL_m	is the lower explosive limit (mass per volume, kg/m^3);
k	is a safety factor applied to the LEL_m; typically:
	k = 0,25 (continuous and primary grades of release)
	k = 0,5 (secondary grades of release);
T	is the ambient temperature (in Kelvin, K).

- **In reality the correlation between hydrogen gas clouds of various concentrations is more complicated. CFD modeling indicates that 4% vol. cloud is often about an order of magnitude smaller than that of 2% vol. cloud**

Key Deficiencies of IEC 60079-10
Confined Areas and Effects of Surface and Geometry

- **Group Exercise:**
  - ✓ **Determine congestion coefficient "*f*" of the Generator Room on the scale from 1 to 5, 1 being least confined (open space) and 5 – with maximum confinement**



Key Deficiencies of IEC 60079-10

- **Unclear method of determining a "congestion coefficient" or efficiency of ventilation "*f*"**
- **Unclear effect of geometry and distribution of congestion on efficiency of ventilation:**

$$V_z = f \times V_k = \frac{f \times (dV/dt)_{min}}{C} \quad (B.4)$$

where f is the efficiency of the ventilation in terms of its effectiveness in diluting the explosive gas atmosphere, with f ranging from $f = 1$ (ideal situation) to, typically $f = 5$ (impeded air flow).

C is the number of fresh air changes per unit time (s^{-1}) and is derived from

$$C = \frac{dV_0/dt}{V_0} \quad (B.3)$$

where

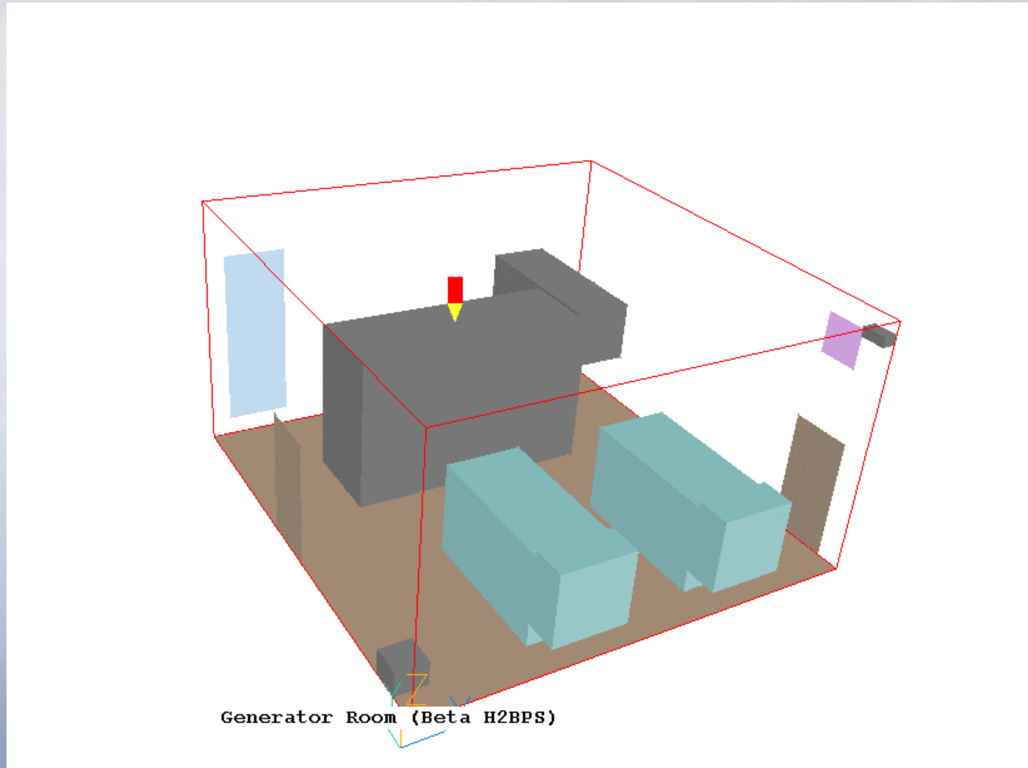
dV_0/dt is the total flow rate of fresh air through the volume under consideration, and

V_0 the entire volume (within the control of the plant) served by the actual ventilation in the vicinity of the release being considered.

Comparison with IEC 60079-10 Requirements for Hazardous Zones

Hydrogen Release into the Generator Room of the Hydrogen Energy Station

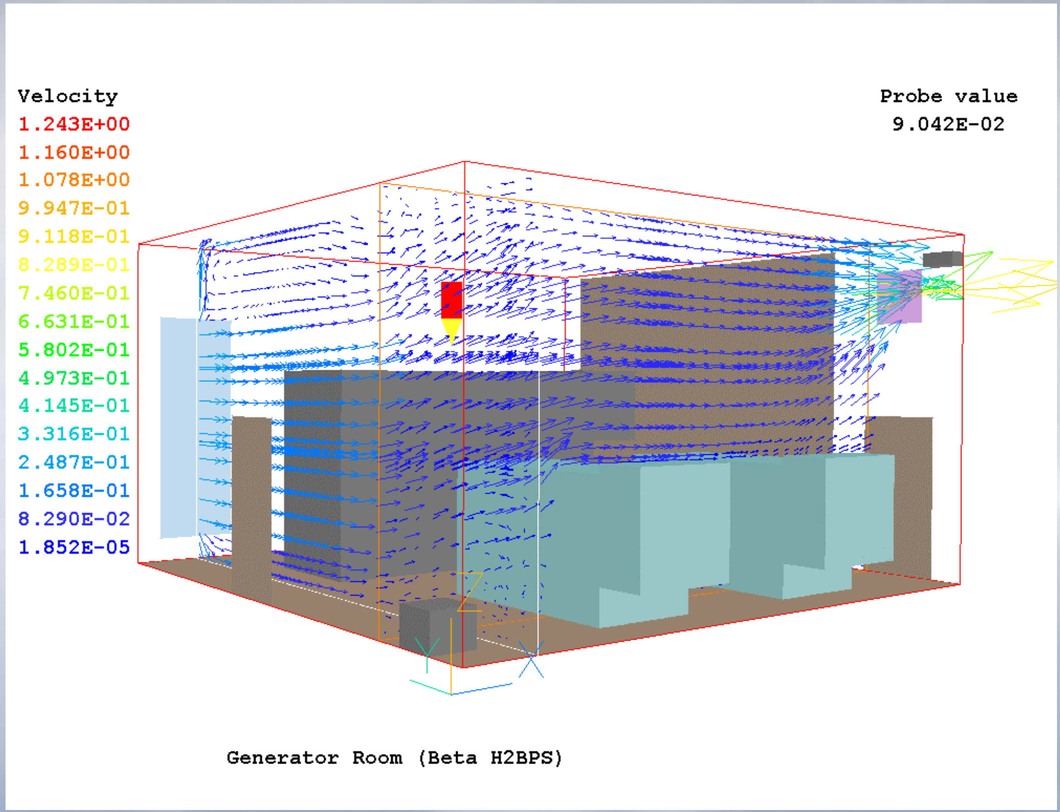
- ✓ Source of release – EH2 generator
- ✓ Point of release –vent pipe 5 cm dia
- ✓ Duration – 10 min
- ✓ Full H2 production
- ✓ Low pressure
- ✓ Continuous exhaust ventilation 1 m^3/s
- ✓ Room vol = 230 m^3
- ✓ Net room vol = 185 m^3



Comparison with IEC 60079-10 Requirements for Hazardous Zones

"Before Leak" Simulation

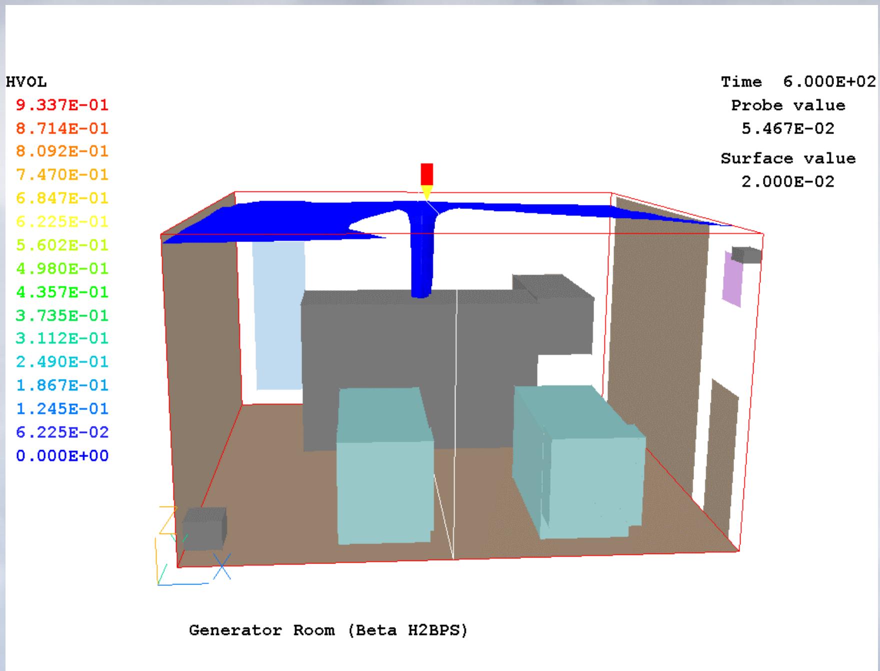
- **The existence of a louver and an exhaust fan in the Generator Room creates a steady-state airflow with 3-D fluid flow pattern.**

