Presentation Start

State of the Art: Unintended Release

Jay Keller,
Sandia National Laboratories

Topical Lecture
European Summer School on Hydrogen Safety

September 7-16, 2009

Acknowledgements

The author wishes to recognize the following people for their contribution to the science discussed in this presentation who are not otherwise recognized in the reference list.

LaChance, Jeff; Sandia National Laboratories
Evens, Greg; Sandia National Laboratories
Groethe, Mark; SRI International
Houf, Bill; Sandia National Laboratories
James, Scott; Sandia National Laboratories
Merilo, Eric; SRI International
Moen, Chris; Sandia National Laboratories
Ruggles, Adam; Sandia National Laboratories
Schefer, Robert; Sandia National Laboratories
Winters, William; Sandia National Laboratories
Zhang, Yao; Sandia National Laboratories

Lecture Outline

- Dispel some myths about hydrogen
  - We cannot build a safe hydrogen infrastructure on false perception
- Unintended release behavior
  - Momentum dominated flows
  - Buoyancy dominated flows
- Effect of barriers on:
  - Flame impingement, Radiation, Pressure effects
- Ignition
  - Spontaneous ignition
  - Flammability limits (flame stability)
    - Quiescent flows, Turbulent jets, Detonation, Explosion
- Quantitative risk assessment

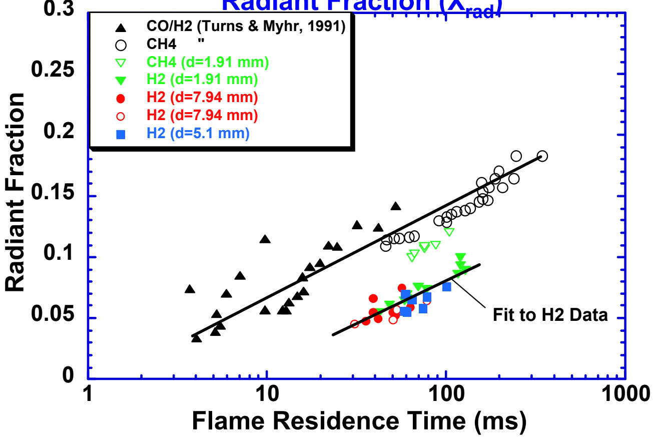
Understanding the Consequences of Unintended Releases

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.

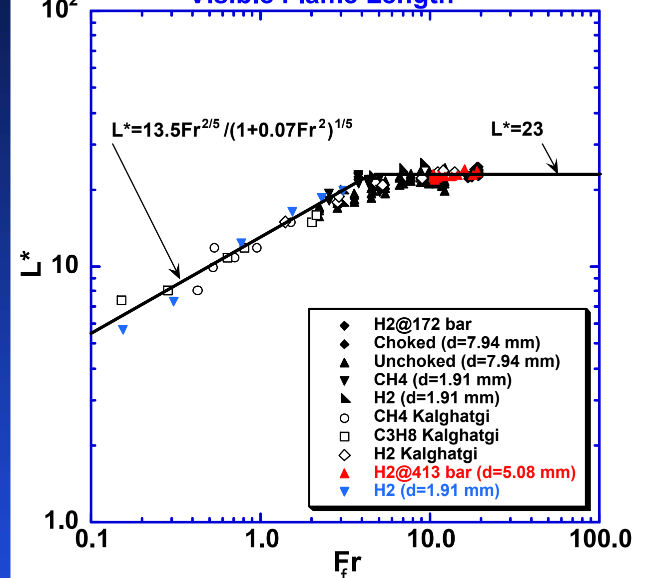
- **Objects exposed to a hydrogen plume can encounter**
  - Heating from radiation (ignited jet)
  - Flame impingement (ignited jet)
  - Combustible cloud contact (unignited jet)
- **Each of these items impacts the development and determination of risk-informed codes and standards**
- **Experimental measurements**
  - Flame shape and flame impingement distances for different flow rates
  - Hydrogen flame radiation values
  - Lean ignition limit for hydrogen/air mixtures
- **Computational models with validation**
  - Jet flame radiation model
  - Unignited jet flammability limit contour model
  - Predictions outside the range of available data
- **Develop hazard mitigation strategies (includes detection)**
- **Models and experiments published in peer reviewed journal articles (C&S based on studies which can be referenced)**

Predictive Model: Radiant Fraction, Flame Length & Heat Flux

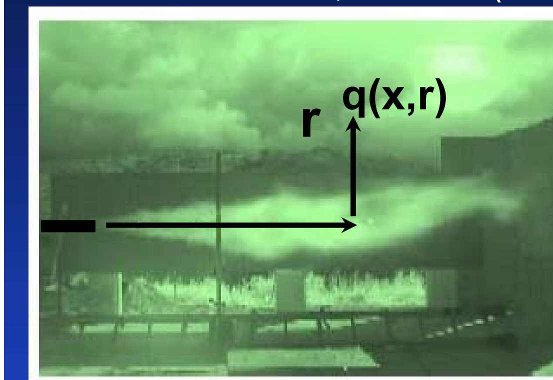
Radiant Fraction (X_{rad})



Visible Flame Length

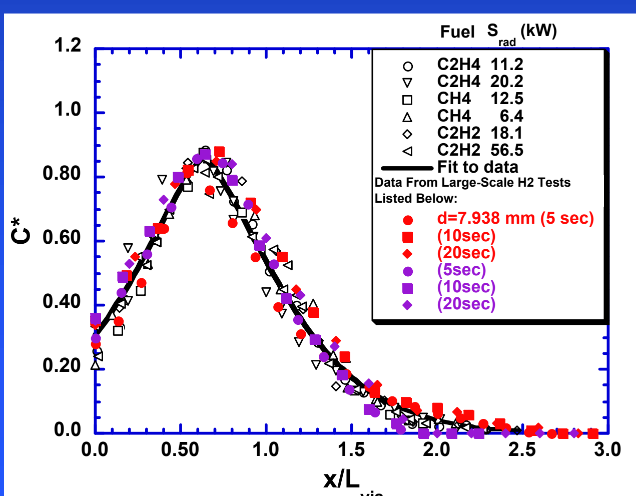


SRI Test Facility
Baseline circular nozzle, 7.9375 mm (5/16 in)



Horizontal Flame
3.6 - 4.3 m long, 0.6 - 1m wide

Radiant Power



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

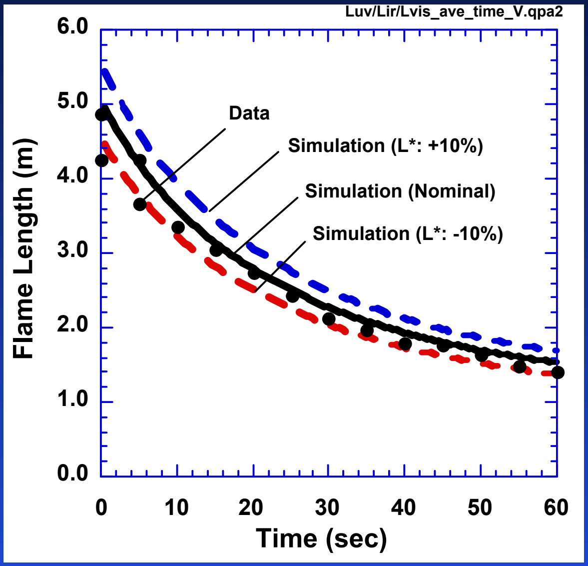
H_2 jet-flame radiation model verified at source pressures of 172 bar (2500 psig), & 413 bar (6000 psig).

(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.

