Risk-Informed Separation Distances for Hydrogen Gas Storage Facilities

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Effective and appropriate codes and standards enable technology deployment

Consider Refueling Stations:

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

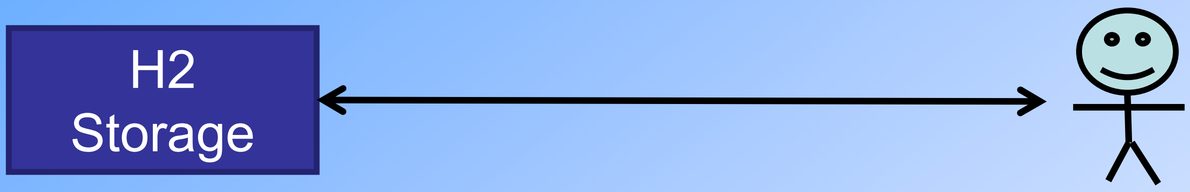
Courtesy of Air Products

Availability of fuel within existing fueling station footprint is integral to fuel cell technology deployment

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

Separation Distances largely define spatial requirements for the installation location

- Specified distances between a hazard source and a target



human, equipment, ignition sources, etc

  - Established distances did not reflect high pressures (70 MPa) being used in refueling stations
  - Undocumented basis for distances

- Several options possible to help establish new separation distances
  - Subjective determination (expert judgment)
  - Deterministically determined based on selected break size (e.g., 20% flow area)
  - 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 requirements

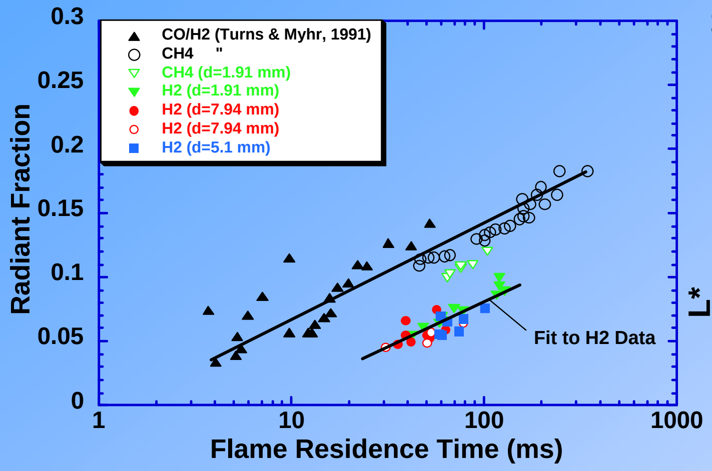
Understanding & quantifying the consequences of unintended releases of H_2 is integral for determining separation distances

Nighttime photograph of 413 bar (6000 psig) large-scale H2 jet-flame test (d_j = 5.08mm, L_{vis} = 10.6 m) from Sandia/SRI tests.

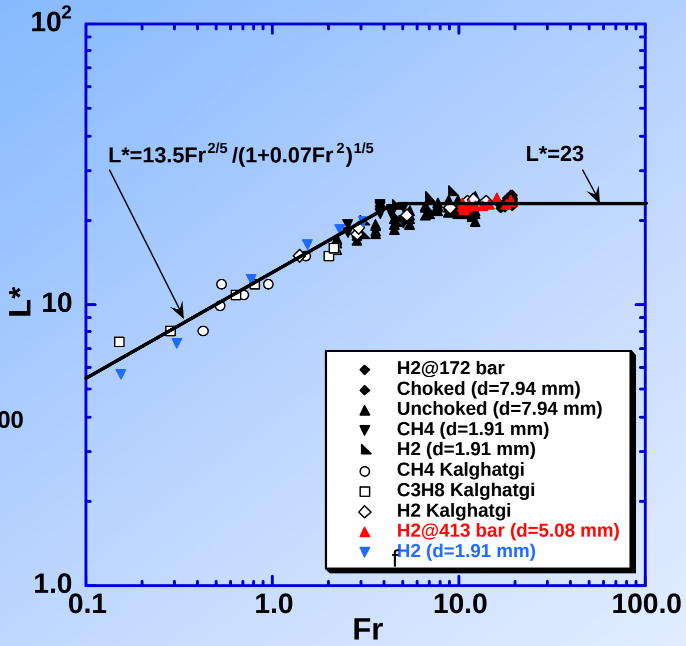
- Exposure to a hydrogen plume can result in
  - Heating from radiation (ignited jet)
  - Flame impingement (ignited jet)
  - Combustible cloud contact (unignited jet)
- Experimental measurements are necessary to characterize behavior
  - Flame shape and flame impingement distances for different flow rates
  - Hydrogen flame radiation values
  - Lean ignition limit for hydrogen/air mixtures
- Computational models are built and validated with experiments
  - Jet flame radiation model
  - Unignited jet flammability limit contour model
  - Predictions outside the range of available data
- Develop hazard mitigation strategies

SNL developed an engineering model for the radiation heat flux & flame length for H_2 jet flames based on flame data