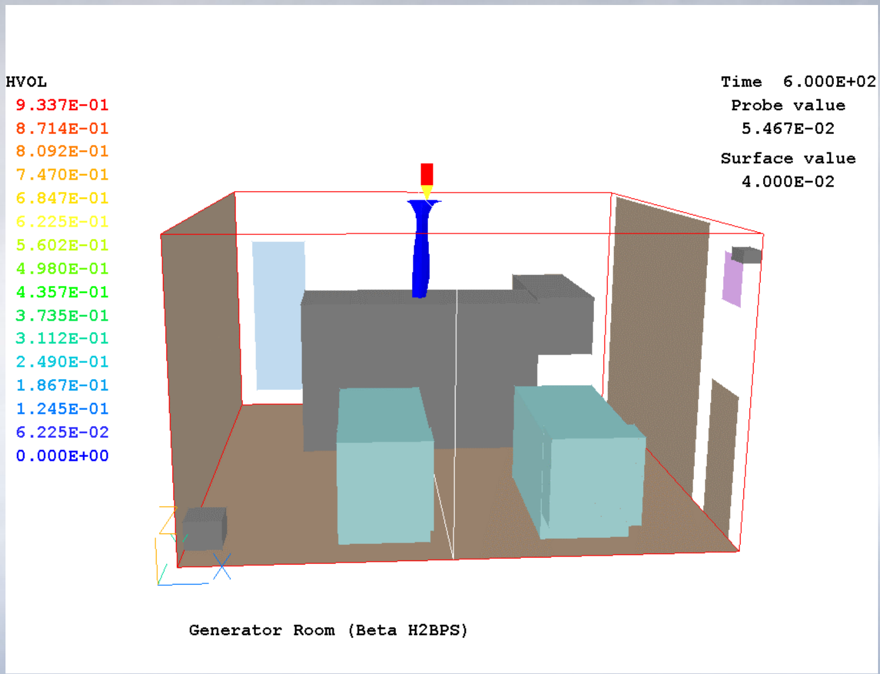


Ventilation velocities (X- and Y-planes) before leak

Comparison with IEC 60079-10 Requirements for Hazardous Zones

"Leak" Simulation





50% LFL **100% LFL**

End of 10-min release from the EH2 vent line

Comparison with IEC 60079-10 Requirements for Hazardous Zones

CFD Modeling Predictions

- 4% vol. cloud size – 0.081 m^3, and
- 2% vol. cloud size – 6.225 m^3

IEC 60079-10 Predictions

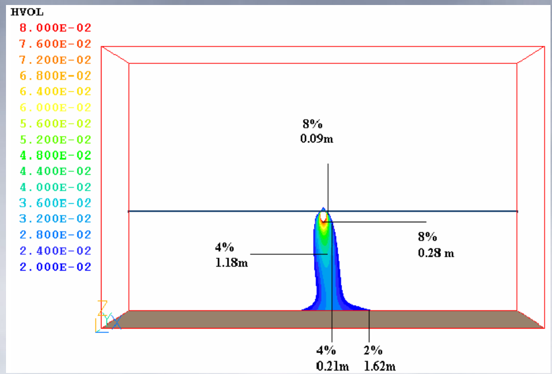
- Minimum volumetric flow rate of fresh air:

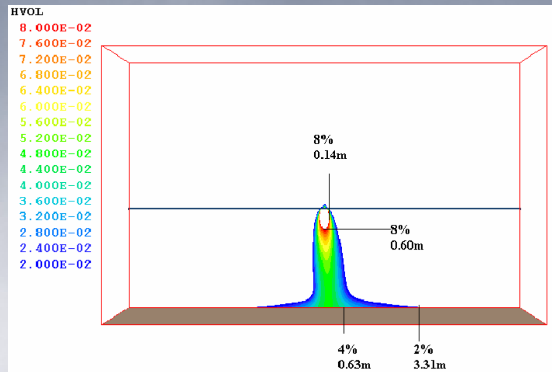
$$(dV/dt)_{\min} = \frac{(dG/dt)_{\max}}{k \times LEL} \times \frac{T}{293} = \frac{2.75 \times 10^{-4}}{0.5 \times 3.3 \times 10^{-3}} \times \frac{308}{293} = 0.175 m^3/\sec$$

- Evaluation of hypothetical volume V_z

$$V_z = \frac{f \times (dV/dt)_{\min}}{C} = \frac{2 \times 0.175}{0.0054} = 64.8 m^3$$

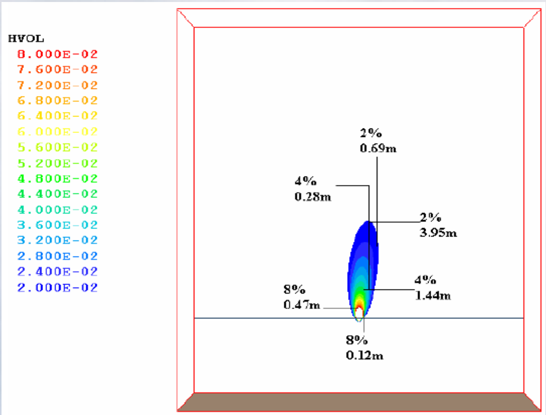
5 and 20 scfm Simulation Results at 400 bars

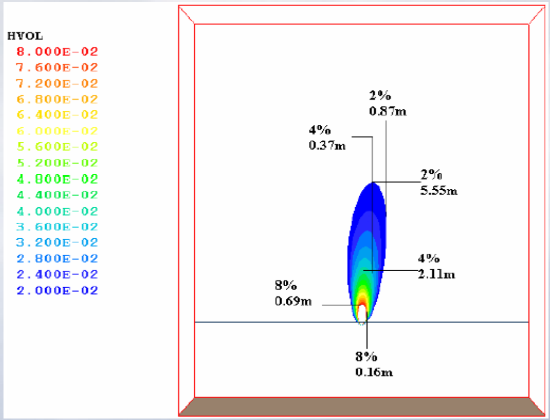




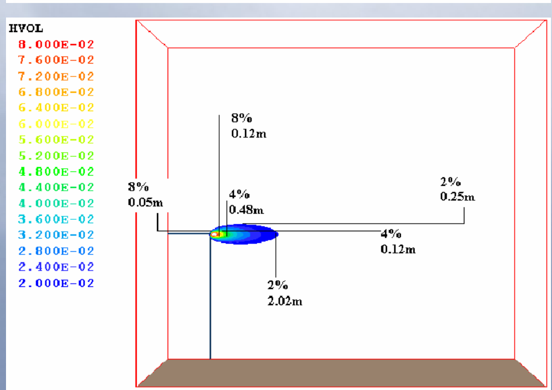
CFD LFL Vol m3

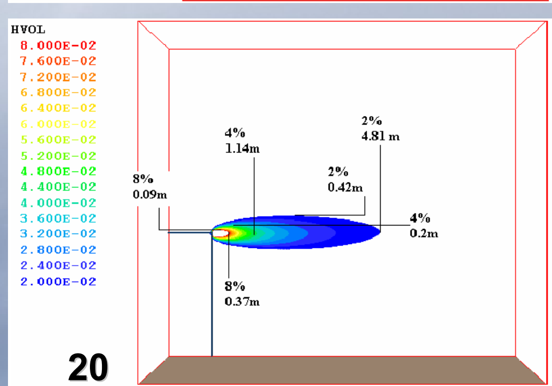
5 cfm	0.103 @ 100% 2.1 @ 50% LFL
20 cfm	0.42 @ 100% 3.7 @ 50% LFL





5 cfm	0.23 @ 100% 2.5 @ 50% LFL
20 cfm	0.52 @ 100% 5.6 @ 50% LFL





5 cfm	0.02 @ 100% 0.2 @ 50% LFL
20 cfm	0.11 @ 100% 1.4 @ 50% LFL

Comparison with IEC 60079-10 Predictions

- H2 leak rates of 5 and 20 scfm (0.0020 and 0.0079 kg/sec) were selected as credible leaks based on experience (0.1 and 0.2 mm leak orifices at 400 bars). Selected leak rates were modelled with a 0.5 m/sec wind (IEC 60079-10).

