Risk-Informed Separation Distances for H_2 Facilities

Jay Keller (Presenting)

Daniel Dedrick, Greg Evans, Bill Houf, Chris Moen, Jeff LaChance, Adam Ruggles, Bob Schefer, Bill Winters, Yao Zhang

Sandia National Laboratories

Erik Merilo, Mark Groethe

SRI

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SCS011

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C&S Enable H_2 Infrastructure Development

Consider Refueling Stations:

- 76 stations in the US and Canada (Oct 2008)

NHA 2010 Fuel Cell Report

Courtesy of Air Products

Availability of fuel within existing fueling station footprint is integral to hydrogen infrastructure development

Need a defensible and traceable basis for Regulations, Codes and Standards

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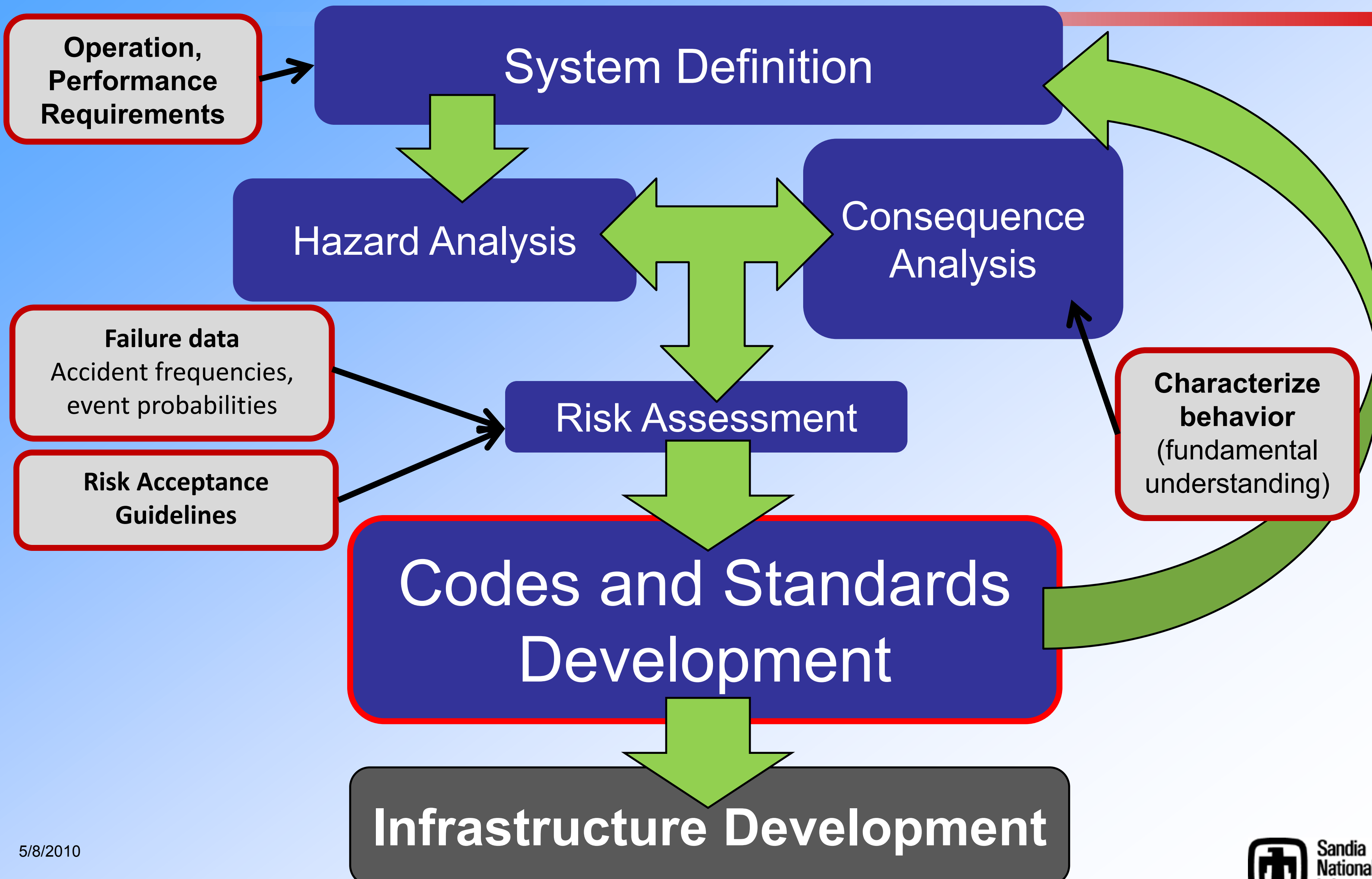
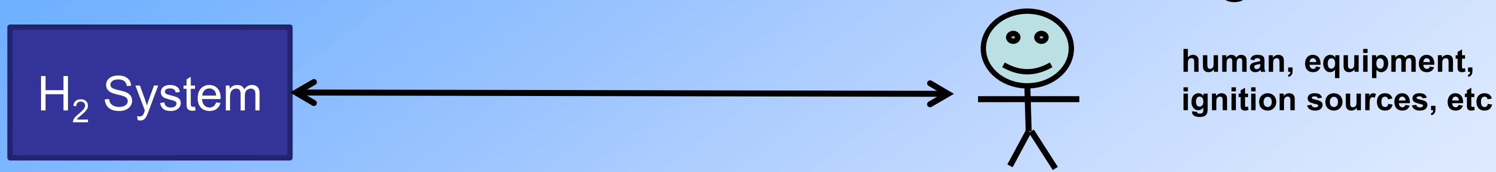
Risk-Informed C&S are Integral to Infrastructure Development