Predictive Model: Heat Flux & Flame Length

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

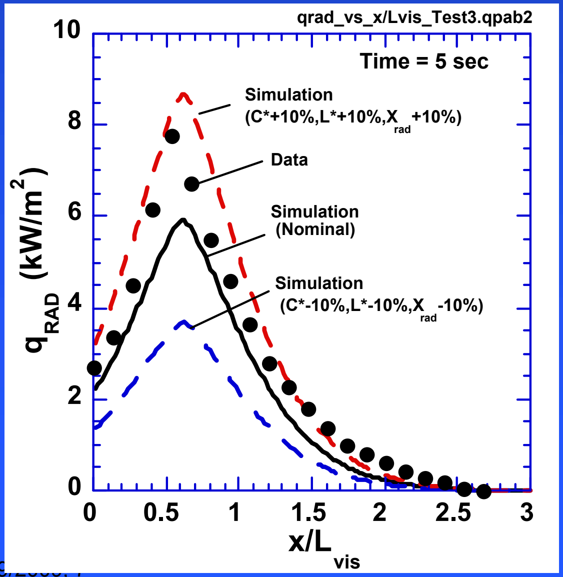
Horizontal Flame 3.6 - 4.3 m long, 0.6 - 1m wide



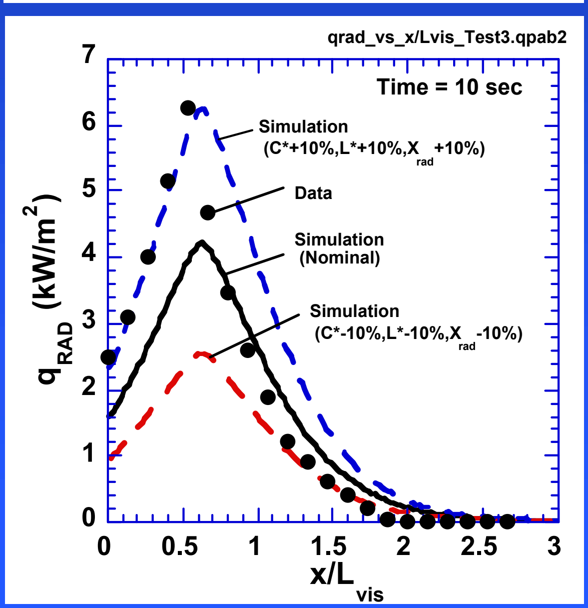
Simulation of SRI/Sandia Jet Flame Experiment

Tank Pressure = 172 bar (2500 psia)

Tank Volume = 0.098 m^3



Comparison of Simulations with Heat Flux Data

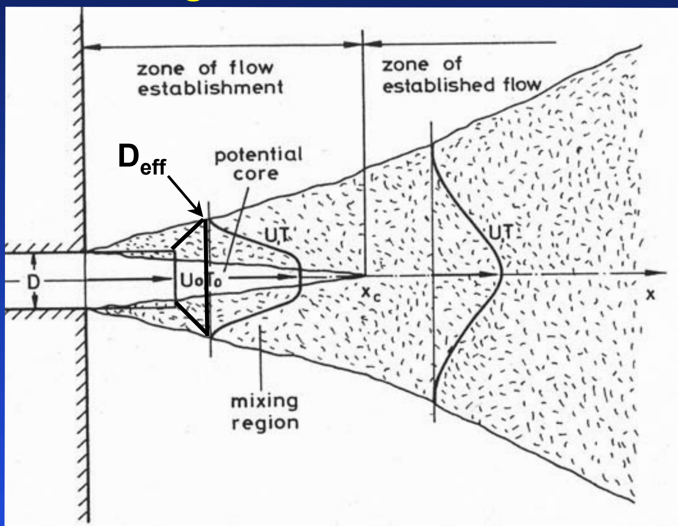


Comparison of Simulations with Heat Flux Data

Sandia National Laboratories

Predictive Model: Flammability Envelopes

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

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

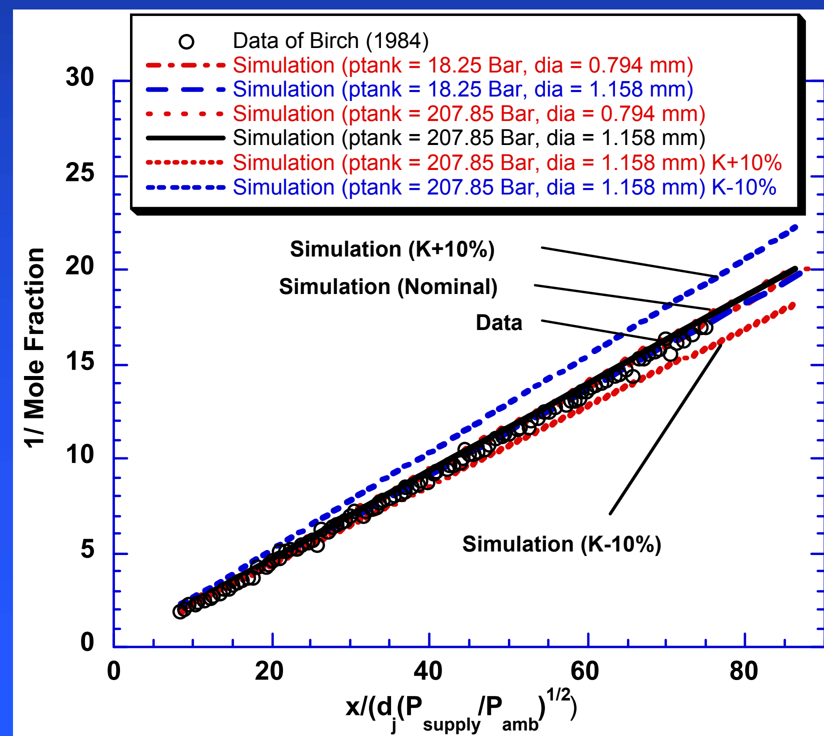
$$C(x,r) = C_{cl}(x)\exp(-K_c (r/(x+x_o))^2)$$

$K_c = 57$

$K = 5.40$

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**

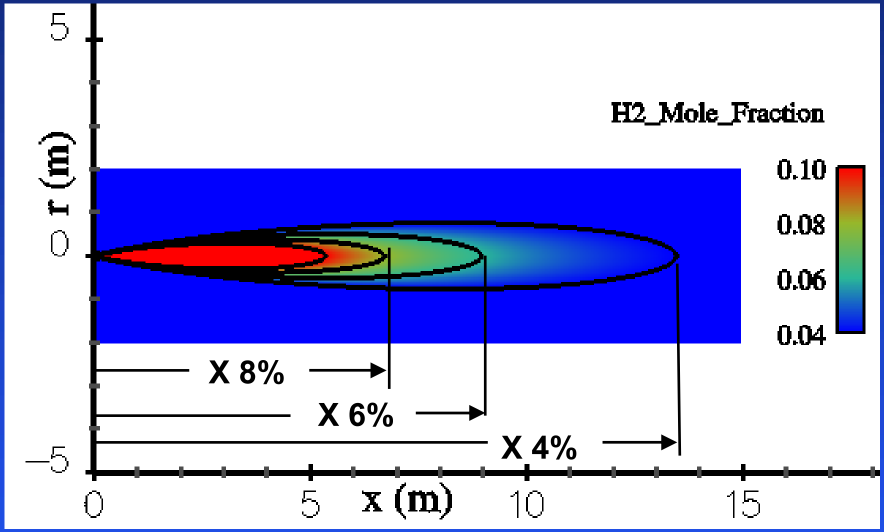


Prediction Compared to NG data

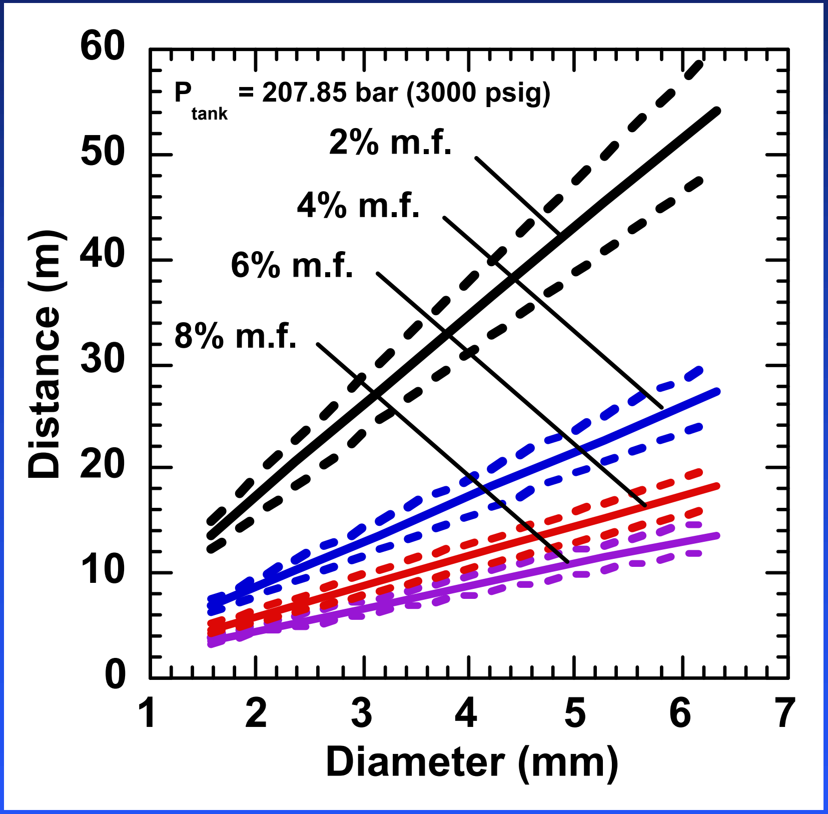
Modeled Unignited H_2 Concentration Profiles

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)