Flowrate (SCFM)	4% vol. H_2 cloud volume (m^3)		Horizontal cloud extent (m)			Vertical cloud extent (m)		
	IEC	CFD	8 % vol.	4% vol.	2% vol.	8 % vol.	4% vol.	2% vol.
20 (down)	2.82	0.41	0.14	0.63*	3.31*	0.6	3*	3*
5 (down)	0.71	0.10	0.09	0.21	1.62*	0.28	1.18	3*
20 (up)	2.82	0.52	0.16	0.37	0.87	0.69	2.11	5.55
5 (up)	0.71	0.23	0.12	0.28	0.69	0.47	1.44	3.95
20 (horiz.)	2.82	0.11	0.37	1.14	4.81	0.09	0.2	0.42
5 (horiz.)	0.71	0.02	0.12	0.48	2.02	0.05	0.12	0.25

* These clouds touch the ground, which is 3 m below the leak orifice

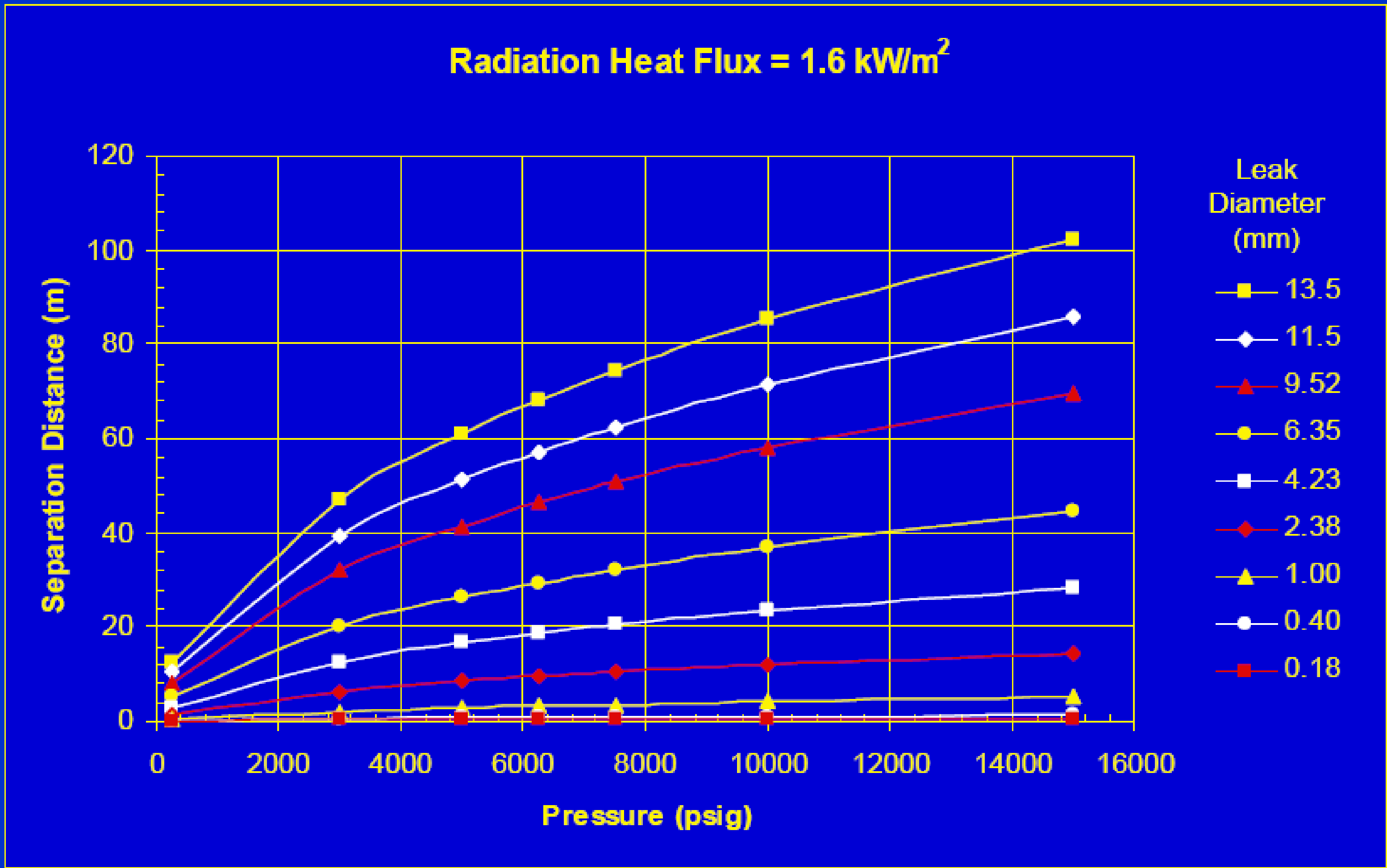
- IEC 60079-10 cannot predict the effect of cross wind on sizes of clouds depending on leak direction

Risk-Informed Separation Distances for Hydrogen Fueling Stations

Jeffrey LaChance
Sandia National Laboratories

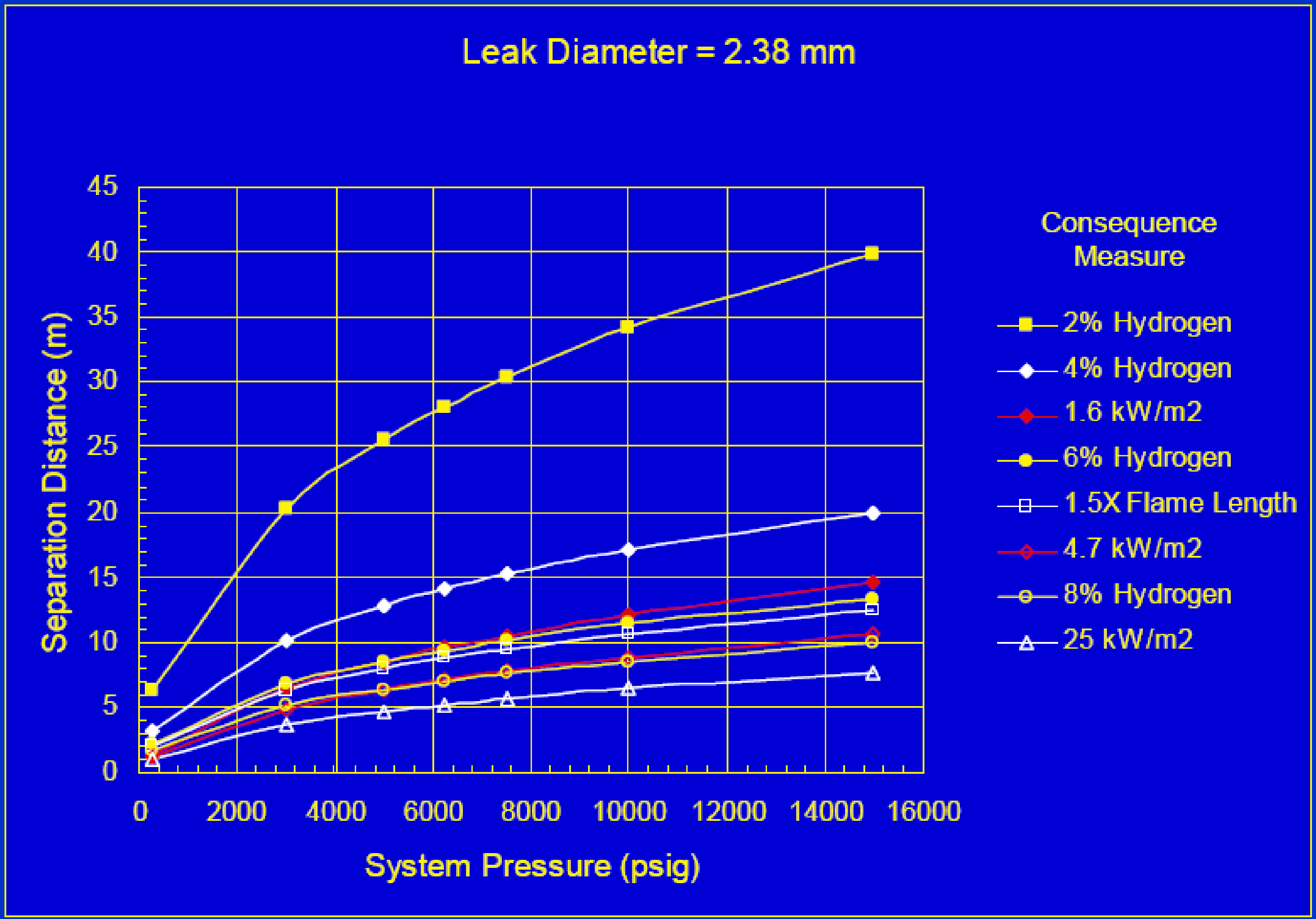
Courtesy of Jeff LaChance, SNL Albuquerque