Separation Distances Define the Spatial Requirements

- Specified distances between a hazard and a target



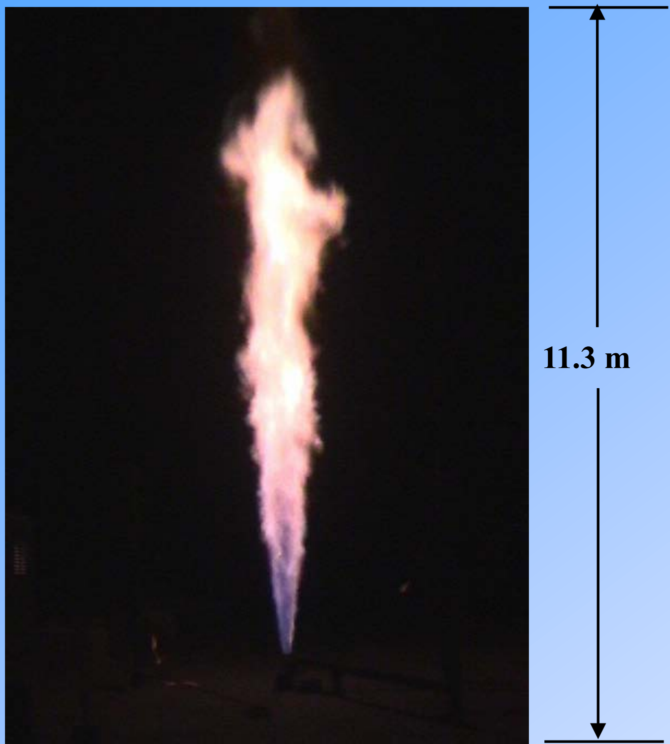
  - Established distances did not reflect high pressures (70 MPa)
  - Basis for established distances are undocumented

- Several options to establish new separation distances
  - Subjective determination (expert judgment)
  - Deterministically, based on leak scenario
  - Based only on risk evaluation as suggested by the European Industrial Gas Association (IGC Doc 75/07/E)

Risk-informed process combines risk information, deterministic analyses, and expert judgment

→ Appropriate and effective requirements

Quantifying the Consequence of a H_2 Release is Integral



Nighttime photograph of 41 MPa large-scale H_2 jet-flame test (d_j = 5.0mm) from Sandia/SRI tests.

- Exposure to a H_2 plume can result in
  - Heating from radiation
  - Flame impingement
  - Combustible cloud contact (unignited jet)
- Experimental measurements are necessary to characterize behavior
  - Flame shape and impingement distances vs flow rates
  - Hydrogen flame radiation values
  - Lean ignition limits for hydrogen/air
- Computational models are built and validated with experiments
  - Jet flame radiation model
  - Unignited jet flammability limit model

Allows for mitigation strategies (e.g. detection)

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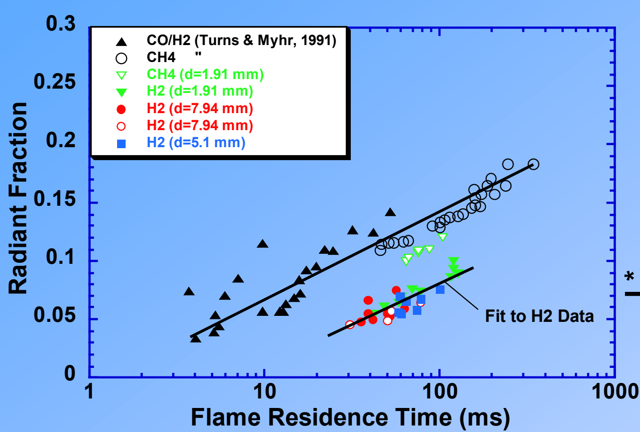
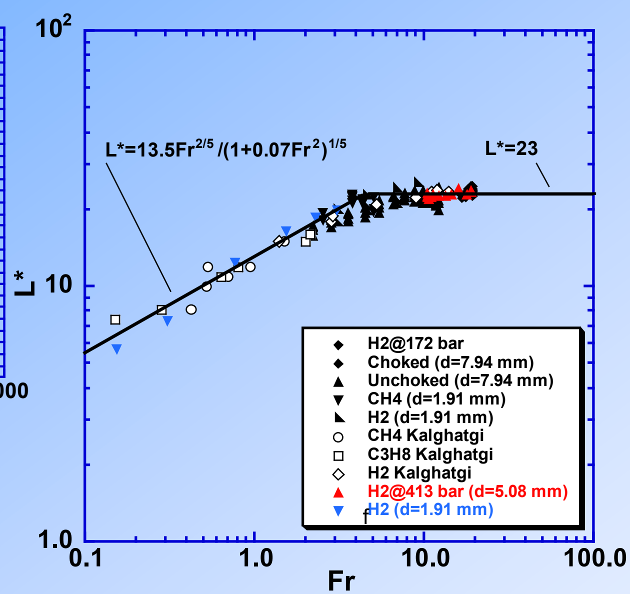
Validated Engineering Model is Based on Jet-flame Correlations

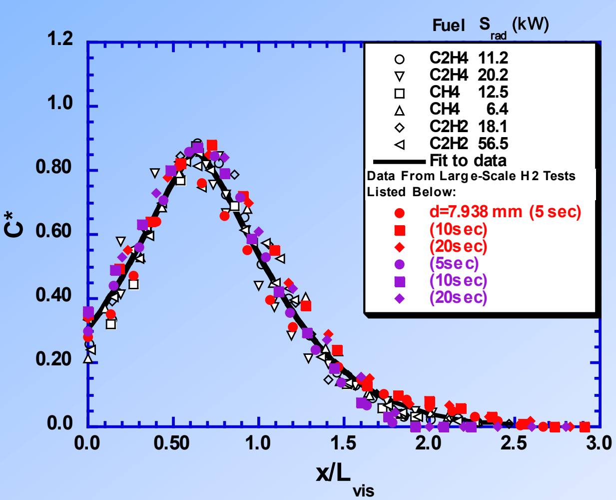
Radiant Fraction (X_{rad})



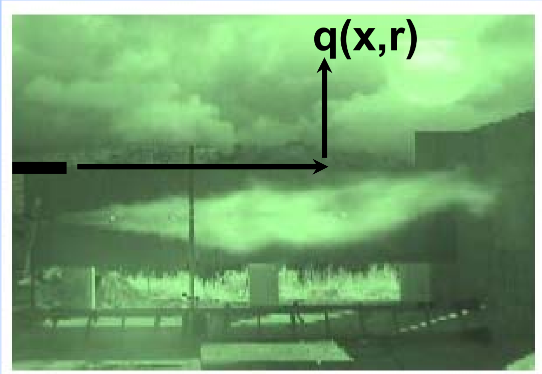
Visible Flame Length



Radiant Power



- SRI Test Facility
- Baseline circular nozzle, 7.94 mm



Horizontal Flame

3.6 - 4.3 m long, 0.6 - 1m wide

$$q(x,r) = \frac{C^* X_{rad} m_{fuel} \Delta H_c}{r^2}$$

H_2 jet-flame radiation model verified at press. of (17 & 41 MPa)

(1) Houf & Schefer, "Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen," Int. Jour. Hydrogen Energy, Vol. 32, pp. 136-151, 2007.