10-20% uncertainty in distances

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

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

Sandia National Laboratories

Consequence Spreadsheet Calculator Developed from the Model

- Leak area based on % of flow area (Cox, Lees, and Ang, 2003, IGC Doc 75/07/E 2007, etc.)
  - 1% - 20% of flow area typical
- Representative inside diameters of pipes for four pressure ranges
  - 0.1 to 18.25 bar - I.D. = 52.50 mm
  - ≥ 18.25 to 207.85MPa - I.D. = 24.31 mm
  - ≥ 207.85 to 518.11 bar - I.D. = 7.92 mm
  - ≥ 518.11 to 1035.21 bar - I.D. = 7.16 mm
- Curve-fit equations in Excel calculator provides hazard distances at alternate component diameters and leak % flow area

Excel Spreadsheet Hazard Distance Calculator

Hazard Distance Calculator

Created by:
William G. Houf
Sandia National Laboratories
Livermore, CA
Feb. 7, 2008
Created based on 5% flow area runs - 2/1/2008

Inputs:

Pipe Dia. for 18.25 bar (250 psig) =	52.50	mm	(2.07 in)
Pipe Dia. for 207.85 bar (3000 psig) =	18.97	mm	(0.75 in)
Pipe Dia. for 518.11 bar (7500 psig) =	7.92	mm	(0.31 in)
Pipe Dia. for 1035.21 bar (15000 psig) =	7.16	mm	(0.28 in)
Percentage of Pipe Flow Area for Leak =	3.00	Percent	

Factor = 0.775

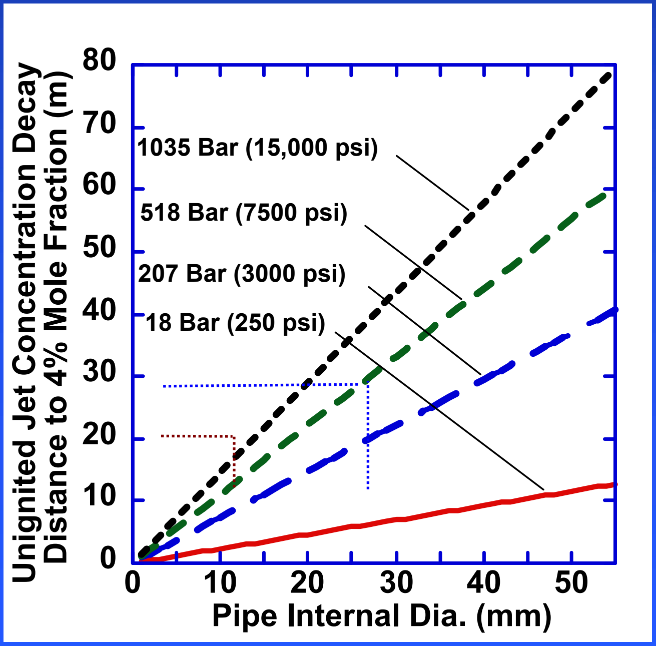
Outputs:

	(a) Unignited jet concentration decay to 4% mole fraction		(b) Drad - radiation heat flux level of 1577 W/m2 (500 Btu/hr ft2)		(c) The greater of Drad for combustible heat flux level of 20,000 W/m2 (6340 Btu/hr ft2) or the visible flame length		(d) The greater of Drad for non-combustible equipment heat flux level of 25,237 W/m2 (8000 Btu/hr ft2) or the visible flame length		(e) Drad for heat flux level of 4732 W/m2 (1500 Btu/hr ft2) exposure to employess for a maximum of 3 minutes	
18.25 bar (250 psig)	12.14 m	(39.81 ft)	7.94 m	(26.04 ft)	5.04 m	(16.55 ft)	5.04 m	(16.55 ft)	5.94 m	(19.48 ft)
207.85 bar (3000 psig)	14.00 m	(45.94 ft)	9.46 m	(31.03 ft)	5.82 m	(19.10 ft)	5.82 m	(19.10 ft)	7.02 m	(23.04 ft)
518.11 bar (7500 psig)	8.75 m	(28.72 ft)	5.46 m	(17.90 ft)	3.64 m	(11.94 ft)	3.64 m	(11.94 ft)	4.13 m	(13.53 ft)
1035.21 bar (15000 psig)	10.38 m	(34.04 ft)	6.77 m	(22.21 ft)	4.31 m	(14.15 ft)	4.31 m	(14.15 ft)	5.05 m	(16.56 ft)

Hazard distances can be counter intuitive

- Leak area based on % of flow area (Cox, Lees, and Ang, 2003, IGC Doc 75/07/E 2007, etc.)
  - 1% - 20% of flow area typical
- Representative inside diameters of pipes for four pressure ranges
  - > 2.0 to 18.25 bar - I.D. = 52.50 mm - 3% leak dia. = 9.09 mm
  - ≥ 18.25 to 207.85 bar - I.D. = 24.31 mm - 3% leak dia. = 4.21 mm
  - ≥ 207.85 to 518.11 bar - I.D. = 7.92 mm - 3% leak dia. = 1.37 mm
  - ≥ 518.11 to 1035.21 bar - I.D. = 7.16 mm - 3% leak dia. = 1.24 mm

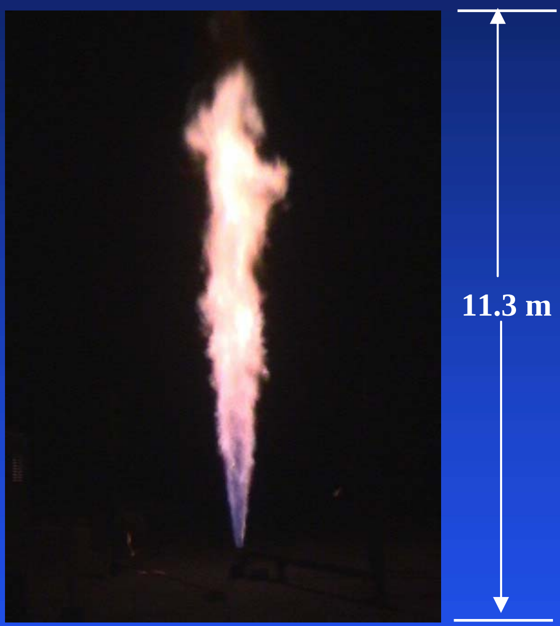
Unignited Jet Concentration Decay Distance (Leak = 3% of flow area)



Example Hazard Distance Calculation For Unignited Jet

Storage Pressure Range	Characteristic Pipe Diameter (mm)	4% Unignited Jet Hazard Distance
>2.0 to 18.25 bar (>15 to ≤ 250 psig)	52.50 mm (2.07 in)	12.14 m (39.81 ft)
≥ 18.25 to 207.85 bar (250 to ≤ 3000 psig)	24.31 mm (0.75 in)	14.00 m (45.94 ft)
≥ 207.85 to 518.11 bar (3000 to ≤ 7500 psig)	7.92 mm (0.31 in)	8.75 m (28.72 ft)
≥ 518.11 to 1035.21 bar (7500 to ≤ 15,000 psig)	7.16 mm (0.28 in)	10.38 m (34.04 ft)

This work is documented in peer reviewed publications.



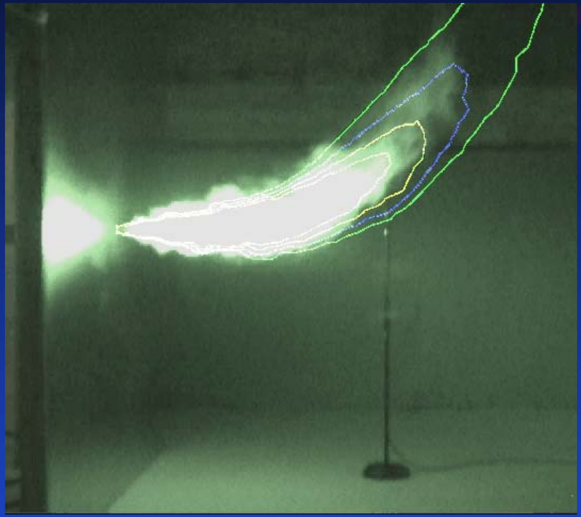
Night time photograph of 413 bar (6000 psig) large-scale H_2 jet-flame test (d_j = 5.08mm, L_{vis} = 10.6 m) from Sandia/SRI tests.