Example of Consequence-Based Separation Distances for a Jet Fire



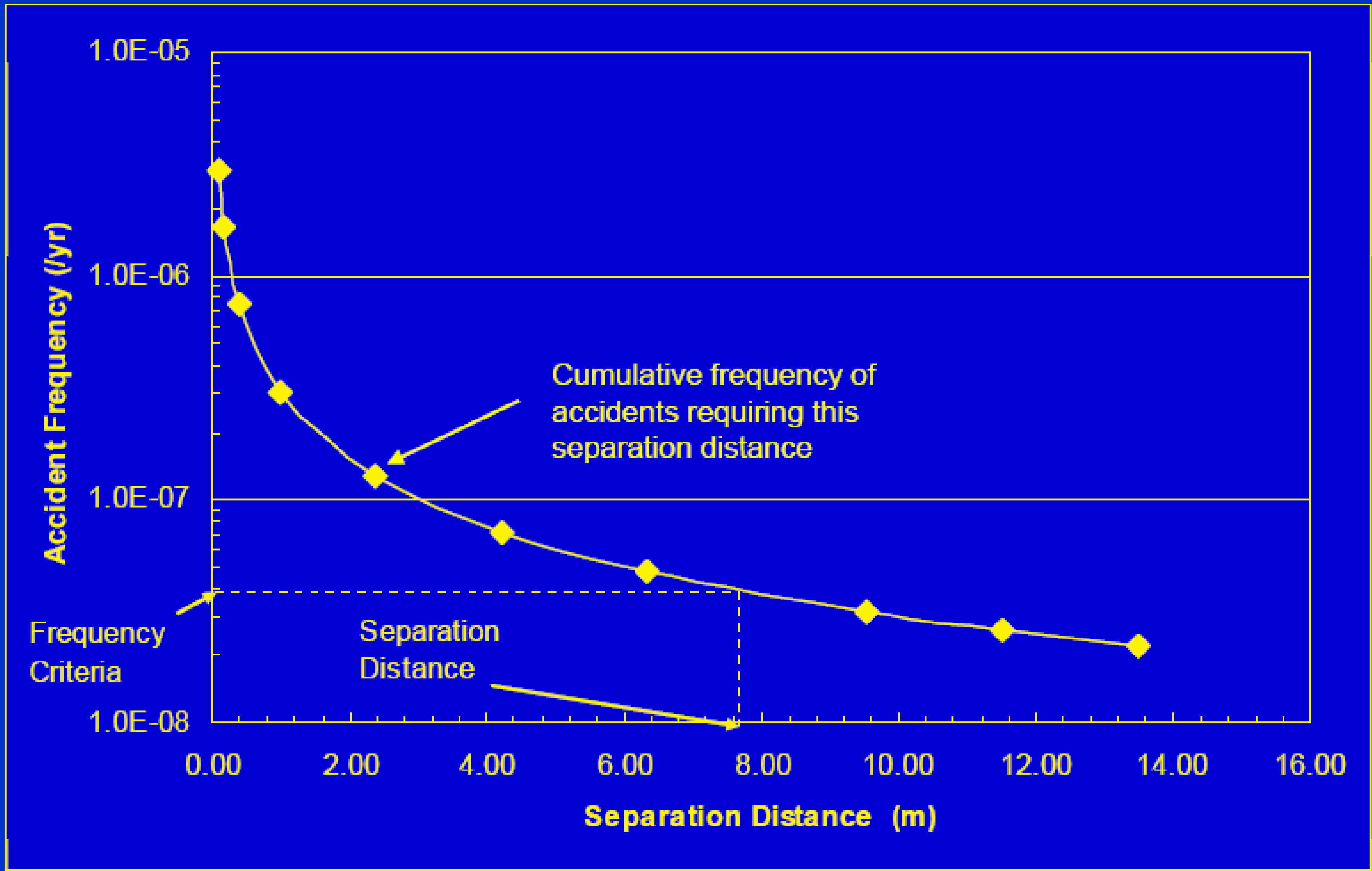
Courtesy of Jeff LaChance, SNL Albuquerque

Separation Distances for Different Consequence Measures



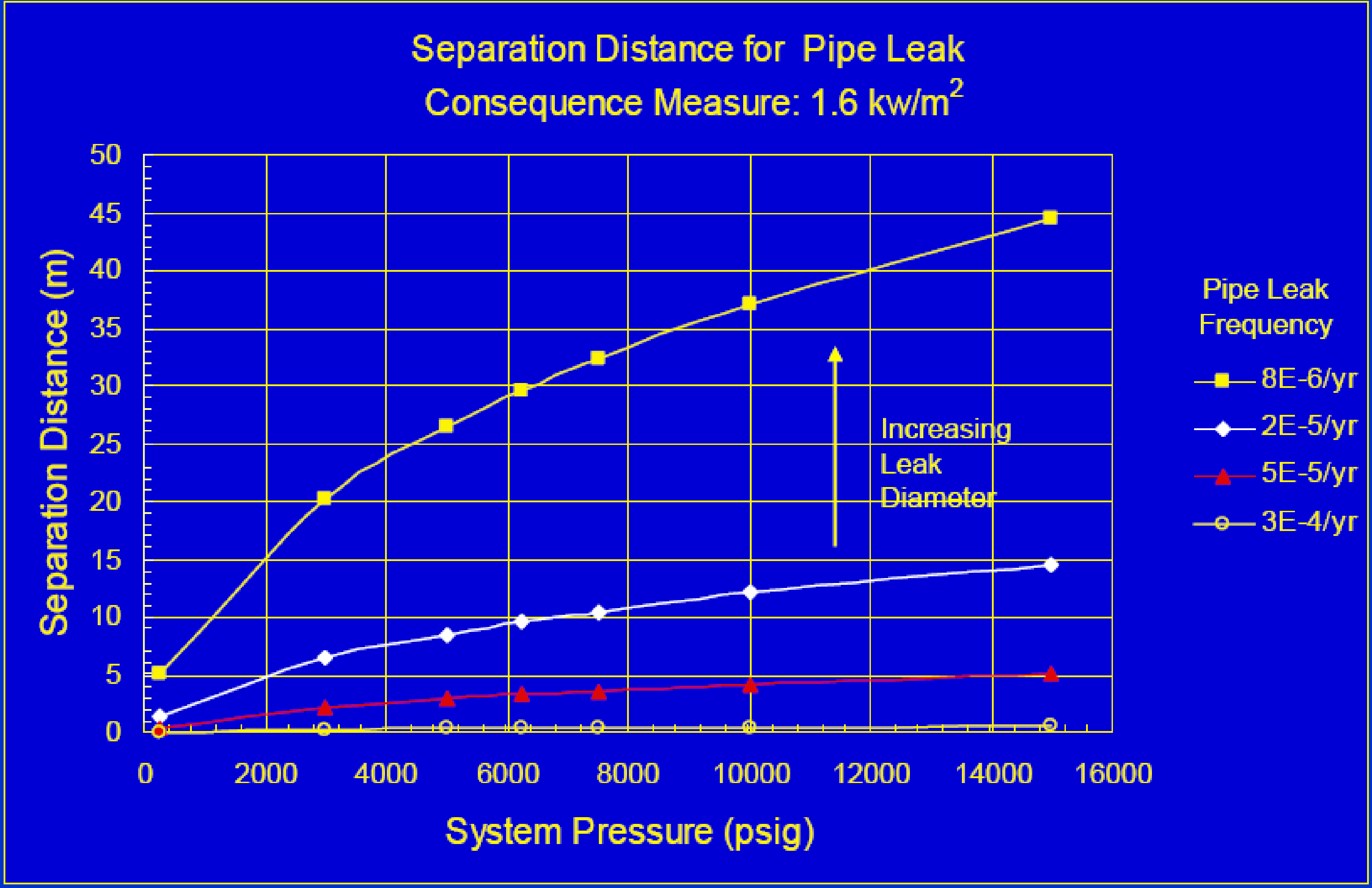
Courtesy of Jeff LaChance, SNL Albuquerque

Risk Approach for Establishing Separation Distances



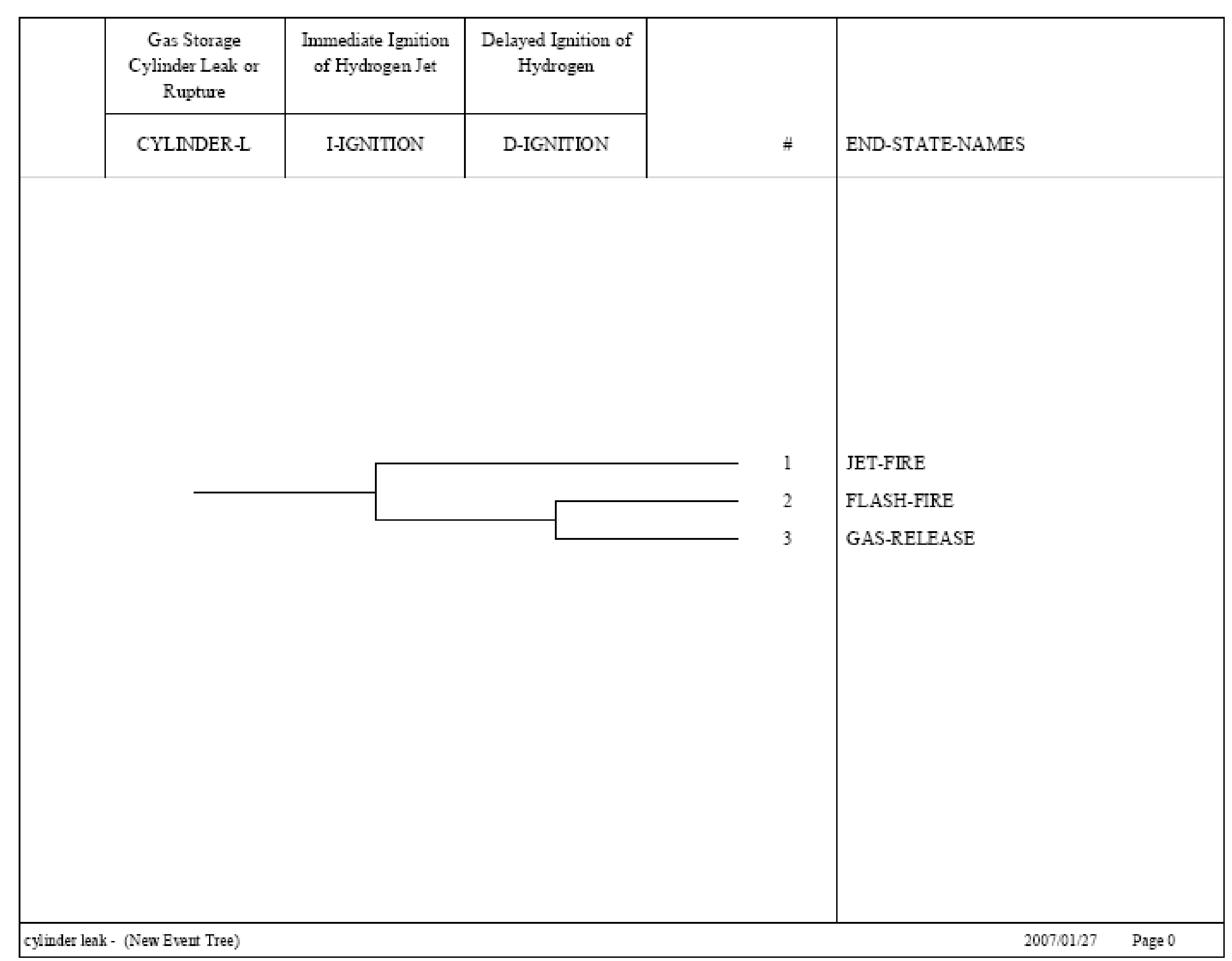
Courtesy of Jeff LaChance, SNL Albuquerque