(2) Schefer, Houf, Bourne, Colton, "Spatial and Radiative Properties of an Open-Flame Hydrogen Plume," Vol. 31, pp. 1332-1340, 2006.

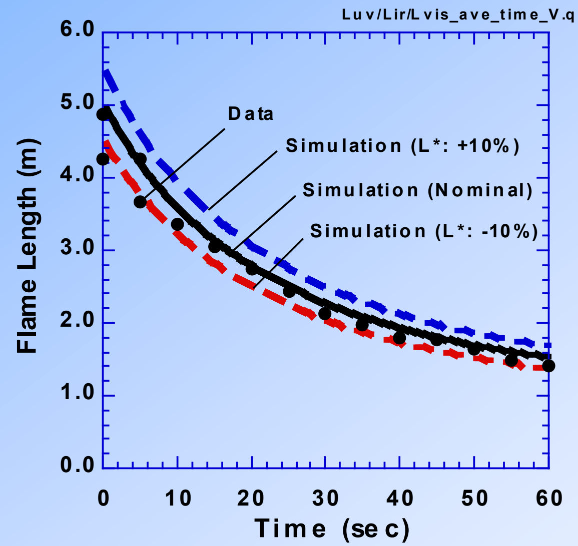
(3) Schefer, Houf, William Bourne, Colton, "Characterization of High-Pressure Underexpanded Hydrogen-Jet Flames," Vol. 32, pp. 2081-2093, 2007.

Model Reproduces H_2 Jet-flame Data

SRI Test Facility
Baseline circular nozzle, 7.94 mm

Horizontal Flame

3.6 - 4.3 m long, 0.6 - 1m wide

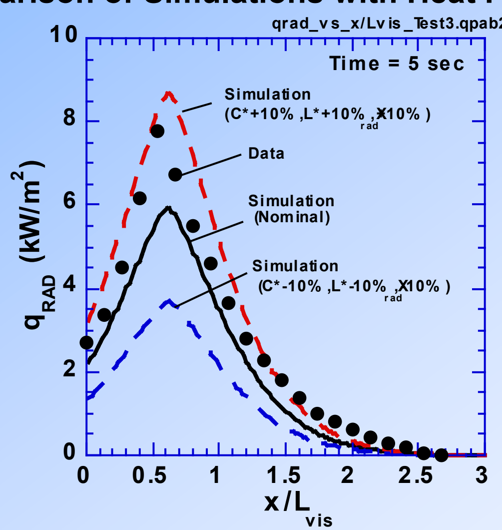


Simulation of SRI/Sandia Jet Flame Experiment

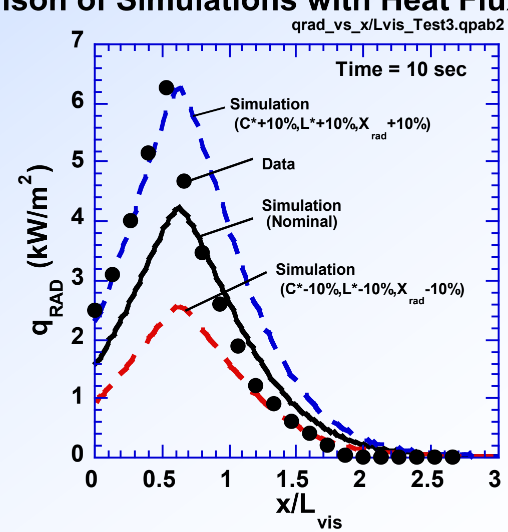
Tank Pressure = 17 MPa

Tank Volume = 0.098 m³

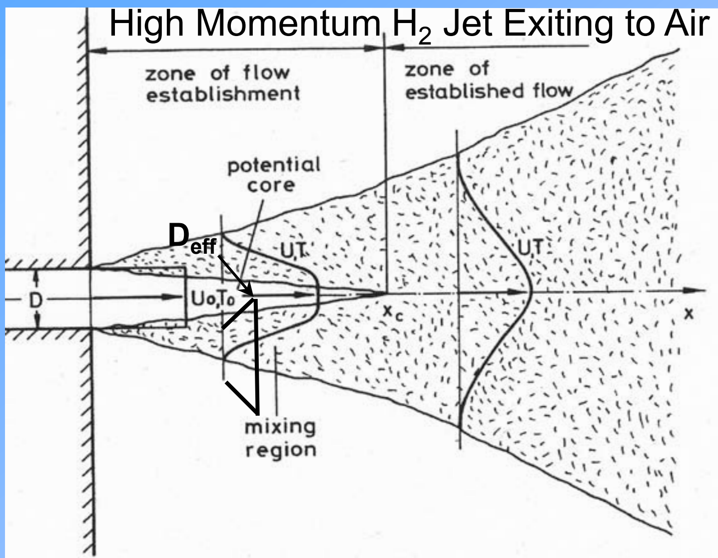
Comparison of Simulations with Heat Flux Data