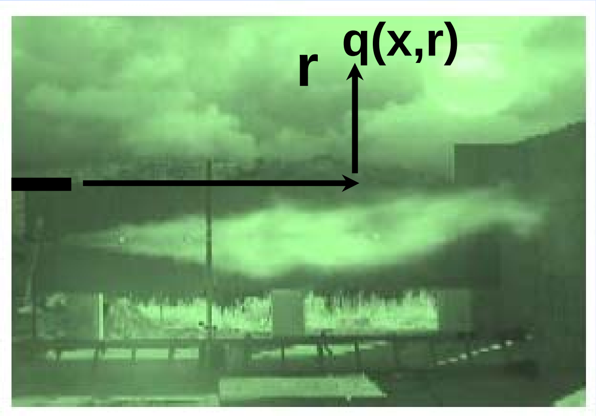
Radiant Fraction (X_{rad})



Visible Flame Length



- SRI Test Facility
- Baseline circular nozzle, 7.9375 mm (5/16 in)

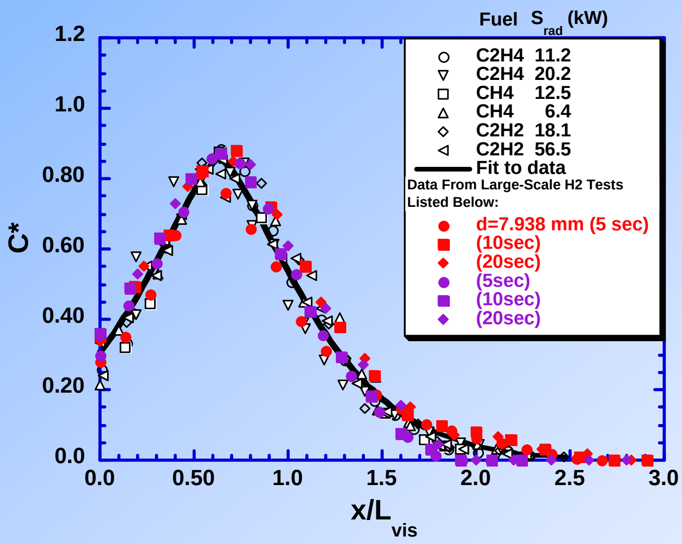


Horizontal Flame

3.6 - 4.3 m long, 0.6 - 1m wide

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

Radiant Power



- H2 jet-flame radiation model verified at source pressures of (172 bar (2500 psig), 413 bar (6000 psig).

(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.

The model is able to reproduce flame lengths measured in the Sandia/SRI H_2 jet flames.

SRI Test Facility

Baseline circular nozzle, 7.9375 mm (5/16 in)

Horizontal Flame

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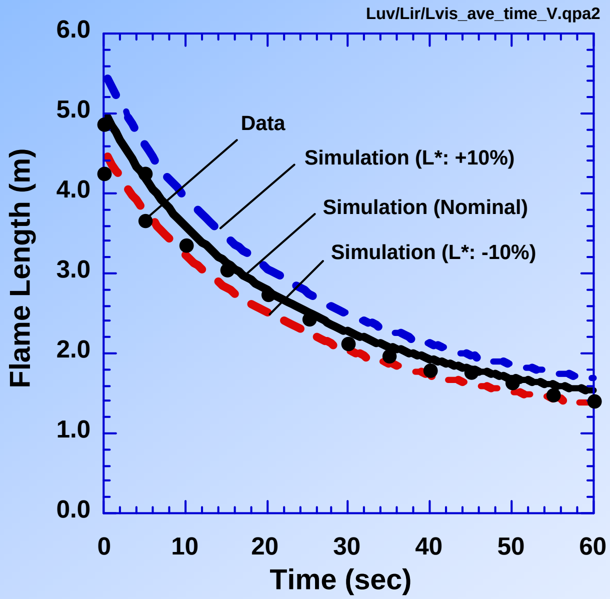
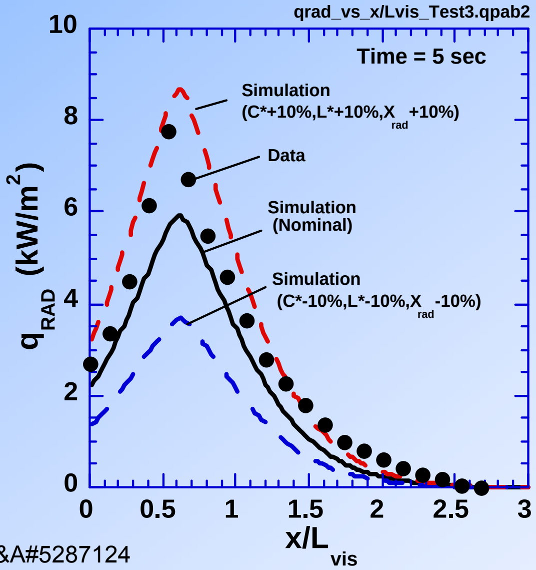