Use of Risk Eliminates Large Leaks from Consideration



Courtesy of Jeff LaChance, SNL Albuquerque

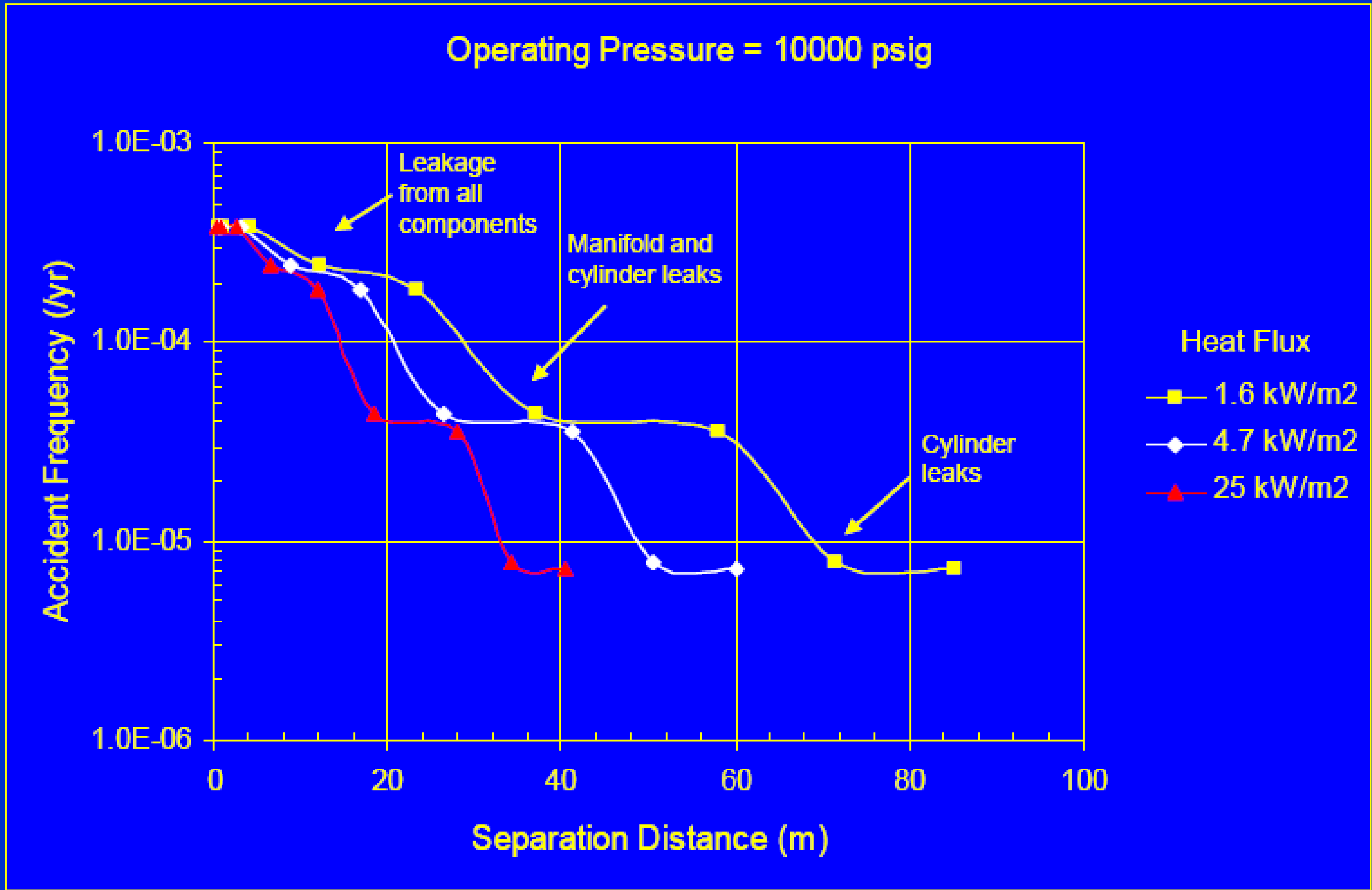
Gas Storage Leak Event Tree



Courtesy of Jeff LaChance, SNL Albuquerque

Gas Storage Results: Un-isolated Jet Fires

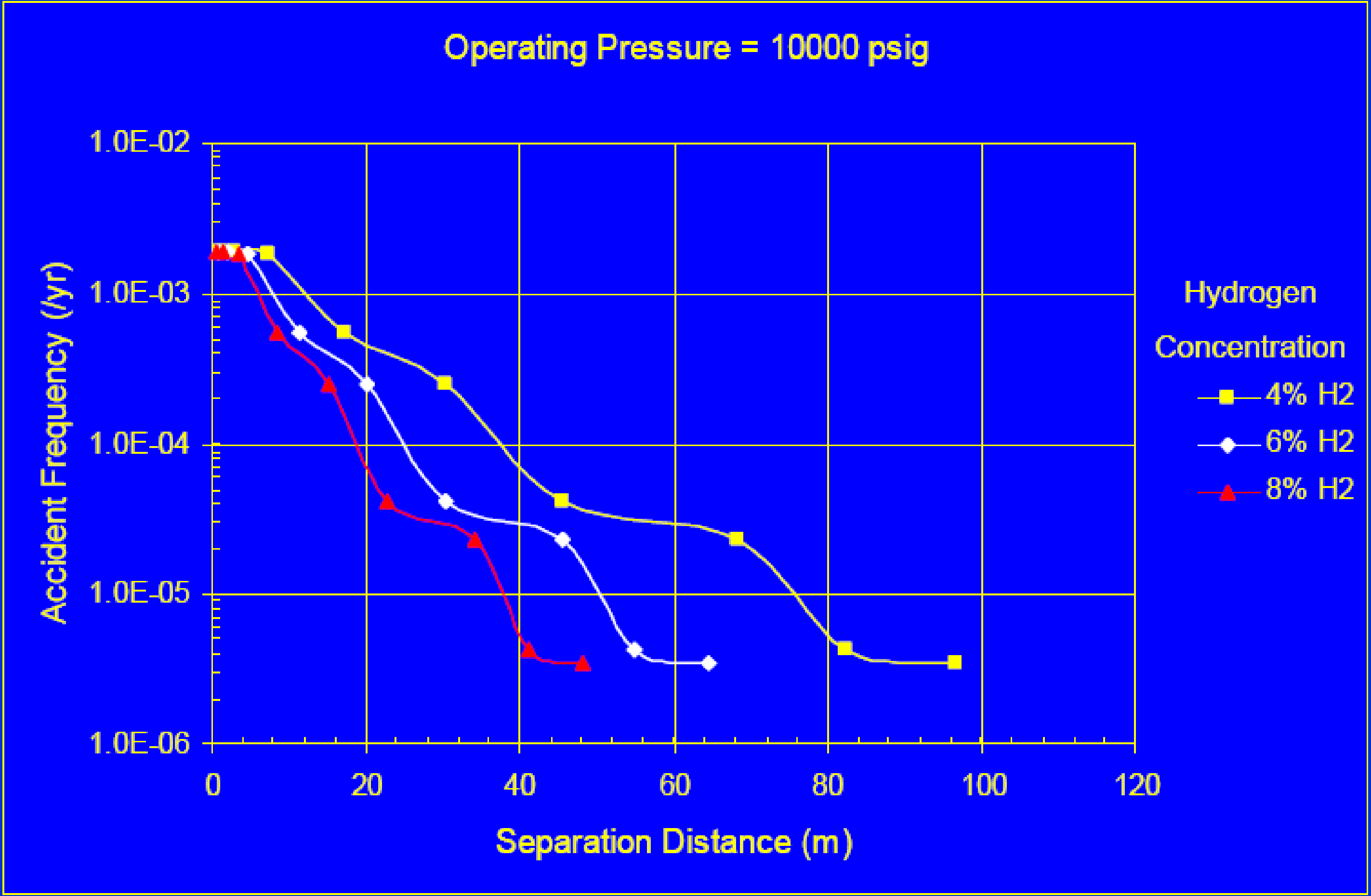
Risk-informed separation distances are affected by leakage contribution from different components.



Courtesy of Jeff LaChance, SNL Albuquerque

Gas Storage Results: Flash Fires

Flash fires require longer separation distances than jet fires.



Courtesy of Jeff LaChance, SNL Albuquerque

Development of Lower Detection Limit Requirements for Hydrogen Detection Apparatus Standard for ISO/TC 197 WG 13

- **Originally suggested lower detection limit – 100 ppm did not appear practical as it could become an operational nuisance – potential for frequent false alarms during refuelling**
- **This dictated the need for detailed analysis of potential hydrogen release scenarios from FC vehicles tail pipes (including CFD modeling) and review of the existing and forthcoming standards for FC vehicle safety**

Background

BALLARD®

- First Fuel Cell industry standard for vehicle-level H2 emissions released in 2002 (SAE J2578)
- Emission limit:
  - 1% H2 in continuous operation
  - 2% H2 for brief transients,
  - Limits based on the generally accepted Lower Flammability Limit (LFL) for H2 in air of 4%-vol
- But…LFL is based on:
  - Quiescent volume
  - Upward flame propagation

Question 1 – Does 4% LFL apply to flowing gas discharges?