Comparison of Simulations with Heat Flux Data



Model Predicts Flammability Region for High-Momentum H_2 Jets

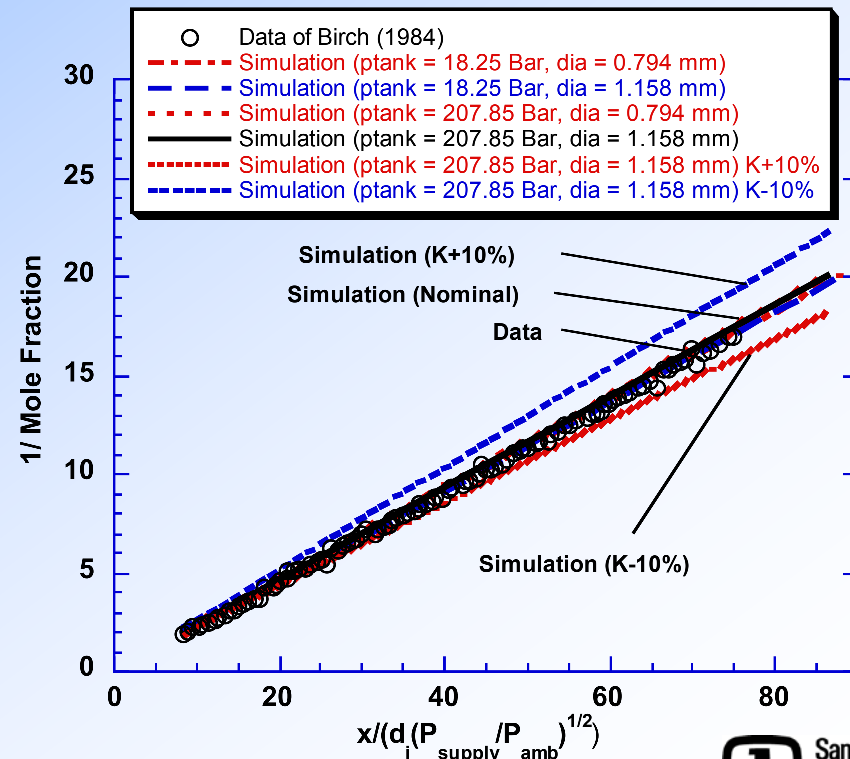


- Effective diameter nozzle expansion for underexpanded jet
  - $D_{eff} = (\rho_{exit} V_{exit} / \rho_{eff} V_{eff}) D$
  - $V_{eff} = V_{exit} + (P_{exit} - P_{amb}) / \rho_{exit} V_{exit}$

- Entrainment law for turbulent jets
  - $C_{cl}(x) = KD/(X+X_o)(\rho_{amb}/\rho_{H_2})1/2$
  - $C(x,r) = C_{cl}(x)\exp(-K_c (r/(x+x_o))2)$
  - $K_c = 57$; $K = 5.40$; D = Diameter

- Model based on experimental data
  - Verified against natural gas and ethylene jets data of Birch et al., 1984
  - Adapted to H_2 properties
  - Verified using H_2 Navier-Stokes CFD

Predicted Jet Centerline Concentration vs Natural Gas Data



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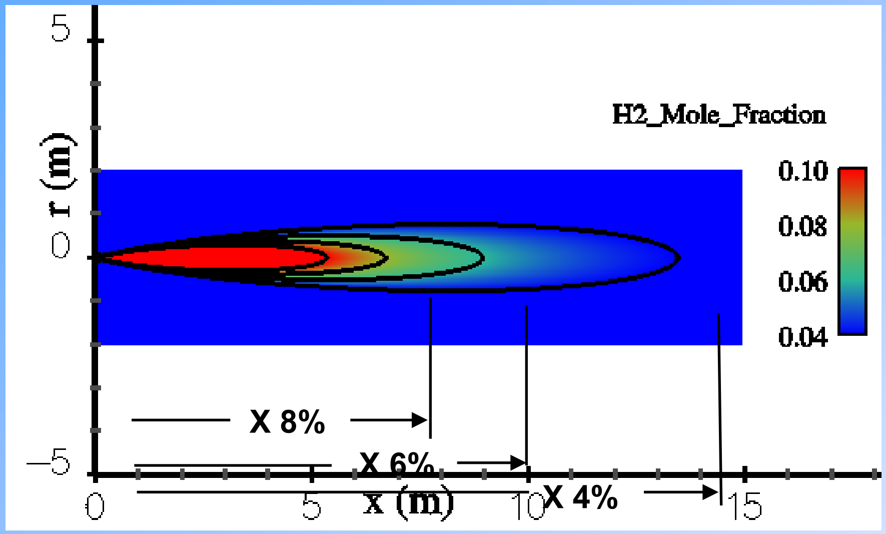
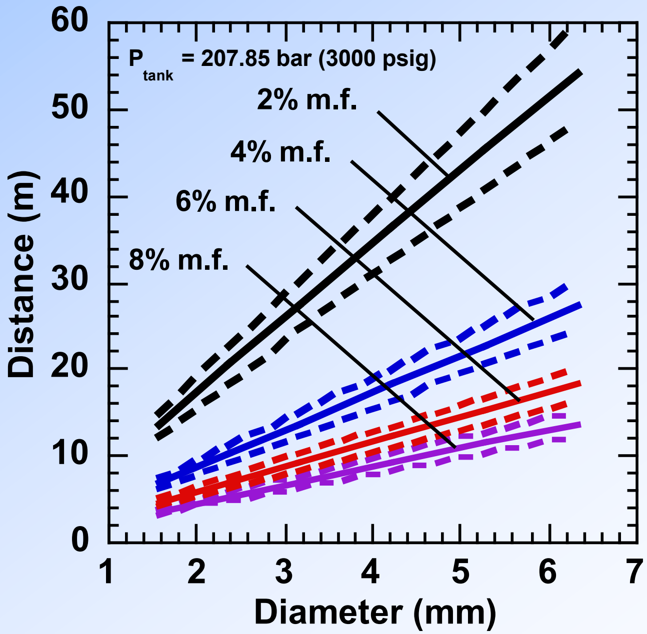
Predicted Flammability Region for High-Momentum H_2 Jets

Simulation of H_2 Concentration in a High Momentum Jet Exiting into Air 20.8 MPa, Dia. = 3.18 mm



Pressure = 20.8 MPa



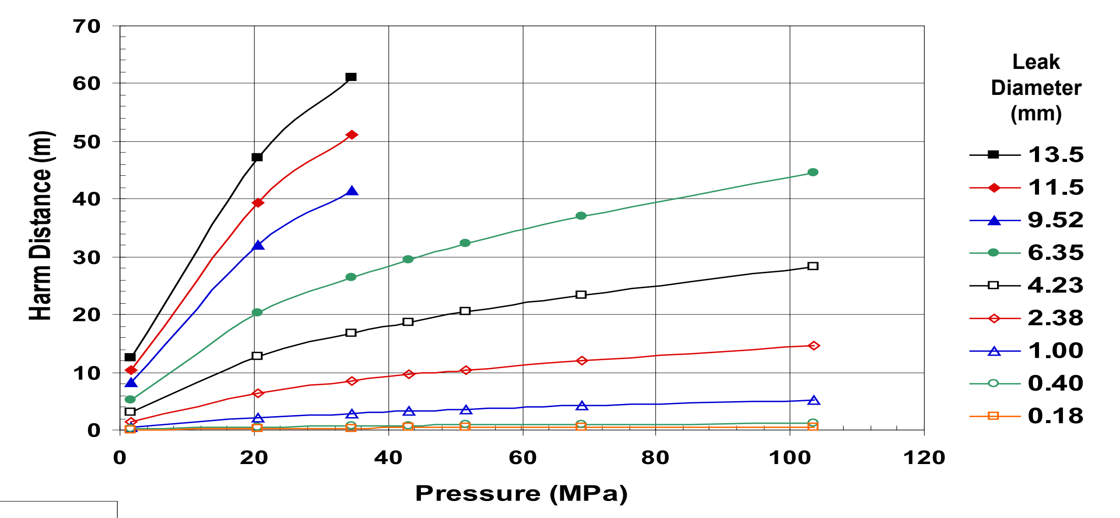
- Lower Flammability Limits for H_2*
  - Upward-propagating flame - 4% v.f.
  - Horizontal-propagating flame - 7.2% v.f.
  - Downward-propagating flame - 9.5% v.f.