Simulation of SRI/Sandia Jet Flame Experiment

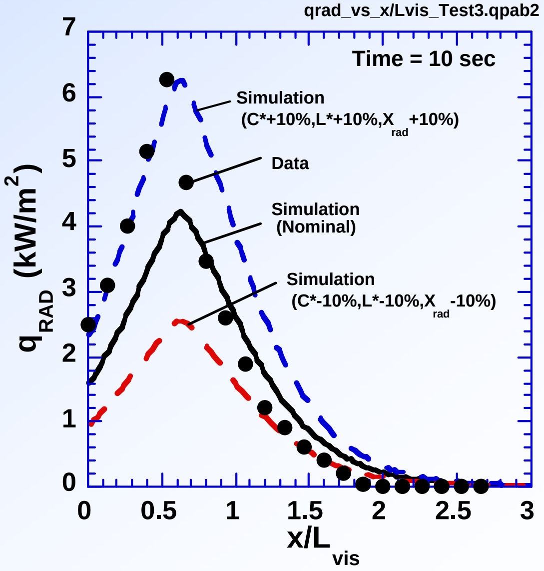
Tank Pressure = 172 bar (2500 psia)

Tank Volume = 0.098 m^3

Comparison of Simulations with Heat Flux Data

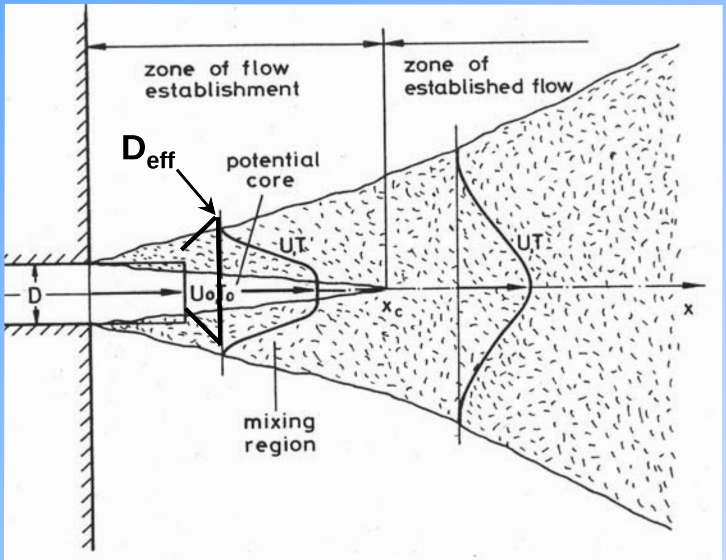


Comparison of Simulations with Heat Flux Data



We have developed a model to predict flammability envelopes from high-momentum unignited H_2 jets.

Schematic of High Momentum H_2 Jet Exiting to Air



- 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

$$C_{cl}(x) = KD/(X+X_o)(\rho_{amb}/\rho_{H2})^{1/2}$$

$$C(x,r) = C_{cl}(x)\exp(-K_c (r/(x+x_o))^2)$$

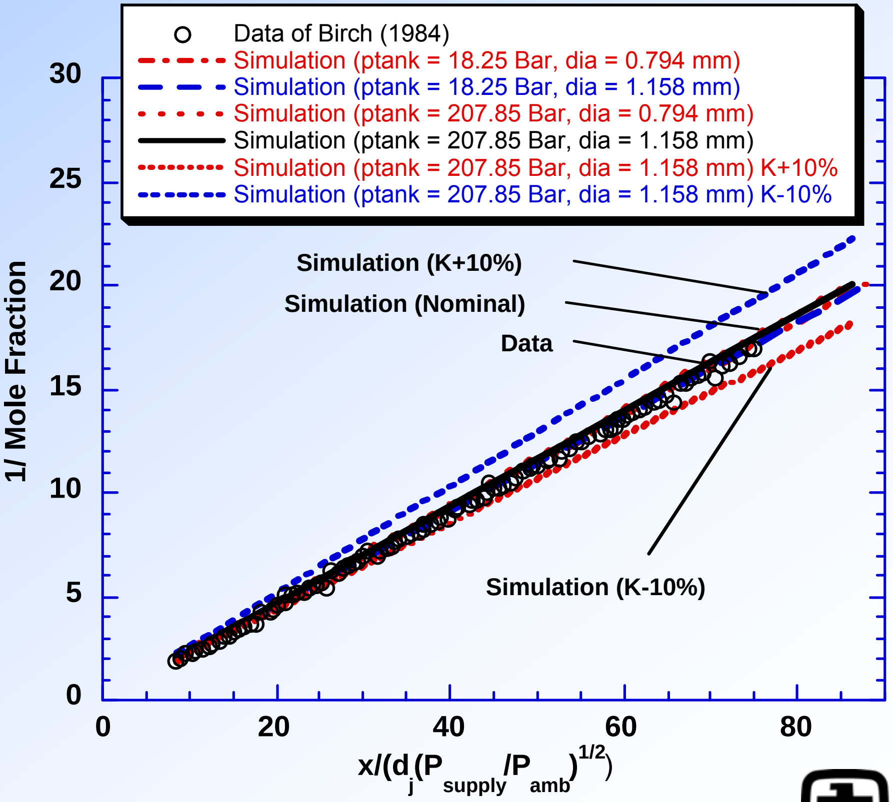
$K_c = 57$

$K = 5.40$

D = Diameter

- Model based on experimental data for entrainment and mixing in high momentum turbulent jets
  - Verified against natural gas and ethylene jets data of Birch et al., 1984
  - Model adapted to H_2 properties
  - Verified against H_2 Navier-Stokes calculations