Courtesy of Jake DeVaal, Ballard

Why? - Rationale for Change

BALLARD®

1) Normal fuel cell system function (vents, purges)

2) Failed Components (H2 leaks)

Emissions Limits

Lead to:

- System design constraints

- Shorter fuel cell stack lifetimes

(stack is prone to H2 leakage as components wear out)

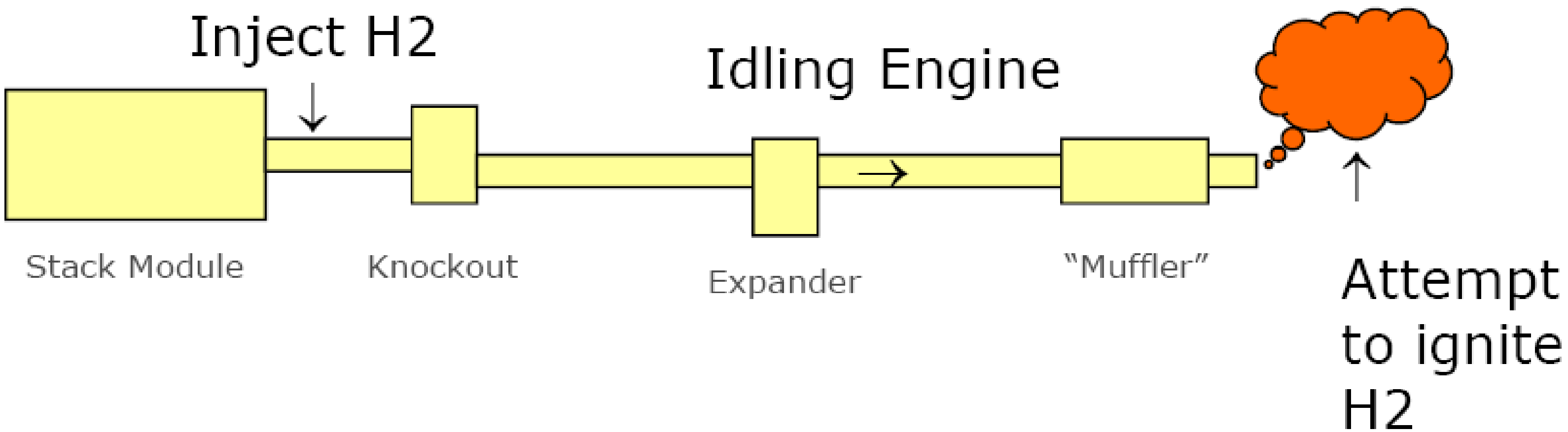
Incentive for rational limits!

Courtesy of Jake DeVaal, Ballard

Idle Flammability Testing

Test Method:

- inject a given flow rate of hydrogen into the vehicle air exhaust system downstream of stack
- attempt to ignite exiting idle air flow.



Courtesy of Jake DeVaal, Ballard

Conclusions – Flammability Tests

BALLARD®

- Idle flammability tests:
  - 4% H2 in the cathode exhaust is NOT flammable
  - Flammability threshold is near 8% H2
- Startup/Shutdown flammability tests:
  - Resulted in transient flame only, no damage to vehicles.
- These test methods are now referenced in the latest (draft) revision of SAE J2578.
- Option for automotive OEMs to base emissions limits on the results of performance-based tests.
  - Larger design space for fuel cell systems
  - Longer lifetimes for fuel cell stacks

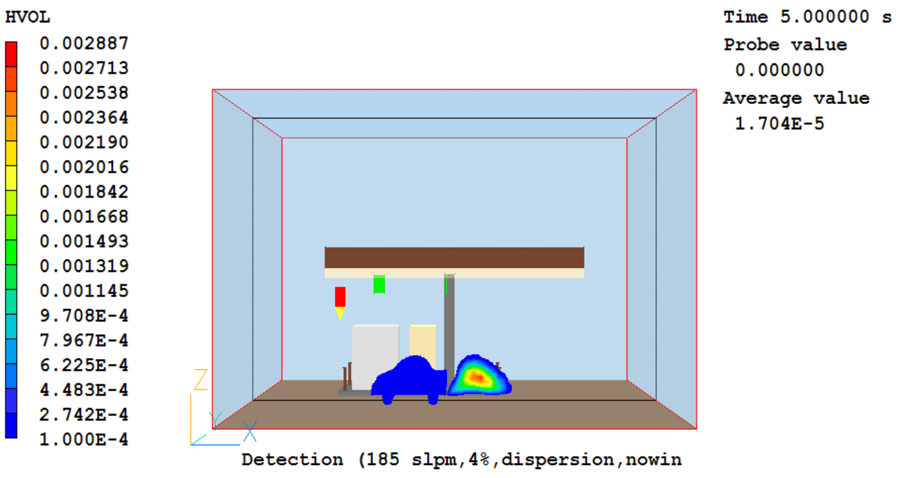
Courtesy of Jake DeVaal, Ballard

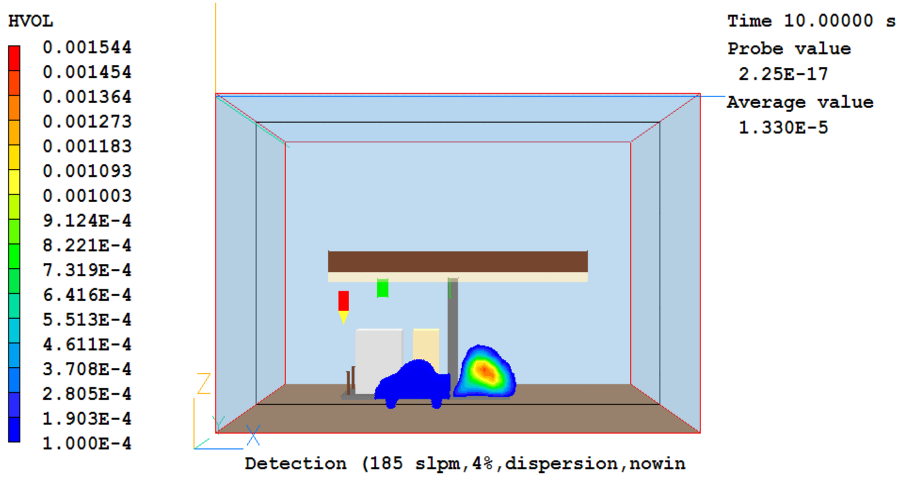
Development of Lower Detection Limit Requirements for Hydrogen Detection Apparatus Standard for ISO/TC 197 WG 13

Input Conditions for Simulations

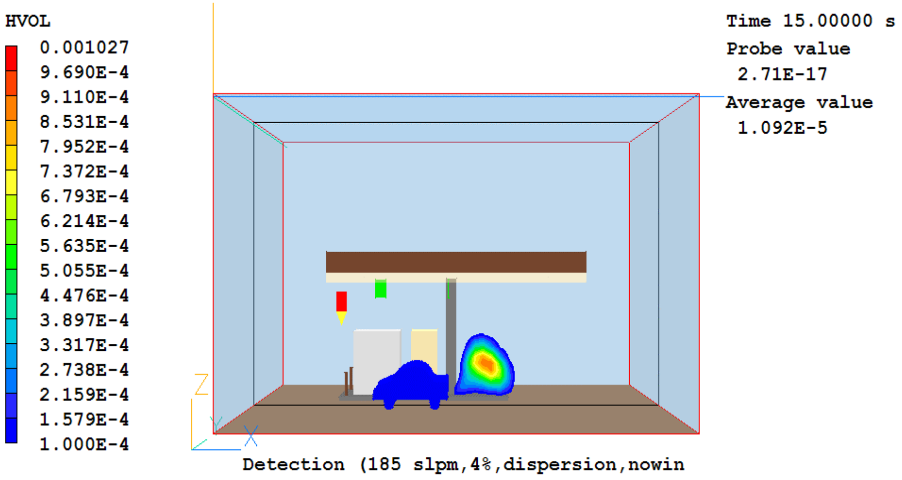
- Tail pipe emissions for 5 sec during shut down and start up of the FC vehicle
- Emissions concentration range: 4 to 10% vol. of hydrogen
- Idle flow rate – 185 slpm
- Dispersion simulation time – within 30 sec after the end of the 5-sec release

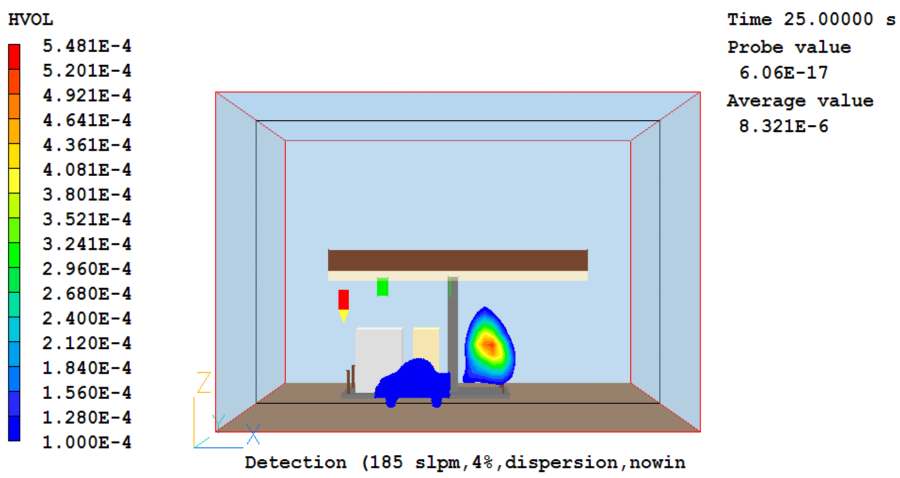
Tailpipe Emissions Dispersion Simulations