- H_2 jet-flame radiation model verified at source pressures of 172 bar (2500 psig), 413 bar (6000 psig)
- Unignited jet concentration decay model verified against natural gas data (source pressure 3.5 - 76 bar) and compressible Navier-Stokes
- Experiments and safety distance modeling results published in peer-reviewed papers

(1) Houf and Schefer, "Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen," Int. Jour. of Hydrogen Energy, Vol. 32, Jan. 2007.
(2) Schefer, Houf, San Marchi, Chernicoff, and Englom, "Characterization of Leaks from Compressed Hydrogen Dispensing Systems and Related Components," Int. Jour. of Hydrogen Energy, Vol. 31, Aug. 2006.
(3) Molina, Schefer, and Houf, "Radiative Fraction and Optical Thickness in Large-Scale Hydrogen Jet Flames," Proceedings of the Combustion Institute, April, 2006.
(4) Houf and Schefer, "Rad. Heat Flux & Flam. Env. Pred. from Unintended Rel. of H2," Proc. 13th Int. Heat Tran. Conf., Aug., 2006.
(5) Schefer, Houf, Williams, Bourne, and Colton, "Characterization of High-Pressure, Under-Expanded Hydrogen-Jet Flames," In Press, Int. Jour. of Hydrogen Energy, 2007.
(6) Houf and Schefer, "Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen," 16th NHA Meeting, Washington, DC, March 2005.
(6) Schefer, R. W., Houf, W. G., Bourne, B. and Colton, J., "Turbulent Hydrogen-Jet Flame Characterization", Int. Jour. of Hydrogen Energy, 2005.
(7) Schefer, R. W., Houf, W. G., Bourne, B. and Colton, J., "Experimental Measurements to Characterize the Thermal and Radiation Properties of an Open-flame Hydrogen Plume", 15th NHA Meeting, April 26-30, 2004, Los Angeles, CA.
(8) Schefer, "Combustion Basics," in National Fire Protection Association (NFPA) Guide to Gas Safety, 2004.

Sandia National Laboratories

Validated models developed for slow leak regime.



Jet Flame from an Ignited H_2 Slow Leak*
Flowrate = 20 scfm, Hole Dia. = 9.44 mm
Exit Mach Number = 0.1 (Unchoked Flow)
F_{den} = 117

*Photograph from:
Dr. Michael Swain, (Univ. of Miami)
Fuel Cell Summit Meeting
June 17, 2004

(1) Houf and Schefer, "Analytical and Experimental Investigation of Small-Scale Unintended Releases of Hydrogen," Int. Jour. of Hydrogen Energy, Vol. 33, pp 1435-1444, 2008.

(2) Schefer, and Houf, "Investigation of Small-Scale Unintended Releases of Hydrogen: Momentum–Dominated Limit", accepted for publication International Journal of Hydrogen Energy, May 2008.

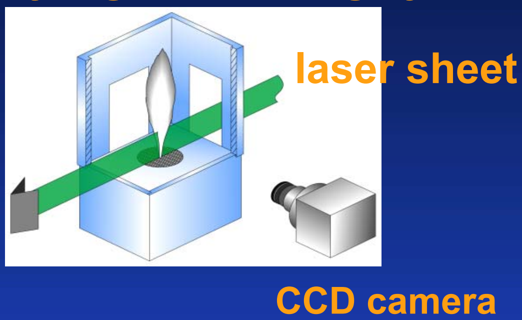
(3) Schefer, and Houf, "Investigation of Small-Scale Unintended Releases of Hydrogen:Buoyancy Effects", accepted for publication International Journal of Hydrogen Energy, May 2008.

(4) Houf and Schefer, "Investigation of Small-Scale Unintended Releases of Hydrogen, SAE 2007 Transactions, Journal of Materials and Manufacturing, March 2008.

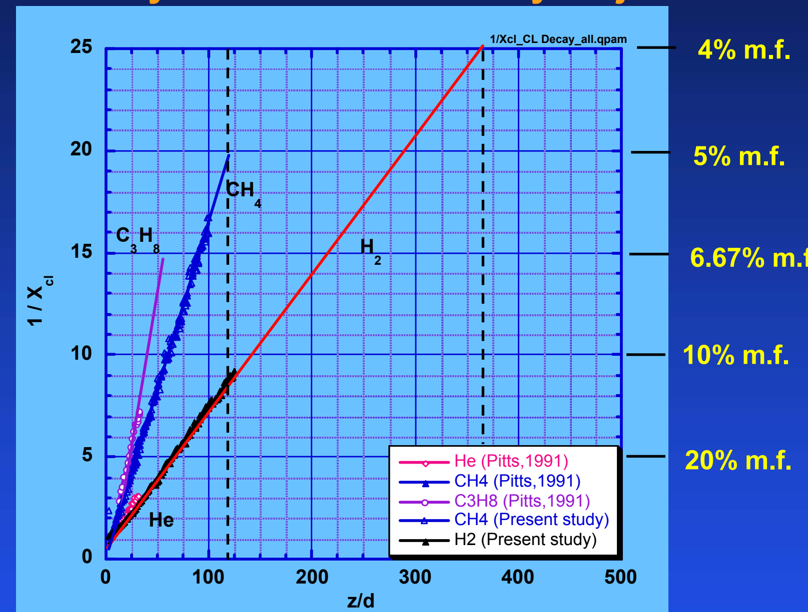
- Goal - Provide technical information on small/slow leaks from hydrogen-based systems
- Slow leaks may occur from
  - Low pressure electrolyzers
  - Leaky fittings or O-rings with large amounts of pressure drop
  - Vents from buildings or storage facilities containing hydrogen
- Previous work focused on the high-momentum leak regime where the effects of buoyancy on the flow were small
- In the slow leak regime both momentum and buoyant forces are important
  - Buoyant forces affect the trajectory and rate of entrainment
    - Significant curvature can occur in jet trajectory
    - Concentration decay and the distance to mean lower ignition limit
  - The ratio of momentum to buoyant forces for the leak can be characterized by the exit densimetric Froude number
    - $F_{den} = U_{exit} / (gD(rho_{amb} - rho_{exit})/rho_{exit})^{1/2}$ Approach
  - Experimentally characterize slow leaks (leak size and geometry)
  - Develop validated engineering models
  - Use engineering models to generate safety information
    - Safety distance to (mean) lower concentration ignition limit

Rayleigh scattering is used to map concentration contours

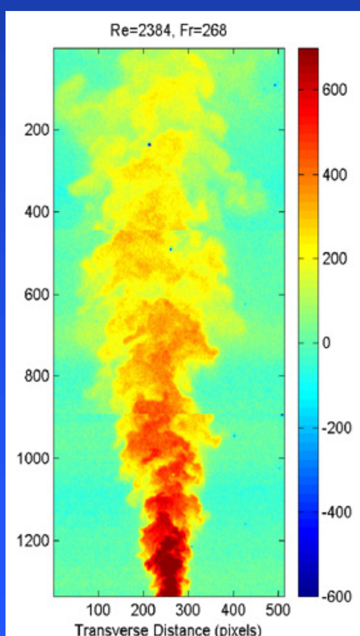
Rayleigh scattering system



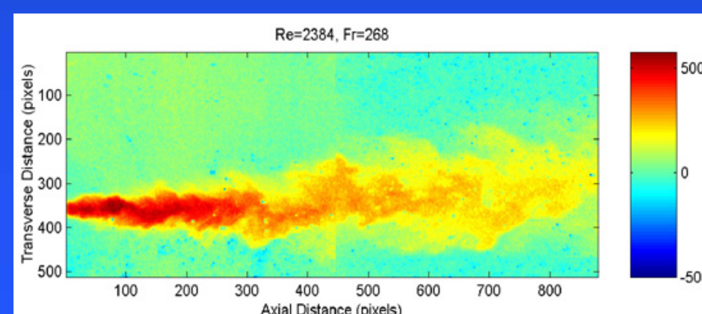
Experimentally measured centerline concentration decay rates in vertical buoyant jets