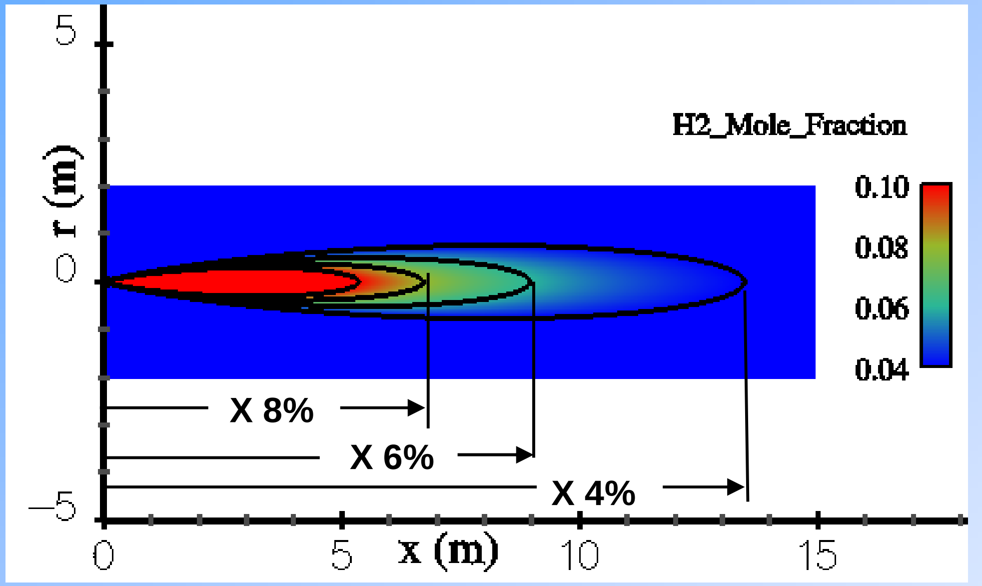
Comparison of Predicted Jet Centerline Concentration Fall-Off with Natural Gas Data



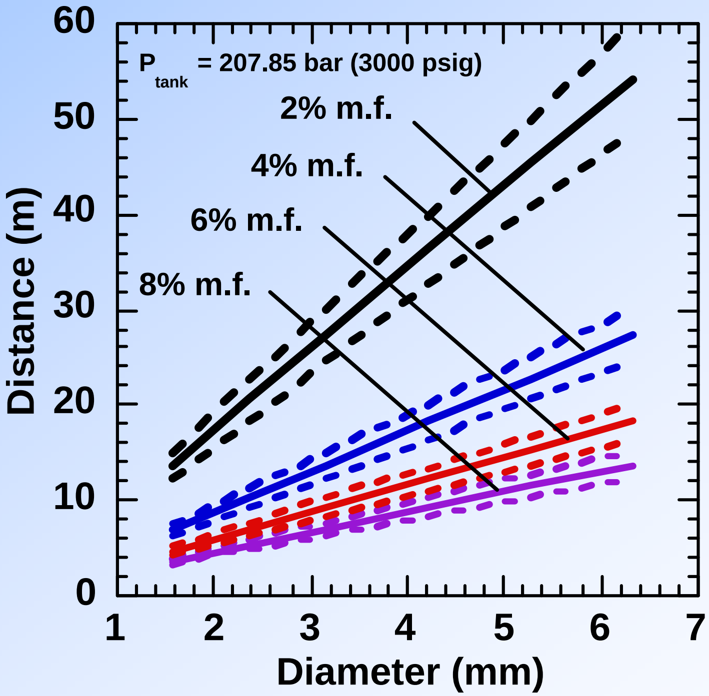
We have computed unignited H_2 jet concentration decay distances over the range of diameters and pressures.

Simulation of H_2 Concentration in a High Momentum Jet Exiting into Air

207.8 bar (3000 psig), Dia. = 3.175 mm (1/8 inch)



Pressure = 207.8 bar (3000 psig)



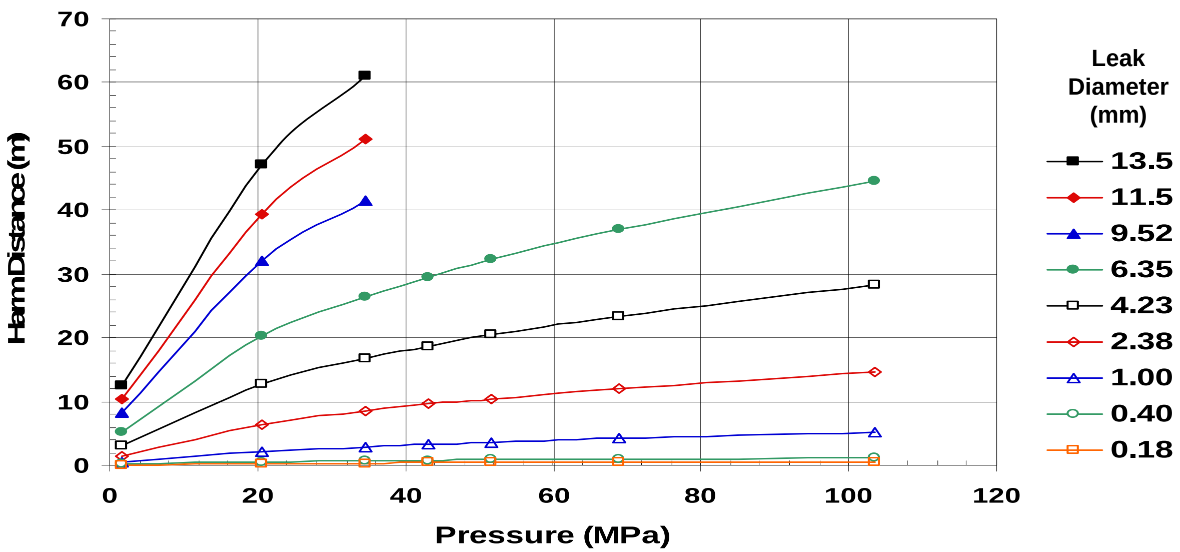
- **Lower Flammability Limits for H_2***
  - **Upward-propogating flame - 4% m.f.**
  - **Horizontal-propogating flame - 7.2% m.f.**
  - **Downward-propogating flame - 9.5% m.f.**