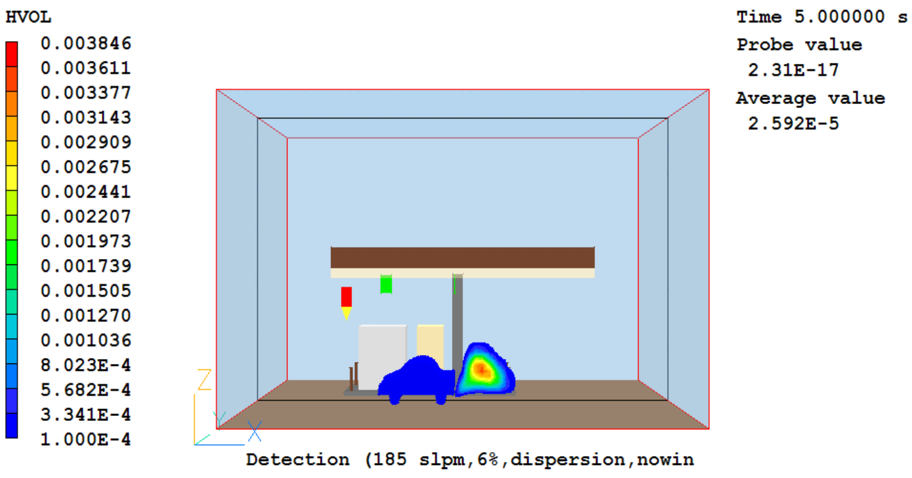


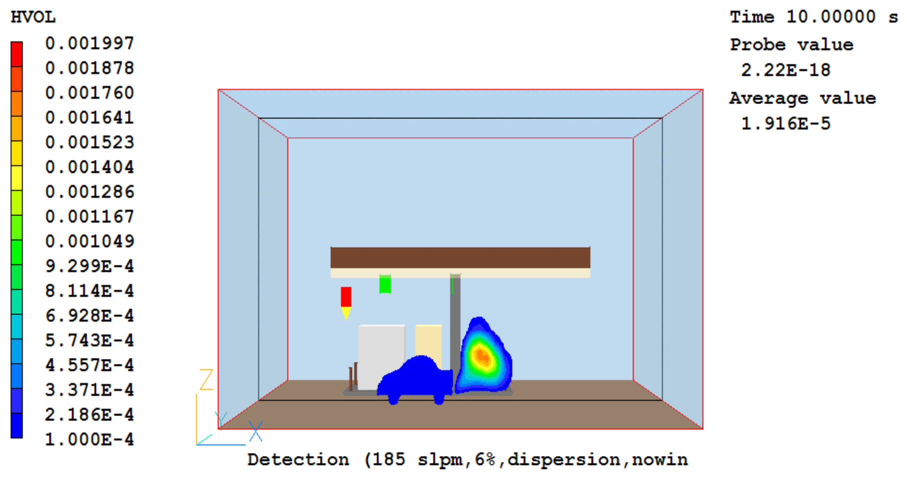
4% vol.



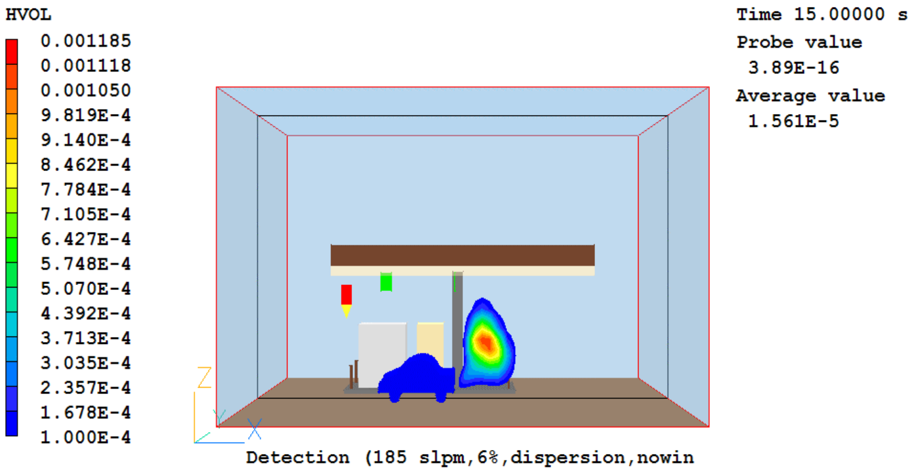


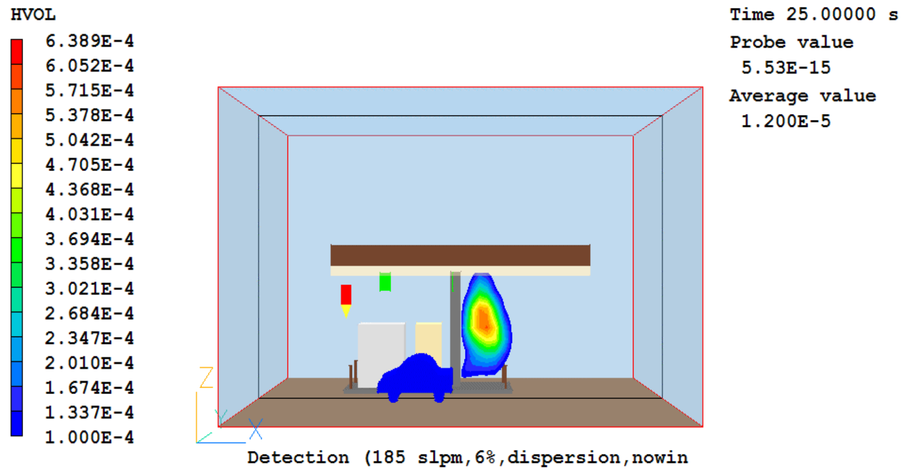
Tailpipe Emissions Dispersion Simulations



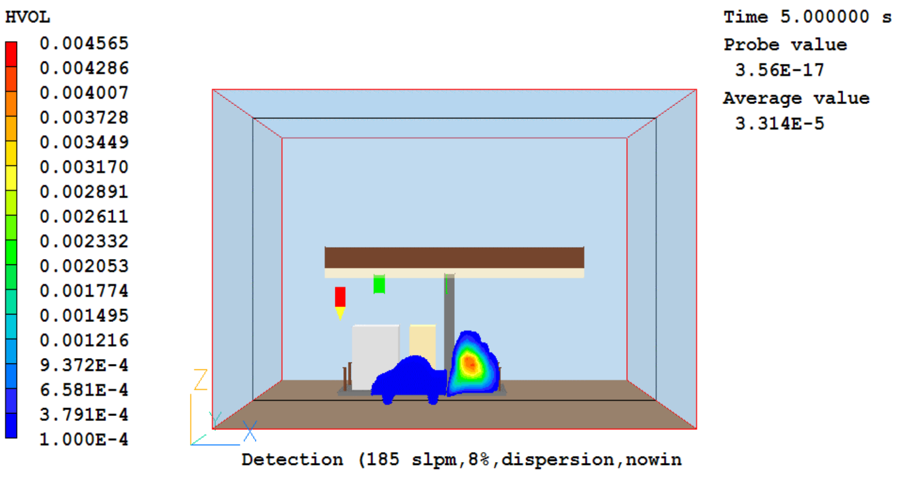


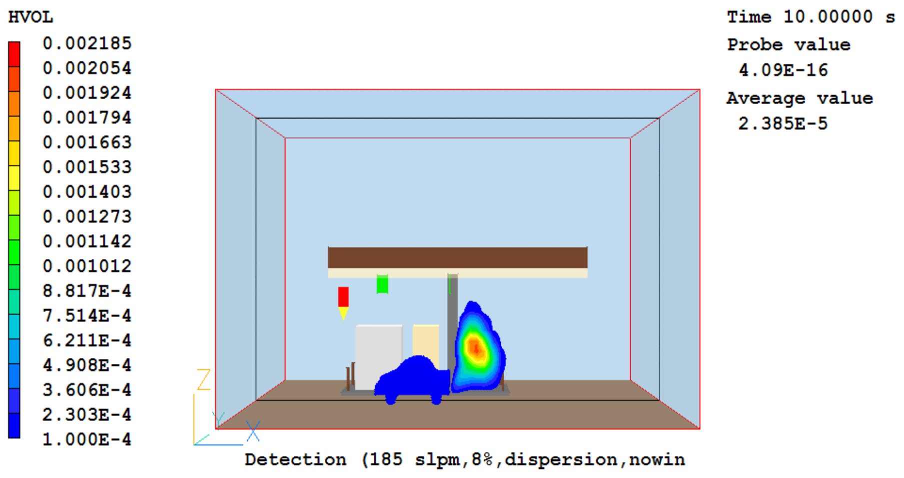
6% vol.