g



Instantaneous H_2 mole fraction images in unignited vertical jet

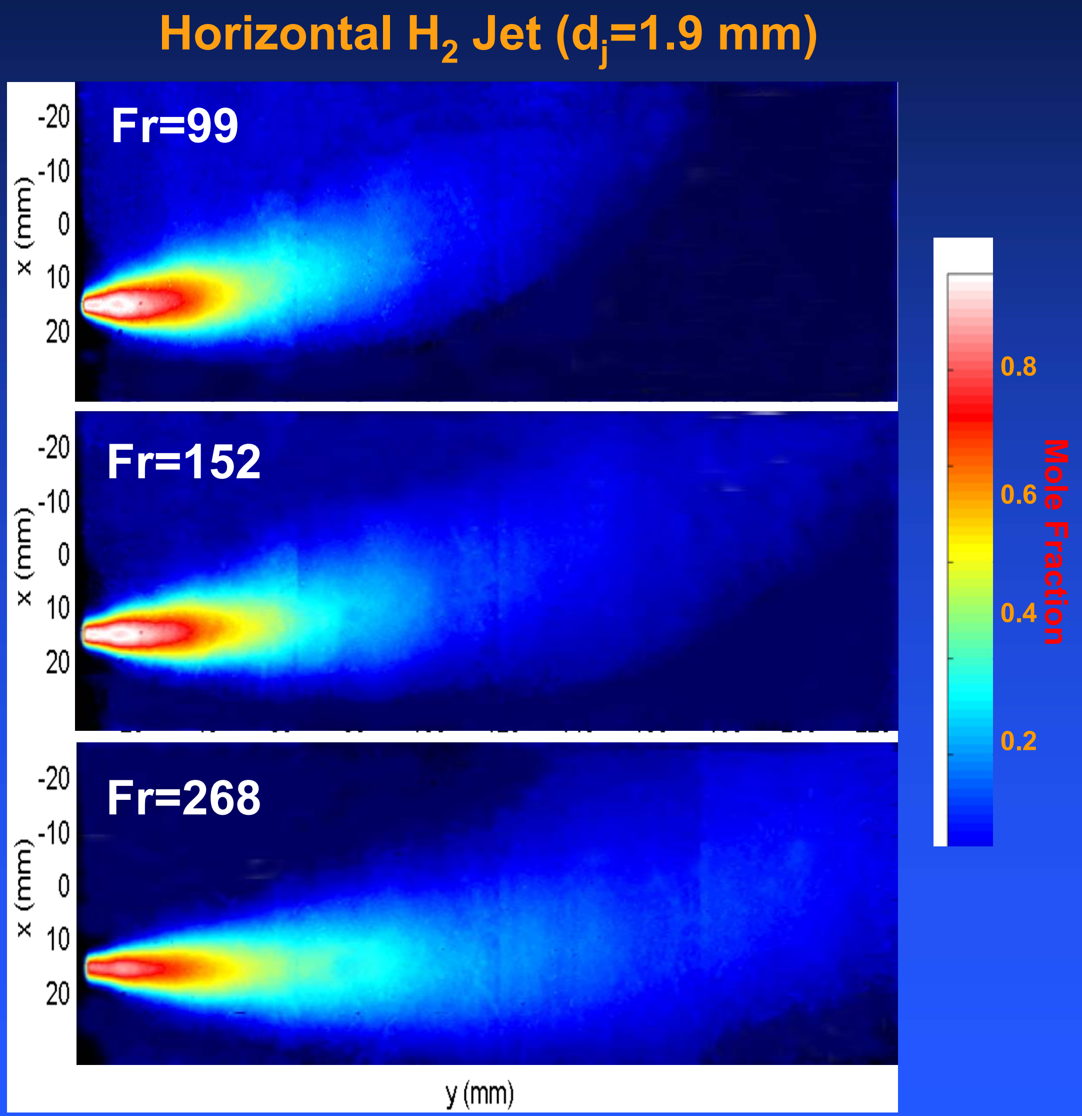


g

Instantaneous H_2 mole fraction images in unignited horizontal jet

Sandia National Laboratories

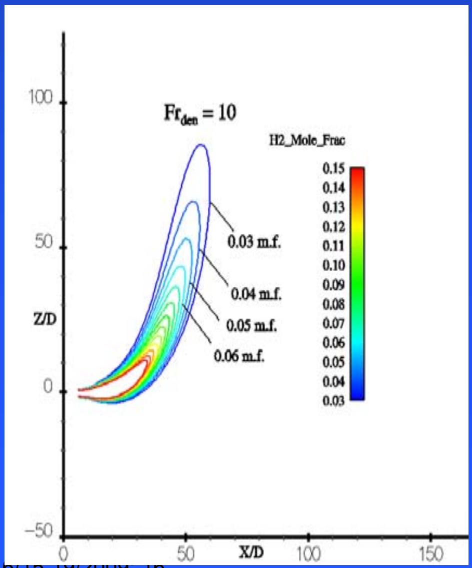
Buoyancy effects are characterized by Froude number



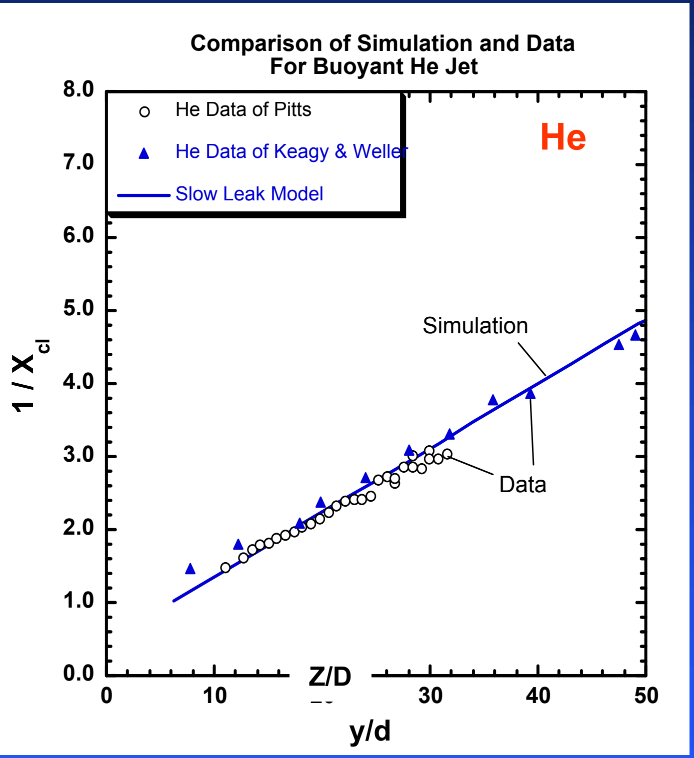
- Time-averaged H2 mole fraction distributions.
- Froude number is a measure of strength of momentum force relative to the buoyant force
- Increased upward jet curvature is due to increased buoyancy at lower Froude numbers.

The engineering model has been validated against data

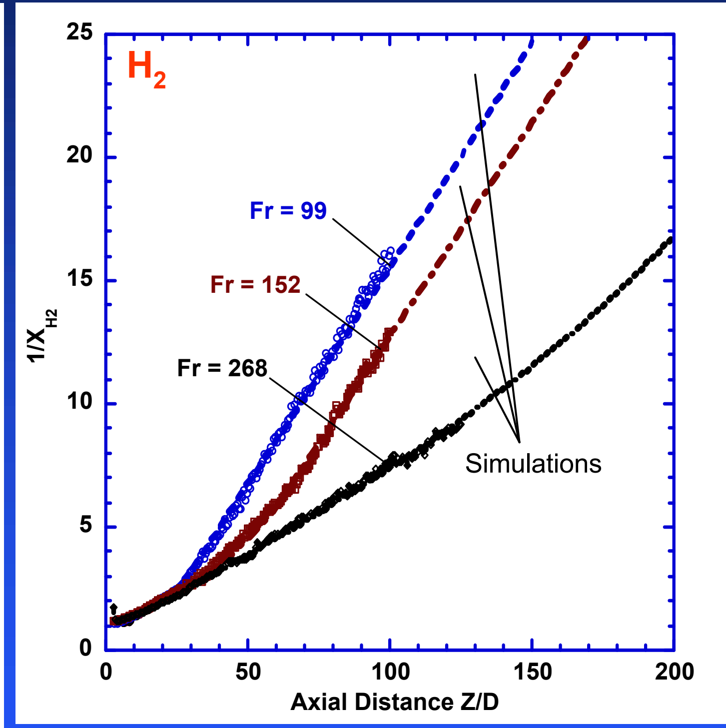
- The buoyantly-driven flow model :
  - uses a different entrainment law than our momentum jet model
  - integrates along the stream line to capture plume trajectory



Comparison of model and data for concentration decay of vertical buoyant He plume



Comparison of model with data from the Sandia slow-leak experiments for buoyant H_2 plumes



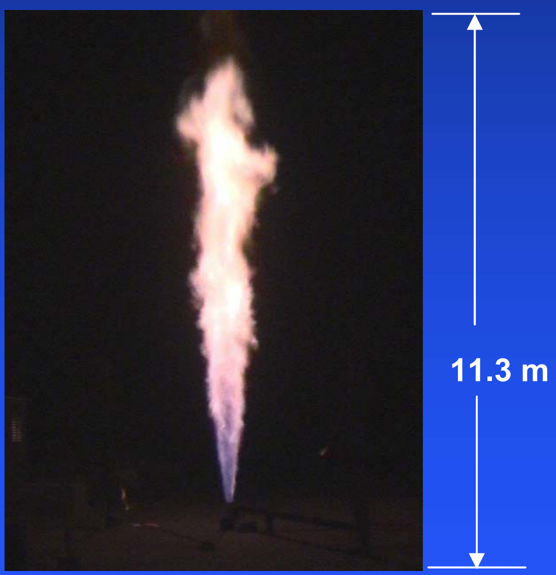
- Lower Froude number leaks are more buoyant
- Buoyancy increases entrainment rate causing faster concentration decay
- New entrainment law adds buoyancy-induced entrainment to momentum induced entrainment

Lecture Outline

- Dispel some myths about hydrogen
  - We cannot build a safe hydrogen infrastructure on false perception
- Unintended release behavior
  - Momentum dominated flows
  - Buoyancy dominated flows
- Effect of barriers on:
  - Flame impingement, Radiation, Pressure effects
- Ignition
  - Spontaneous ignition
  - Flammability limits (flame stability)
    - Quiescent flows, Turbulent jets, Detonation, Explosion
- Quantitative risk assessment

Consequence distances increase as refueling pressure increases.