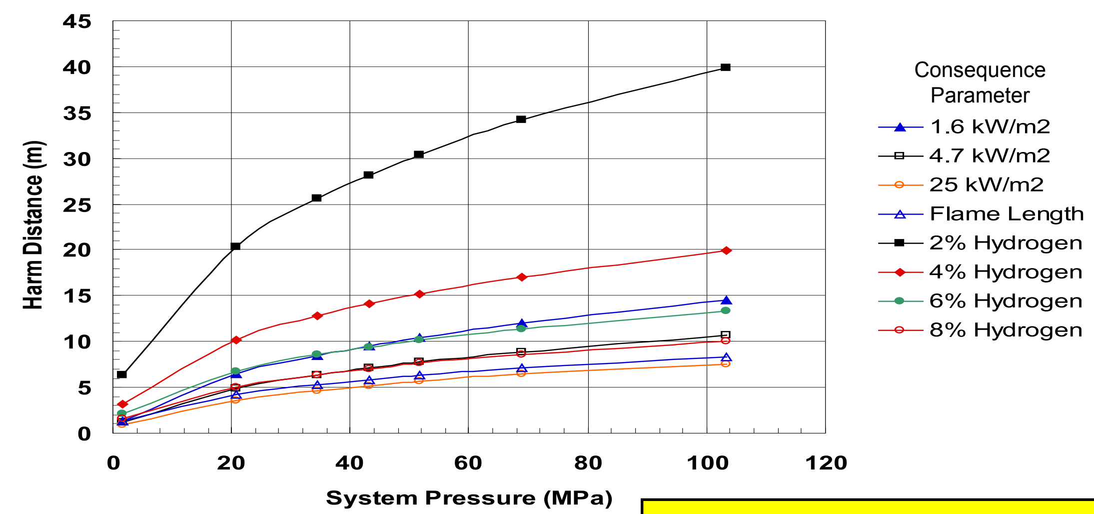
10-20% uncertainty in hazard length scales

*(Coward and Jones, 1952) (Zebetakis, 1965)

Deterministic-based separation distances vary significantly

Harm Distances for a Jet Fire – 1.6 kW/m² Radiation Heat Flux





Harm Distances for Different Consequence Measures – 2.38 mm Leak

Need to select leak diameter with a risk-informed approach

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NFPA Risk-Informed Approach to Select Leak Diameter

- Select typical gaseous storage systems as basis for evaluation
- Examine appropriate leakage data to determine leak size distribution
  - Selected leak size that encompasses a 95% percent of leaks within the typical systems and could be expected during the lifetime of a facility
- Used QRA to determine if risk from leaks greater than selected leak size is acceptable for typical systems

Data needed: component leakage frequency

Very little hydrogen-specific data available:

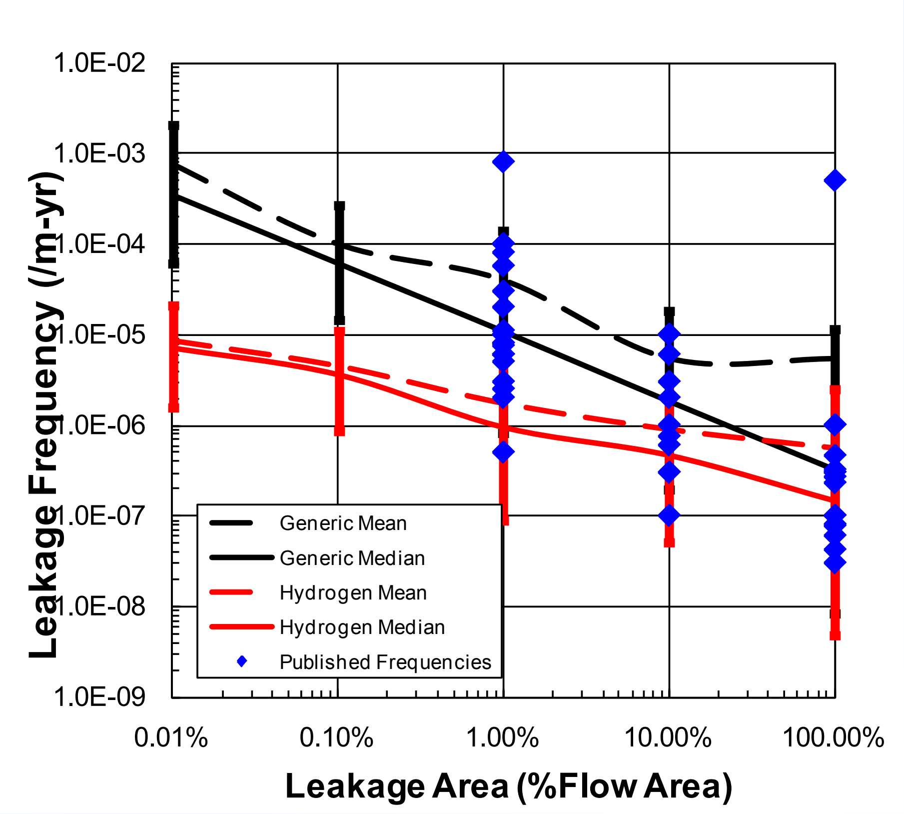
- Not enough for traditional statistical approach
- Instead, representative values are selected from NG systems

Problems with this approach:

- not hydrogen specific
- Parameter uncertainty distribution is uncharacterized

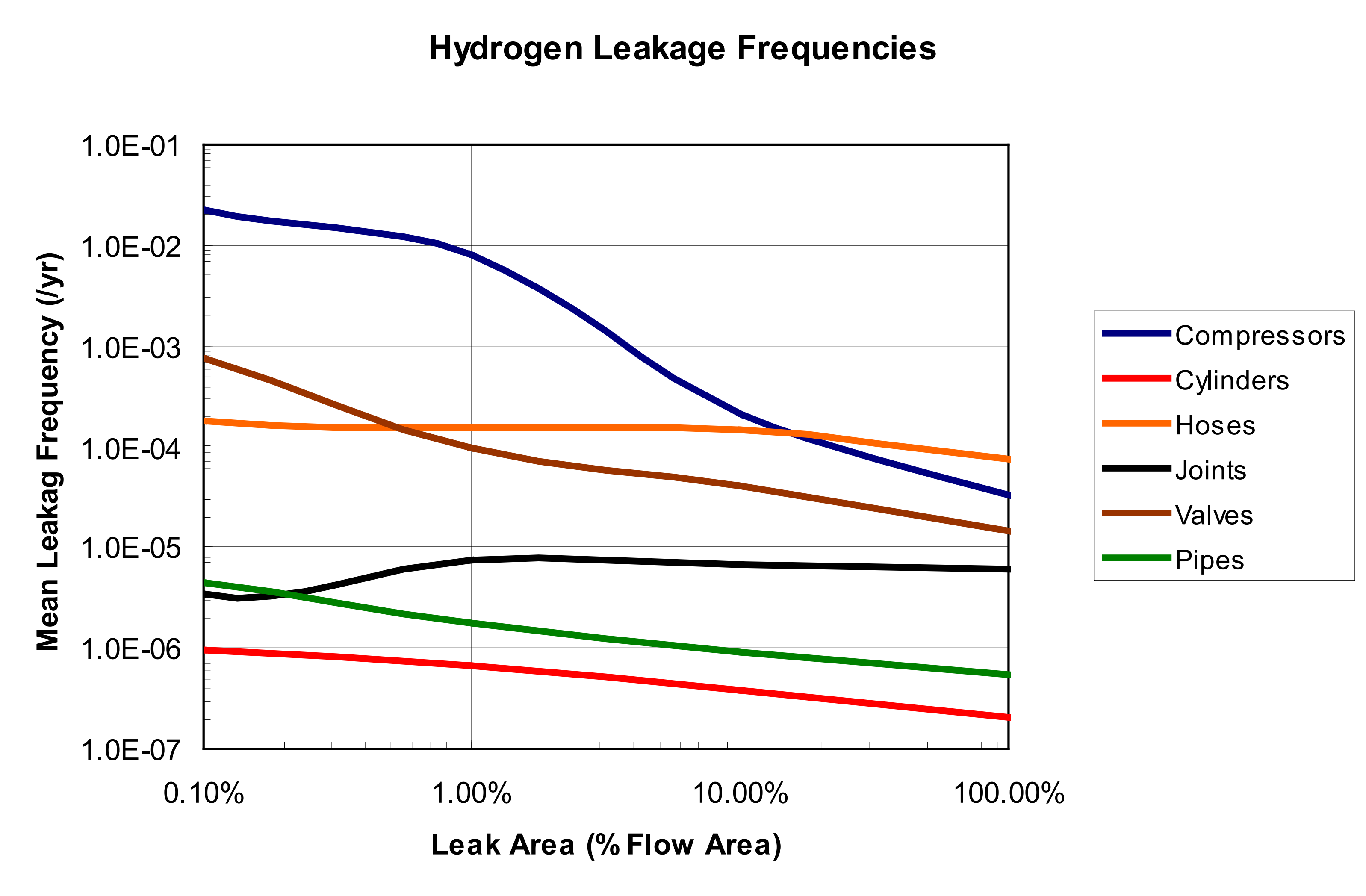
Solution:

- Use Bayesian statistics to generate leakage frequencies
  - Combine sources of generic data with H2 specific data
- Allows attachment of different “layers” of significance to the data



Reference: “Handbook of Parameter Estimation for Probabilistic Risk Assessment,” NUREG/CR-6823, U.S. Nuclear Regulatory Commission, Washington, D.C. (2003).

Mean Component Leakage Frequencies from Bayesian Analysis



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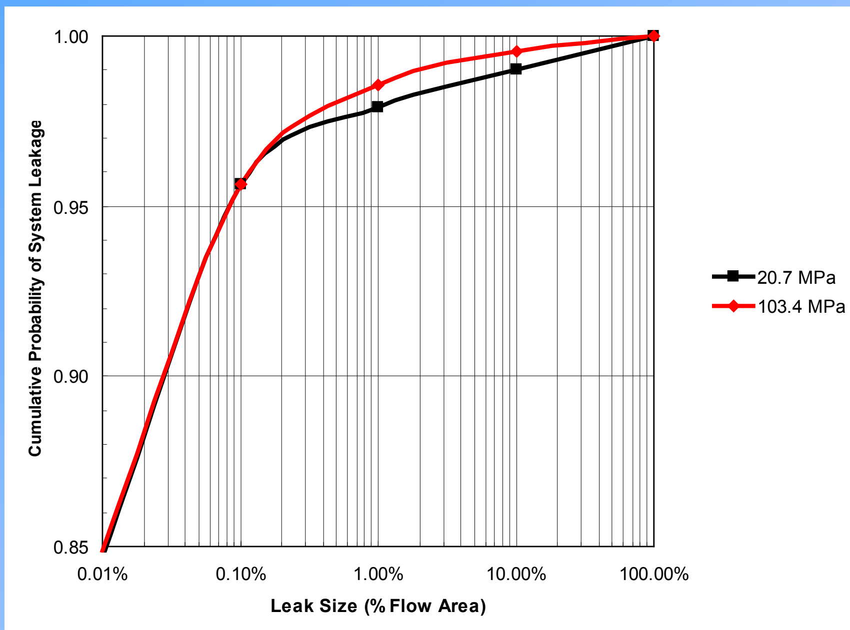
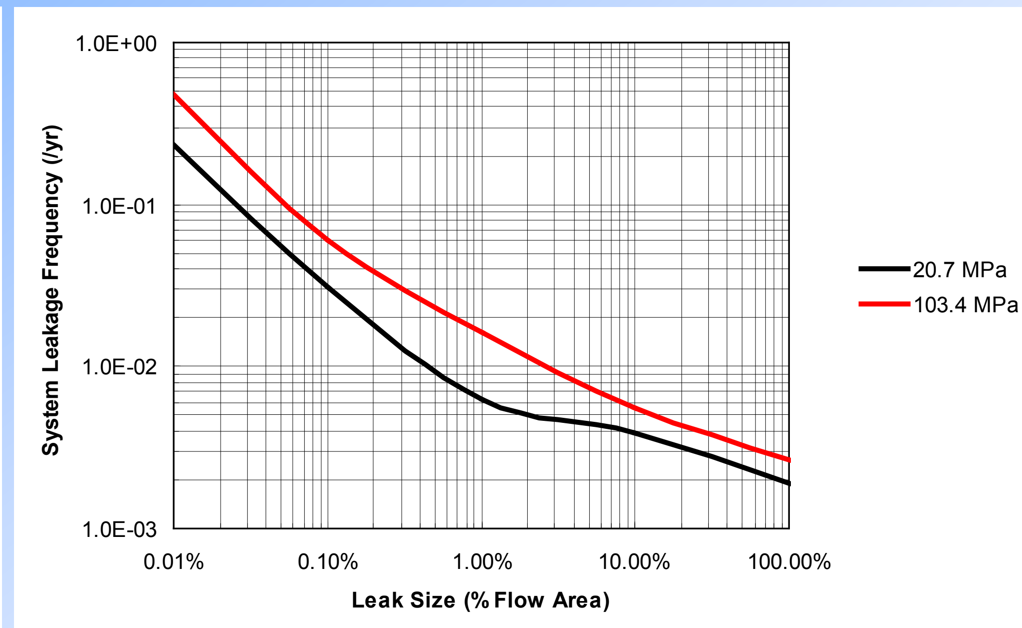
Bayesian leak-frequency data determines system leakage probability