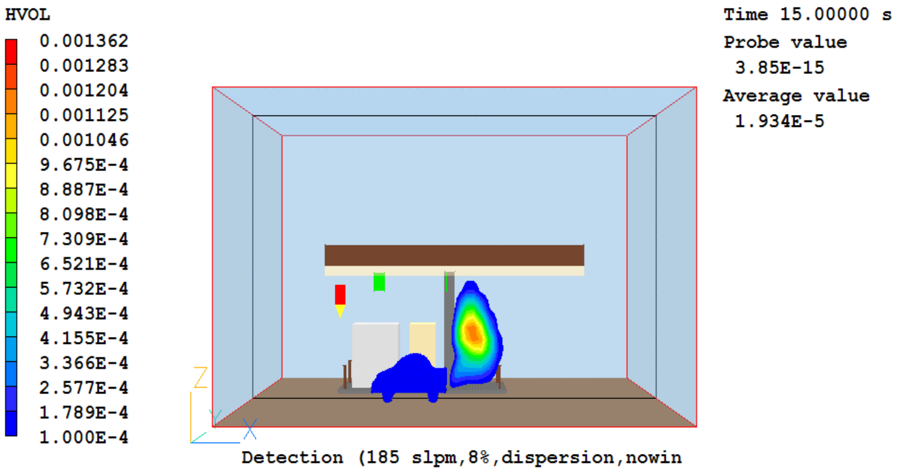


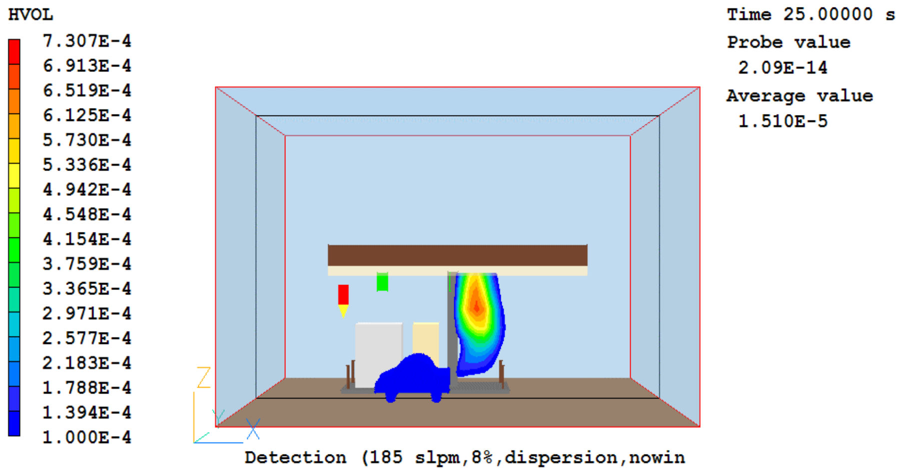
Tailpipe Emissions Dispersion Simulations



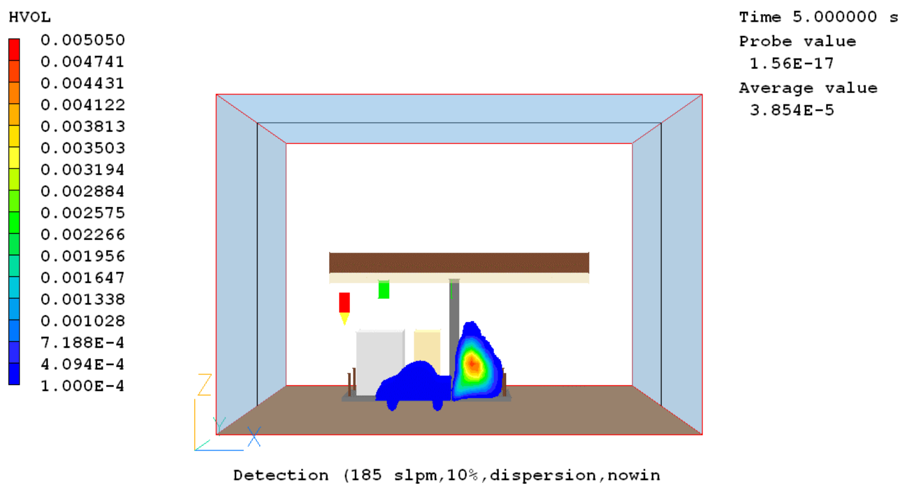


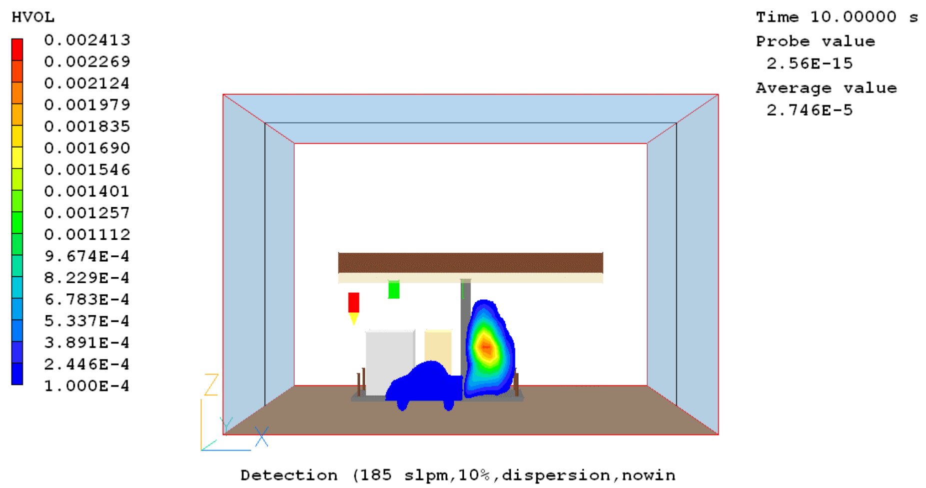
8% vol.



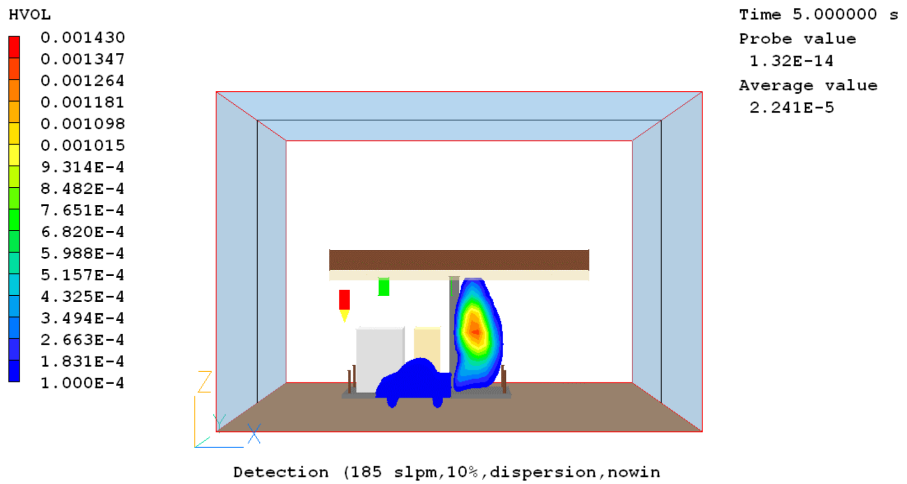


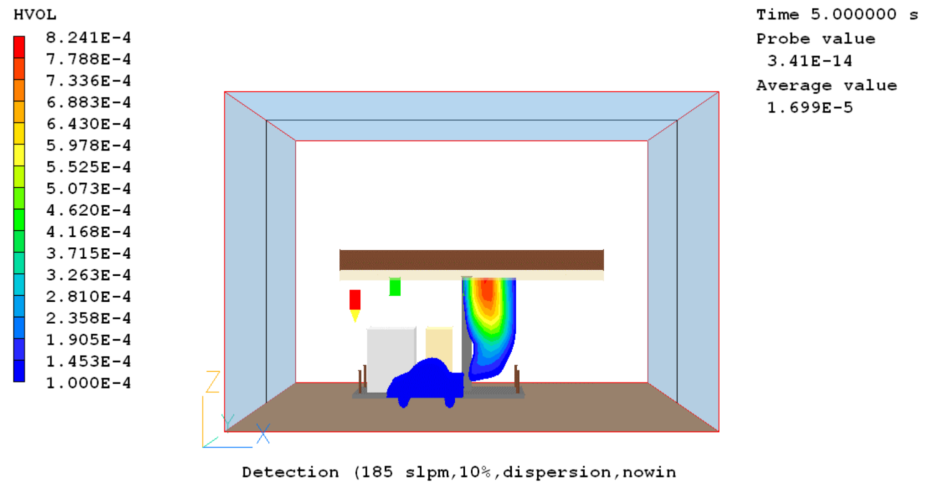
Tailpipe Emissions Dispersion Simulations





10% vol.





Developed Recommendation for WG 13

- Increase the lower detection limit by the factor of 10 to 1,000 ppm. This will ensure that:
  - ✓ No false alarms occur during refuelling of compliant vehicles.
  - ✓ Only vehicles emitting higher than 8% vol. concentrations will set off the alarm.

Conclusions

- Hydrogen codes and standards need to take into account
  - ✓ Unique hydrogen properties, as well as
  - ✓ Specific hazards associated with the use of hydrogen.
- Selection of appropriate risk criteria is one of the key conditions for developing uniform and consistent codes and standards' requirements.
- Use of CFD analysis as well as probabilistic risk assessment might be necessary to help develop those requirements.

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Belfast, 30 July – August 8, 2007

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Risk-Informed and Science-Based Approach to Hydrogen Codes and Standards

Andrei V. Tchouvelev

THE END