- As leak source pressure increases ….
  - Jet flame lengths increase
  - Radiation heat flux levels increase
  - Unignited jet concentration decay distance to LFL increases

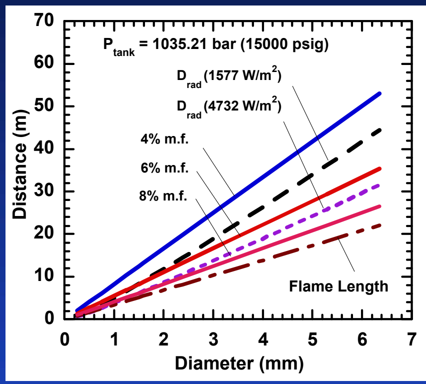


Nighttime Photo of H_2 Jet Flame Test
Source Press. = 41.3 MPa (6000 psig)
Dia. = 5.08 mm
L_{vis} = 10.6 m

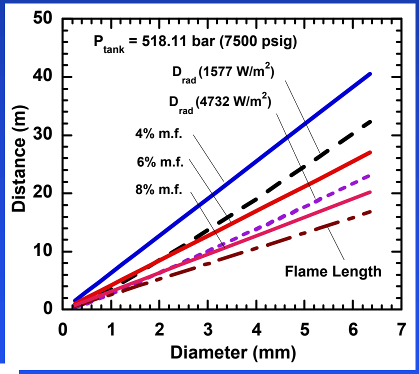
Consequence Distance Calculations

Increasing Pressure

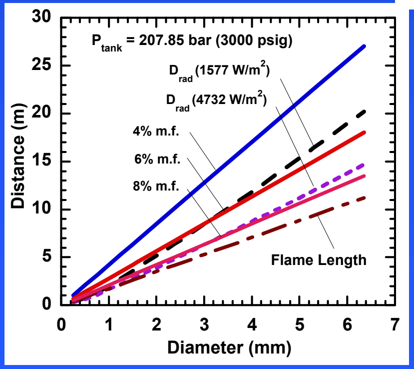
103.5 MPa



51.8 MPa

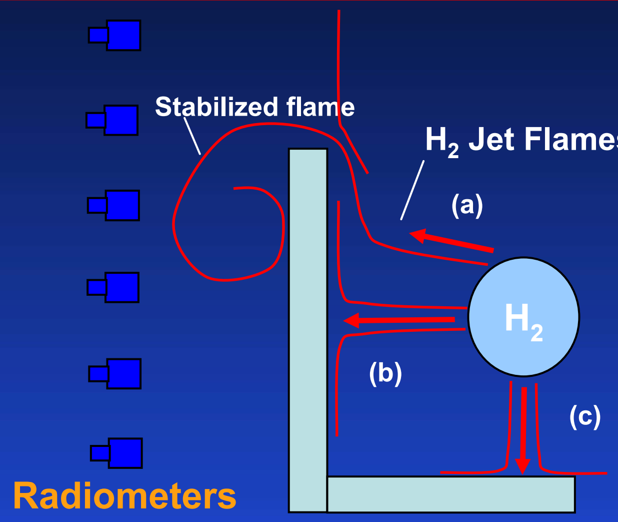


20.7 MPa

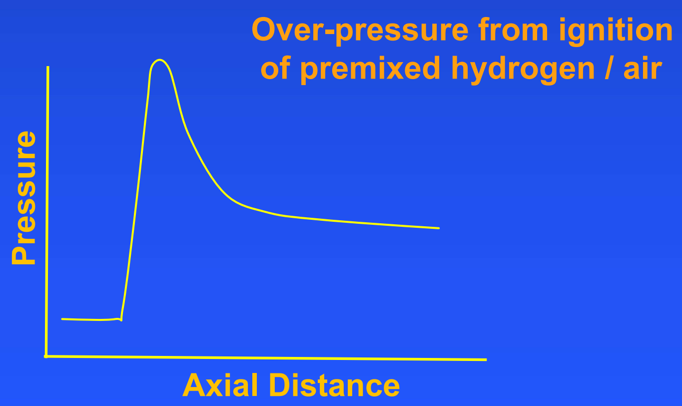


Barriers - effective consequence mitigation strategy?

- Goal: Determine if barriers are an effective jet mitigation technique for reducing safety distances
- Combined experimental and modeling approach
- Issues of importance:
  - Jet flame deflection and protection from impingement
  - Reduction of thermal radiation exposure
  - Reduction of unignited jet flammability envelope
  - Ignition overpressure and attenuation by barrier
- Collaborating with the HYPER project in Europe on barriers
- Experimental data shared the HYSAFE for modeling
- ***Combine data and analysis with quantitative risk assessment for barrier configuration guidance.***



Sandia/SRI H_2 Jet Flame Barrier Test

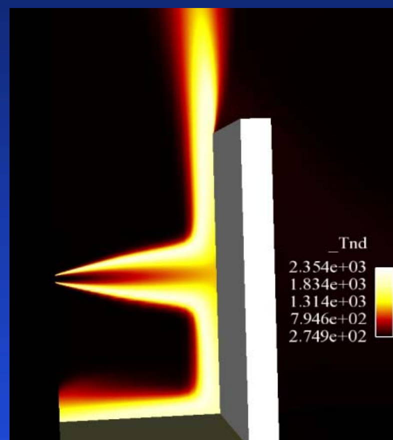


Sandia National Laboratories

Full-scale experiments provide insight and validate modeling

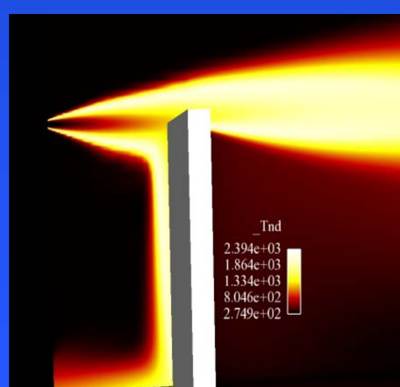
Jet Centerline Aligned with Center of Barrier

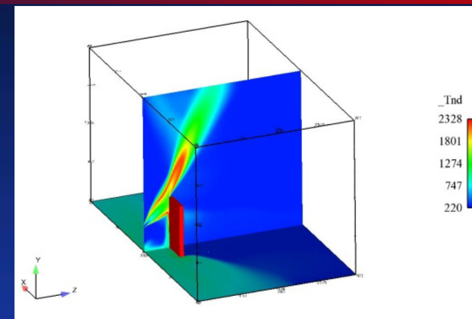
Experiment **Simulation**



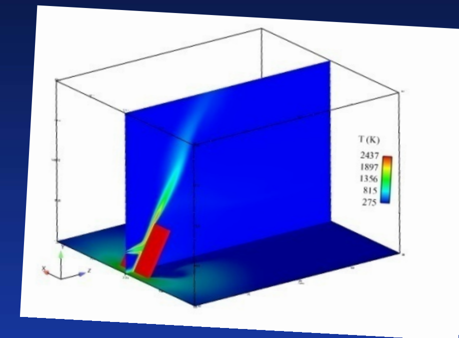
Jet Centerline Aligned with Top of Barrier

Experiment **Simulation**

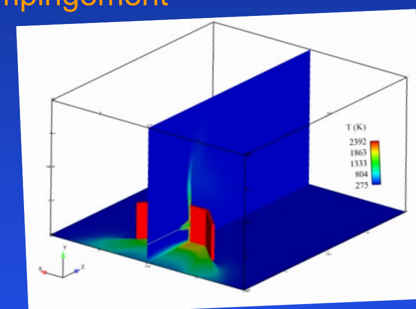




Vertical Wall - +45deg impingement



60º Tilted Wall



3 Wall Configuration (135º between walls)

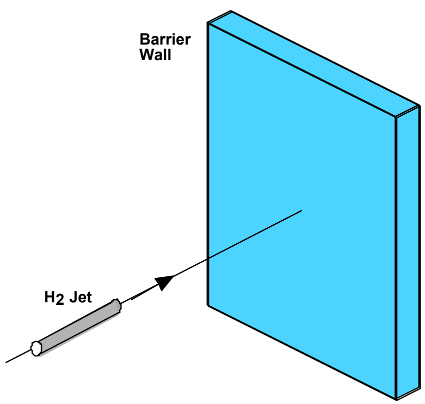
51.8 MPa (7500 psig)