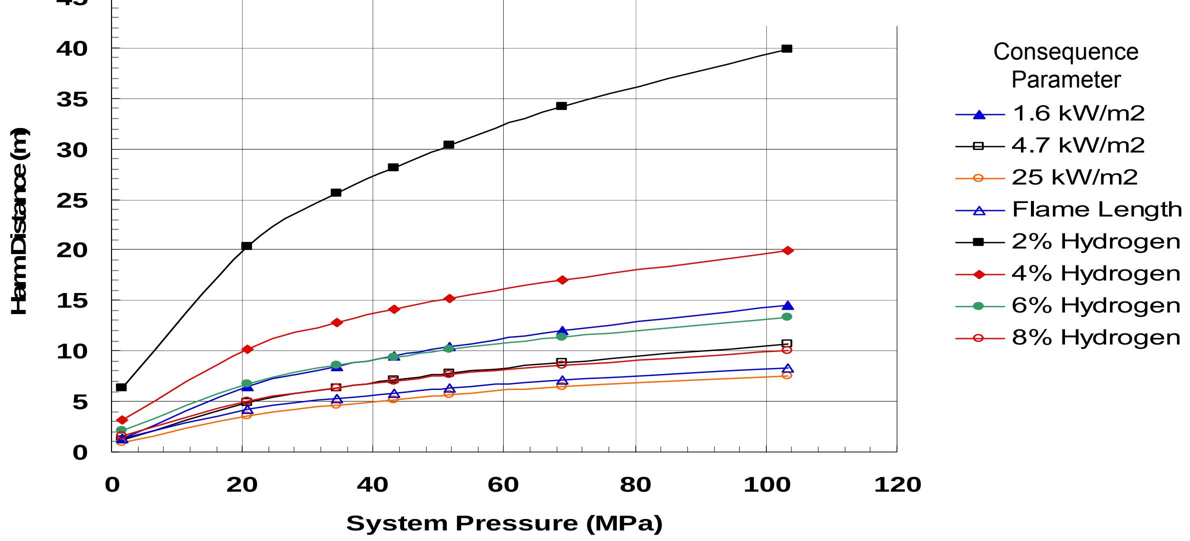
- **10-20% uncertainty in hazard length scales**

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

Deterministic-based separation distances can be very long unless a small leak diameter can be justified as the basis for selection

Harm Distances for a Jet Fire - 1.6 kW/m^2 Radiation Heat Flux





Harm Distances for Different consequence Measures – 2.38 mm Leak

Need to select leak diameter with a risk-informed approach

NFPA Risk-Informed Approach to select leak diameter

- Select typical gaseous storage systems as basis for evaluation

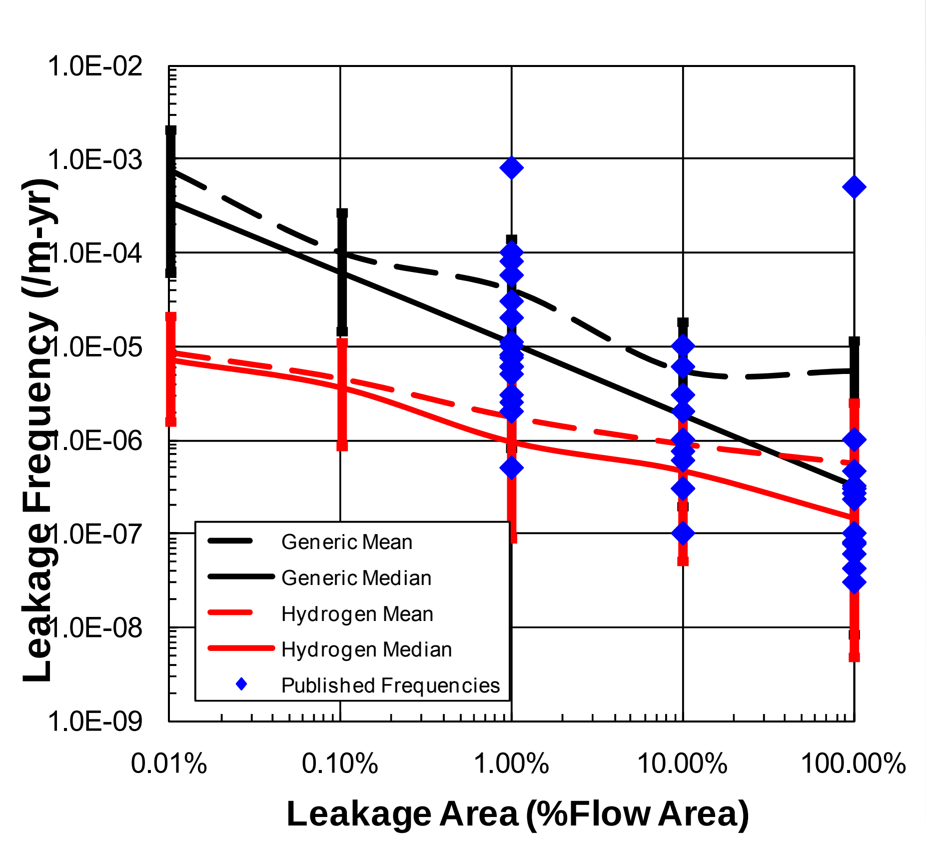
- Examined appropriate leakage data to determine leak size distribution
  - Selected leak size that encompasses a 95% percent of leaks within the typical systems and could be expected during the lifetime of a facility