Considering the representative facility layout diagrams:





Expert opinion used to select 3% of system flow area

- captures >95% percent of the leaks
- the resulting separation distances protect up to the 3% leak size
- A risk analysis (QRA) performed to determine if associated risk from leaks greater than this is acceptable

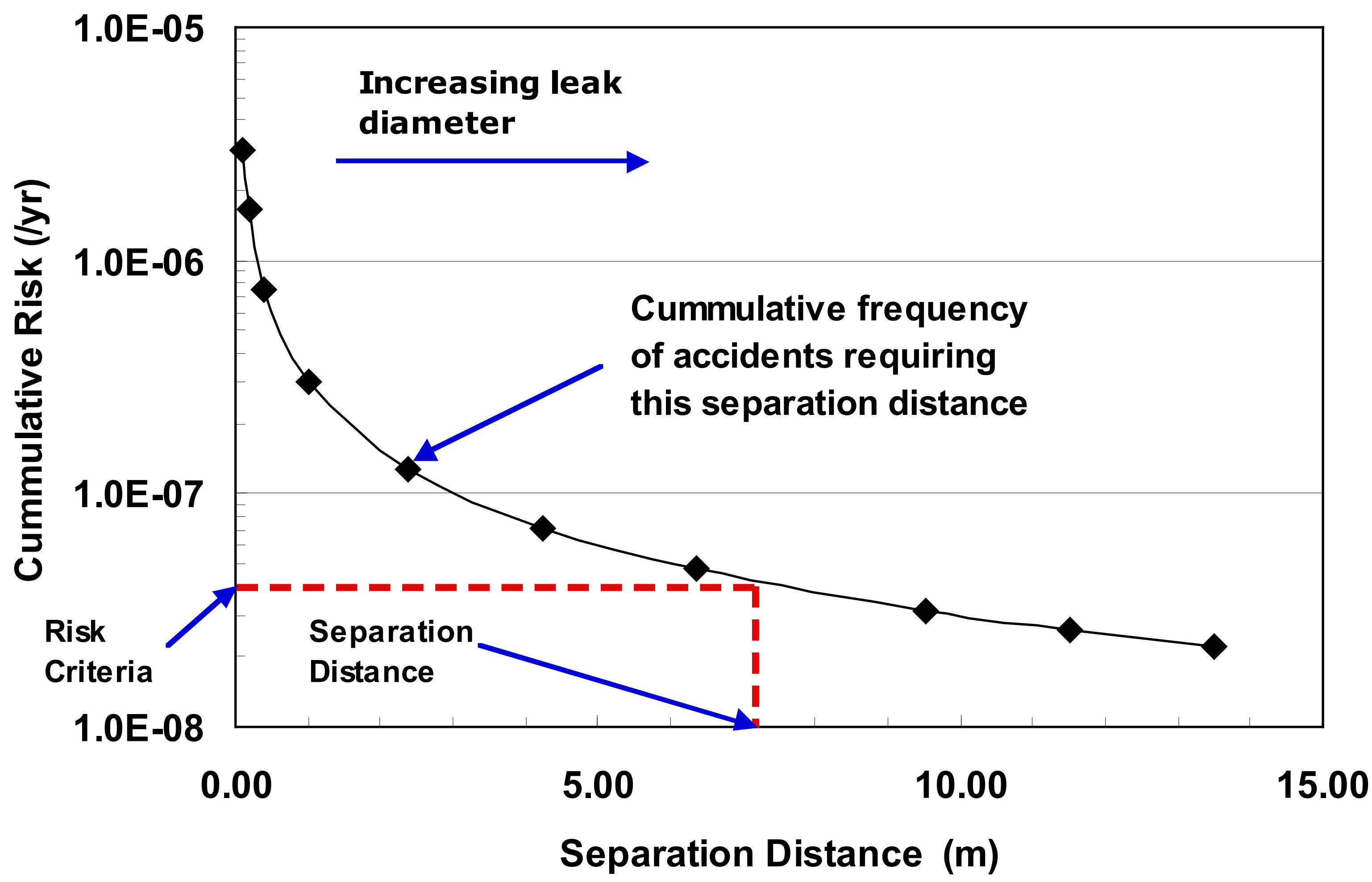
Risk Evaluation Includes Frequency and Consequence

Risk = Frequency X Consequence

Risk evaluation requires:

- Definition of important consequences
- Definition of acceptable risk levels
- Comprehensive evaluation of all possible accidents
- Data analysis for quantification of QRA models
- Accounting for parameter and modeling uncertainty

Risk Approach for Establishing Adequacy of Safety Distances



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Uniform Risk Acceptance Guideline is Required