- Full-scale experiments provide model validation data for simulations of jet flames
- Barriers reduce downstream flame impingement hazar
- No flame stabilization behind barrier (top of wall configuration)
- Validated model is used to predict flame deflection for barrier and leak configurations not tested

Barrier configurations for model validation

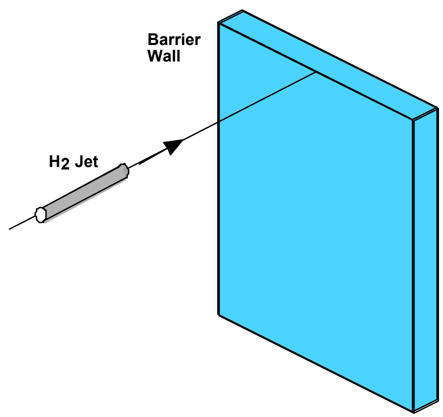
1-Wall Vertical Barrier (Jet at Wall Center)

Jet at Wall Center



1-Wall Vertical Barrier (Jet at Wall Top)

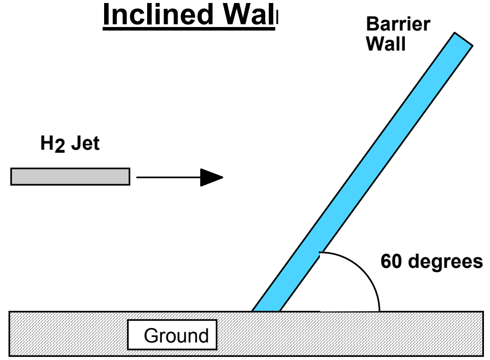
Jet at Wall Top



1-Wall Tilted Barrier[1]

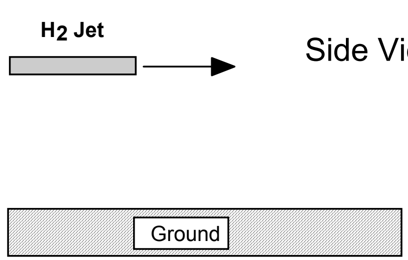
Side View

Inclined Wall



Free Jet

Free Jet

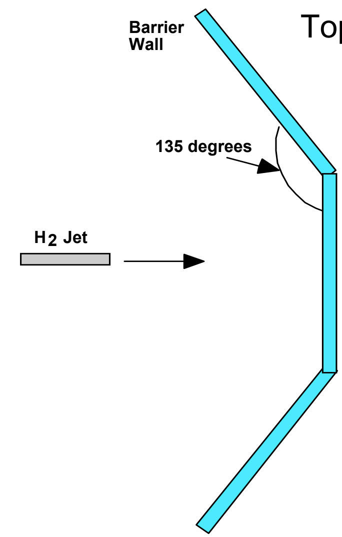


Side View

3-Wall Barrier[2]

Three-sided Wall

Top View

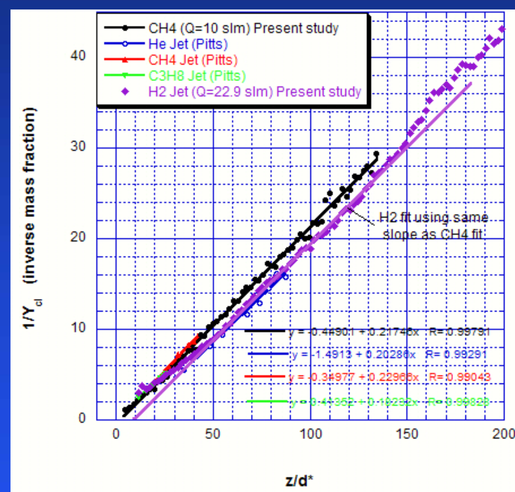


[1] Based of NFPA 68 guidelines for barrier walls.
[2] Recommended by IFC 2006.

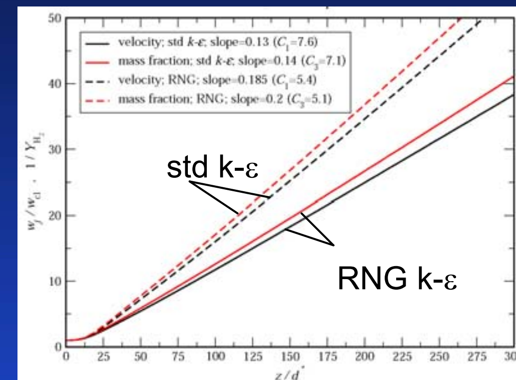
CFD code validated against unignited & ignited free H_2 jets flames

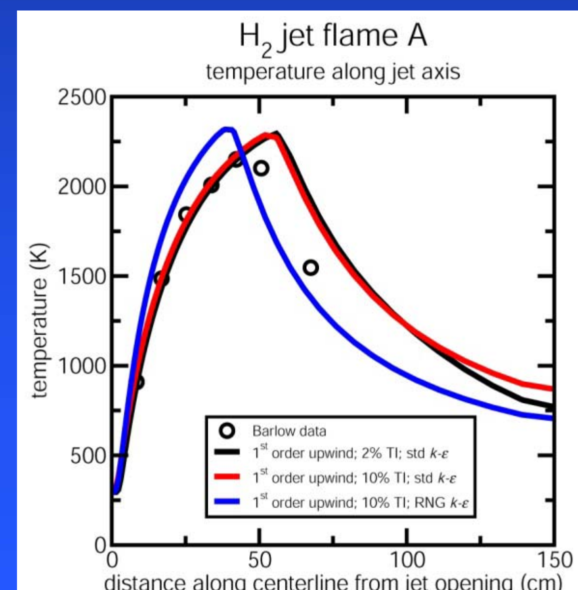
- **Turbulent jet characteristics**
  - Hyperbolic variation of jet centerline mass (or mole) fraction with axial distance

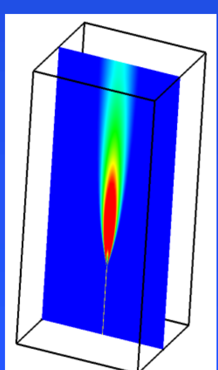
Concentration Decay Data



Concentration and Velocity Decay Simulations







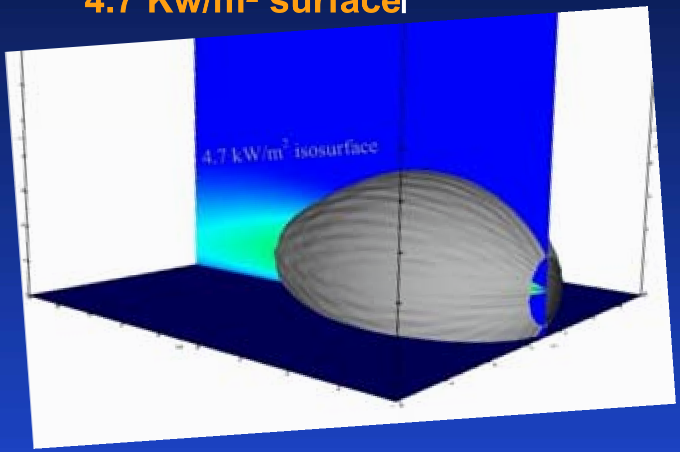
Fuego H_2 Flame Simulation
Barlow flame A (ref. Combustion and Flame, v. 117, pp. 4-31, 1999)

Houf, Evans, and Schefer, "Analysis of Jet Flames and Unignited Jets from Unintended Releases of Hydrogen," Inter. Jour. of Hydrogen Energy, Feb, 2009.