- Used QRA to determine if risk from leaks greater than selected leak size is acceptable for typical systems

Risk analysis requires component leakage frequencies as a function of leak size and pressure

There is little hydrogen-specific data that is available – not enough for traditional statistical approach

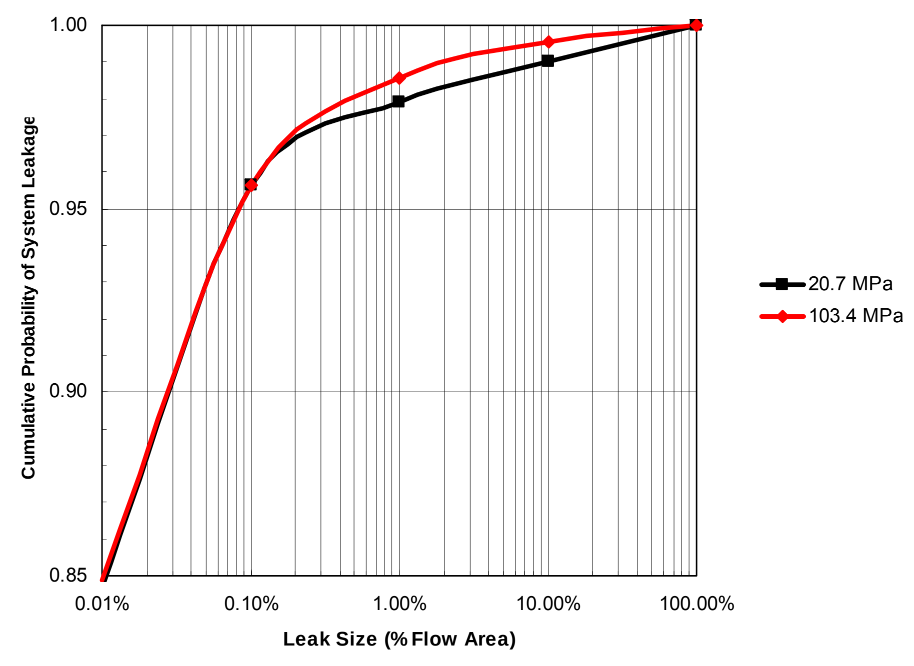
- Instead, representative values are selected from available sources from other industries (e.g. NG)
- Problems with this approach:
  - Data is not necessarily reflective of hydrogen components
  - Parameter uncertainty distribution is not characterized
- Use Bayesian statistics to generate leakage frequencies
  - Combined multiple sources of generic leak data with hydrogen specific data
- Allows attachment of different “layers” of significance to the data