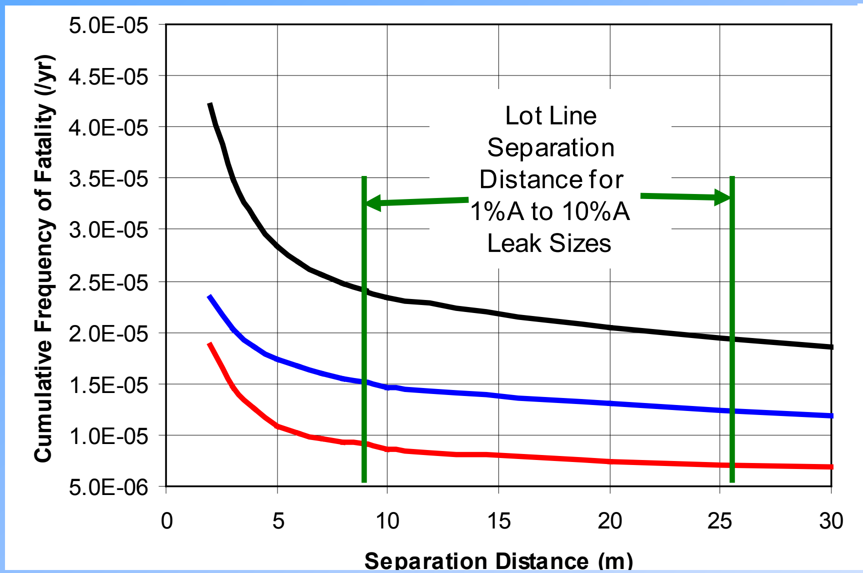
- Individual fatality risk to most exposed person at facility boundary
- Use risk “Guideline” versus “Criteria”
  - Criteria varies for different countries and organizations
  - Making decisions based on comparison to hard risk criteria difficult because of uncertainties in risk evaluations

NFPA Working Group chose 2E-5 fatalities/yr as guideline

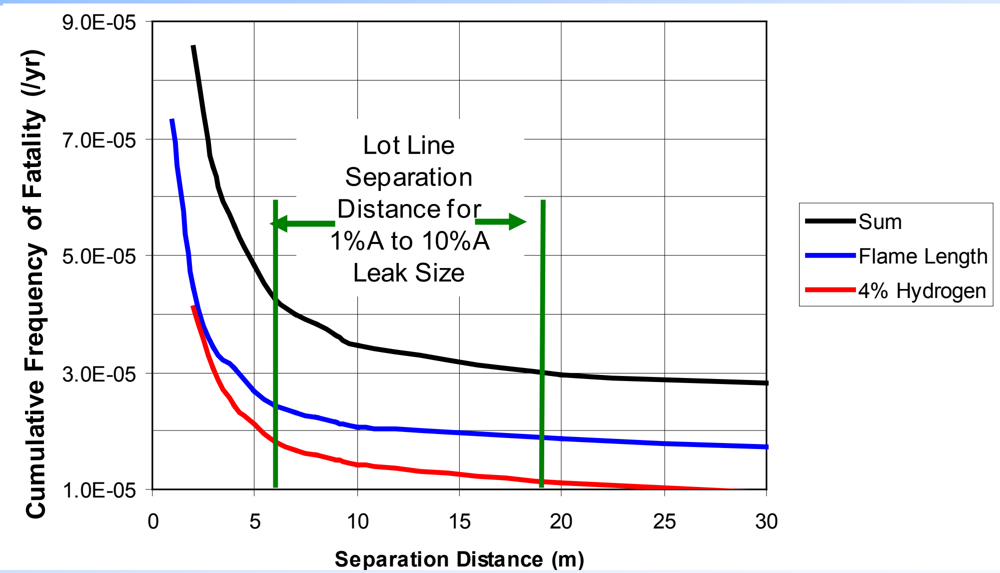
- **Comparative risk to gasoline stations**
- **10% of risk to society from all other accidents**
- **1E-5/yr is a value used by most countries that have established a risk criteria**

Representative Systems with Different Pressure Regimes

Total Risk 20.7 MPa (3000 psig) System



Total Risk 103.4 MPa (15000 psig) System

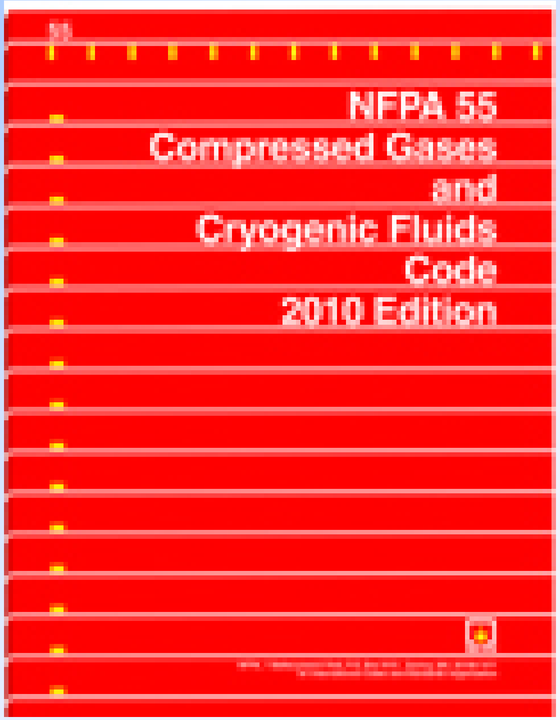


J. LaChance et al., "Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards", SANDIA REPORT, SAND2009-0874, Printed March 2009

- Risk close to the "guideline" of 2E-5 fatalities/yr selected by experts (NFPA Task Group 6)
- Risk from leaks greater than 3% of flow area were deemed acceptable

NFPA Adopts Risk-Informed Approach for Model Codes

- NFPA 55 voted to accept the new hydrogen bulk storage separation distances table
  - New table approved for NFPA 55 and 52 (available in 2010 editions)
  - New table to be included in NFPA 2
  - HYPOC supported inclusion in IFC by referencing back to the new table in NFPA 55 (available in 2010 edition of IFC).
- ISO has adopted a similar approach



This provides a model further C&S development, e.g.
- **Requirements related to liquid hydrogen**
- **Requirements related to indoor refueling**

Conclusion

- The use of risk information in establishing code and standard requirements enables:
  - An adequate and appropriate level of safety
  - Deployment of hydrogen facilities are as safe as gasoline facilities

This effort provides a template for clear and defensible regulations, codes, and standards that will enable <u>International Market Transformation</u>

Courtesy of Nuvera Fuel Cells