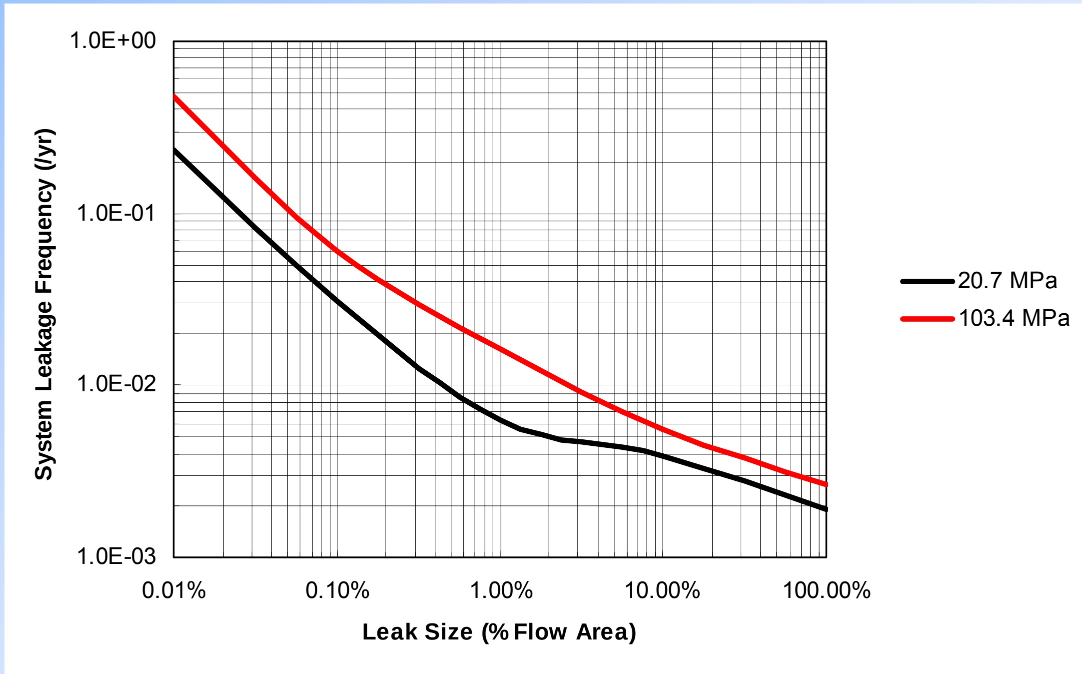


Reference: “Handbook of Parameter Estimation for Probabilistic Risk Assessment,” NUREG/CR-6823, U.S. Nuclear Regulatory Commission, Washington, D.C. (2003).

The Bayesian component leak-frequency data was used to determine cumulative system leakage probability

Considering the representative storage facility layout diagrams:





Expert opinion used to select 3% of system flow area as the leak area of interest

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

Risk Evaluation Includes Frequency and Consequence

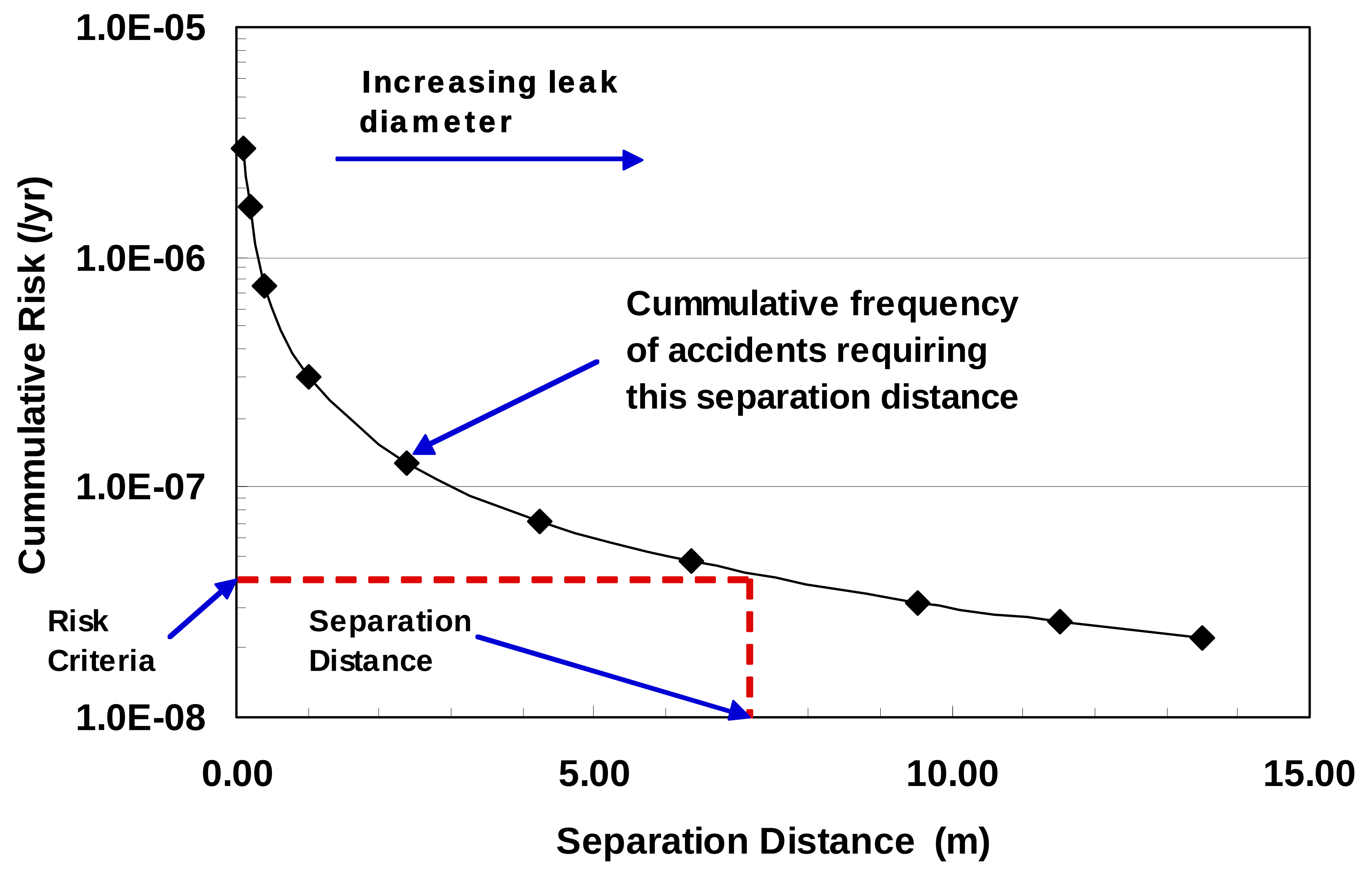
Risk = Frequency X

Consequence from all accidents

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 present in analysis

Risk Approach for Establishing Adequacy of Safety Distances



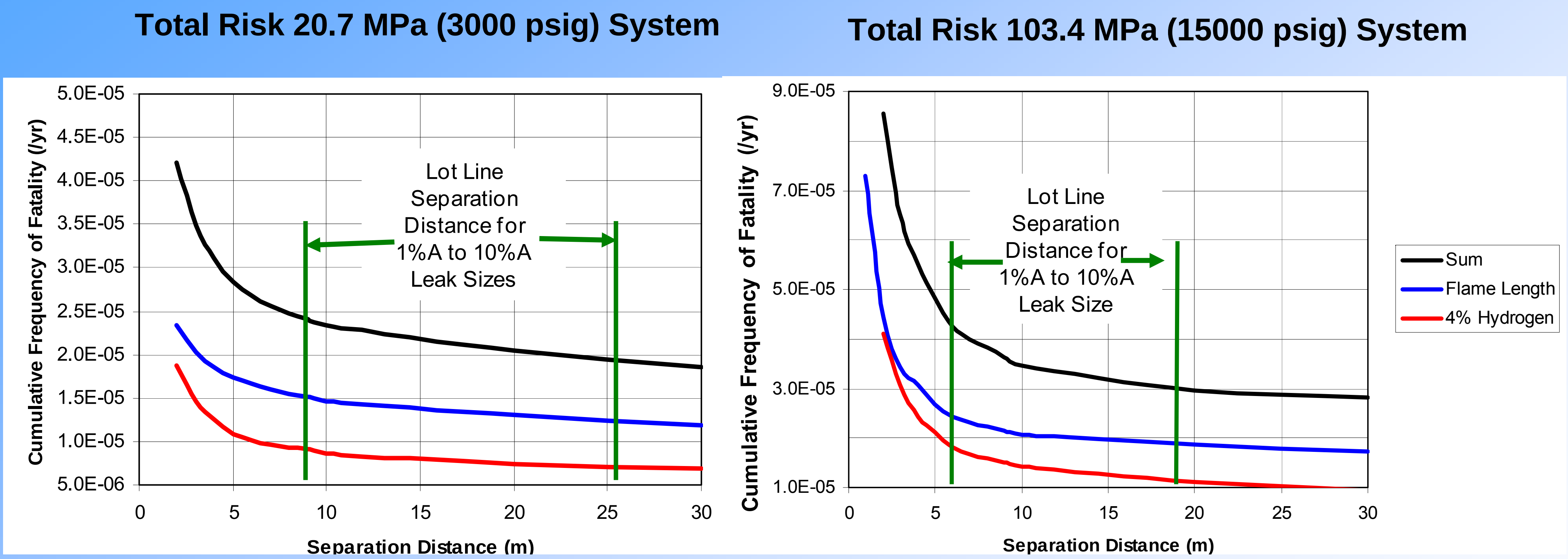
Selected Risk Guideline

- Uniform risk acceptance guideline is required for development of risk-informed codes and standards
- 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 WG chose 2E-5 fatalities/station-yr as guideline

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

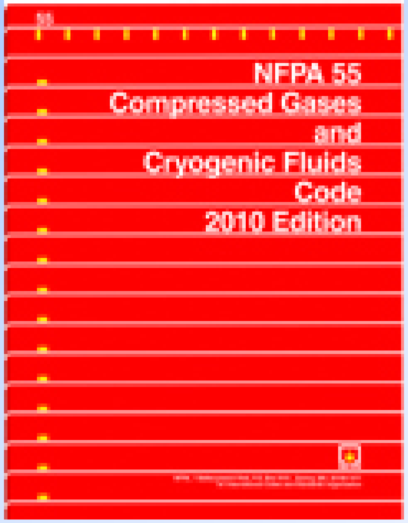
Risk Results for Representative Systems with Different Pressure Regimes



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/station-yr selected by experts (NFPA Task Group 6)
- Risk from leaks greater than 3% of flow area were deemed acceptable

This effort has validated the risk-informed approach for establishing codes and standards requirements


NFPA 55
Compressed Gases
and
Cryogenic Fluids
Code
2010 Edition

- 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
  - HIPOC 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 effort provides a model for codes and standards development efforts, e.g.

- Requirements related to liquid hydrogen
- Requirements related to confined hydrogen releases

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 can enable international market transformation

Additional Slides

Risk of a Fatality at a Gasoline Station

- There are 2 fatalities / year in the U.S. due to refueling station events (fires) (NFPA)
- There are 100,000 refueling stations in the U.S.
- The risk of a fatality is 2 / 100,000 Fatality / yr / station -- (2E-5) Fatality / yr-station
- There are on average 500 refueling events / station / day or 182,500 refueling events / station / yr
- So → There are 2 / 100,000 / 182,500 Fatalities / event

1.0E-10 fatalities / refueling event by a fire at the refueling station