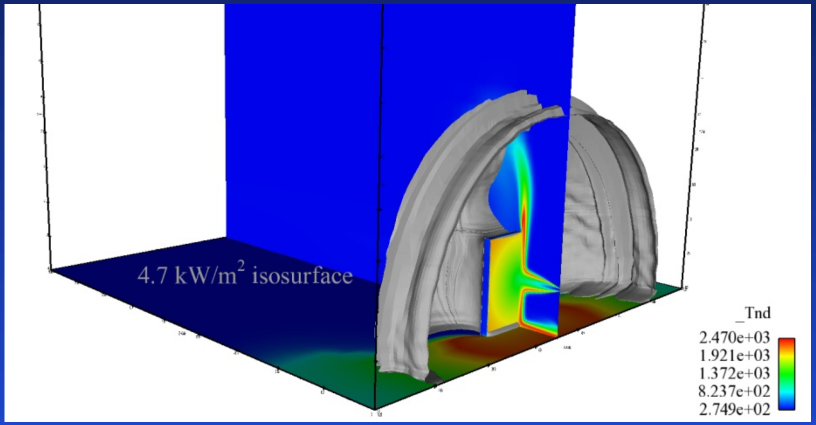
Barriers are effective at reducing radiation & impingement hazards

Free H_2 jet flame

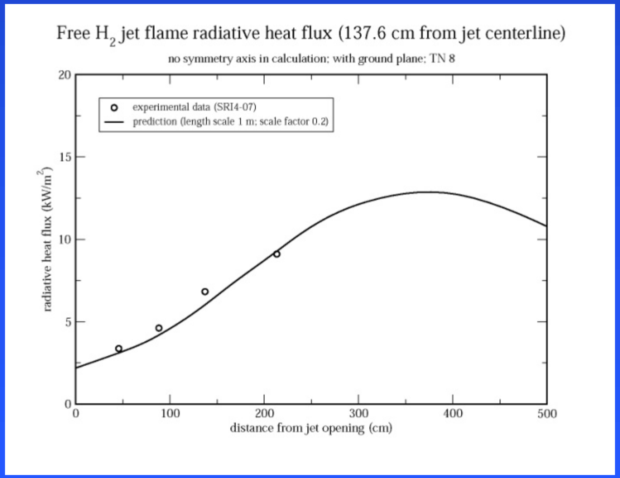
4.7 Kw/m² surface



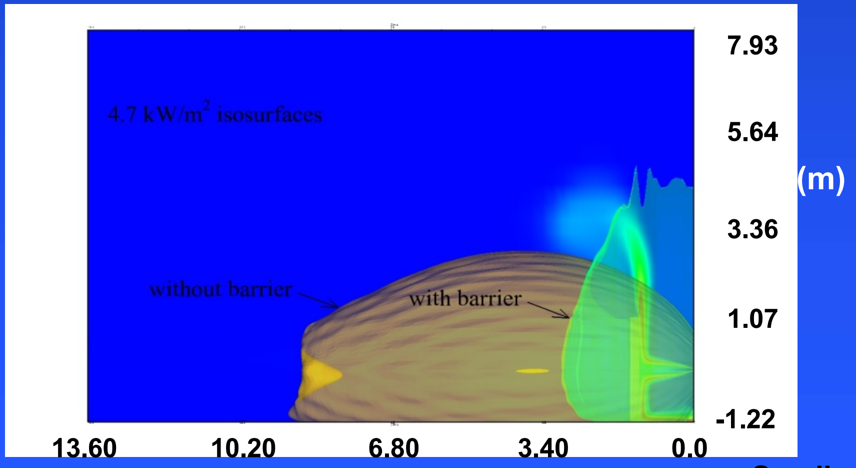
H_2 Jet Flame Impinging on Barrier
4.7 Kw/m² surface



Free jet flame radiation heat flux comparison with experiment



Comparison free jet and barrier



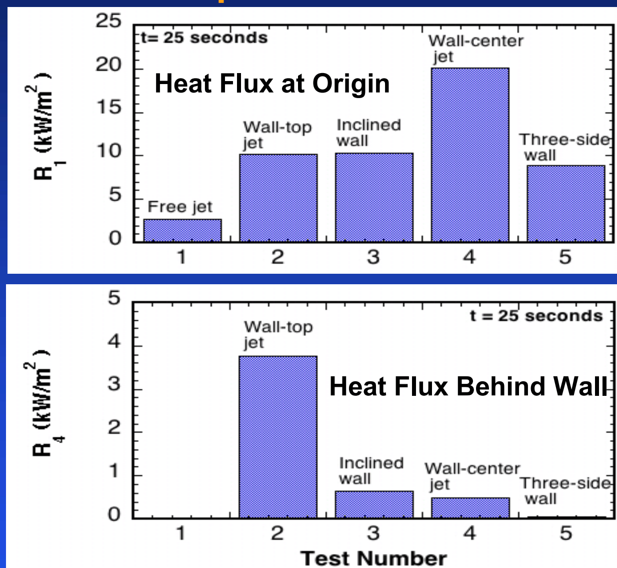
d

Sandia National Laboratories

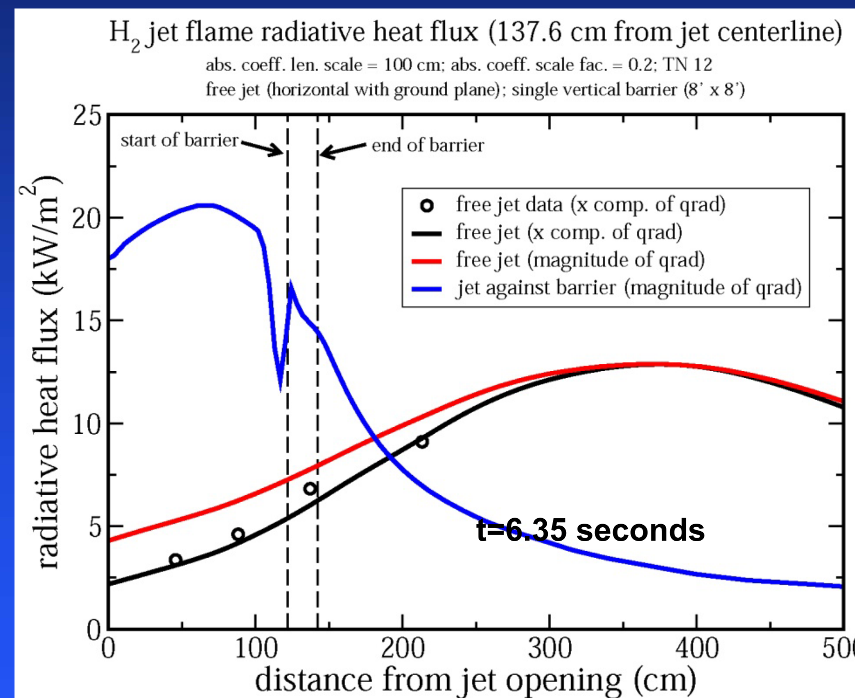
Barriers are effective at reducing radiation & impingement hazards

Both experiments and simulations show reduced radiative heat flux levels downstream of barriers

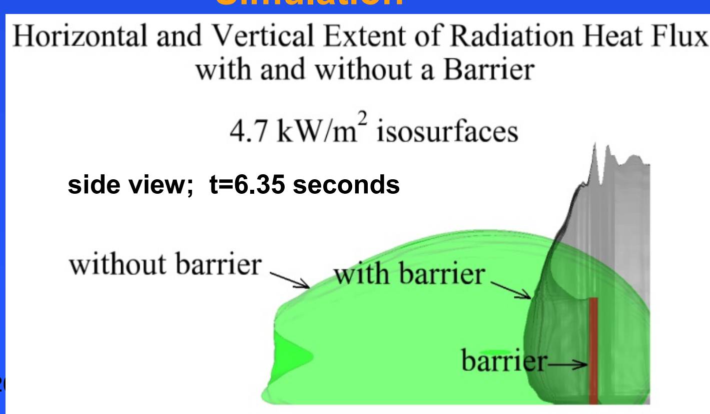
Experiment



Comparison of experiment and simulation



Simulation



Sandia National Laboratories

Model Simulations

Radiative Heat Flux (kW/m^2)	Geometry	Axial Extent (m)	Lateral Extent (m)
1.5	free jet	>13.5	5.7 @ z=3.9
1.5	1-wall vertical barrier	4.9	>6.3 @ z<3.7
1.5	1-wall tilted barrier	9.1	>6.3 @ z<6.5
1.5	3-wall barrier	5	>7.6 @ z<1.9
4.7	free jet	8.8	2.8 @ z=3.8
4.7	1-wall vertical barrier	3. @ x=2.3	4.9 @ z=1.1
4.7	1-wall tilted barrier	4.5 @ y=2.2	4.2 @ z=2.4
4.7	3-wall barrier	2.9 @ y=3.8	6.6 @ z=-2.6
20	free jet	5.2	1. @ z=3.5
20	1-wall vertical barrier	1.5 @ x=1.7	2.4 @ z=1.2
20	1-wall tilted barrier	2.1 @ y=2	1.6 @ z=1.6
20	3-wall barrier	1.5 @ y=2	4.2 @ z=-2.1
25	free jet	4.7	0.8 @ z=3.5
25	1-wall vertical barrier	1.4 @ x=1.6	2. @ z=1.2
25	1-wall tilted barrier	1.6 @ y=1.1	0.86 @ z=1.6
25	3-wall barrier	1.3 @ y=1.8	3.9 @ z=-1.6

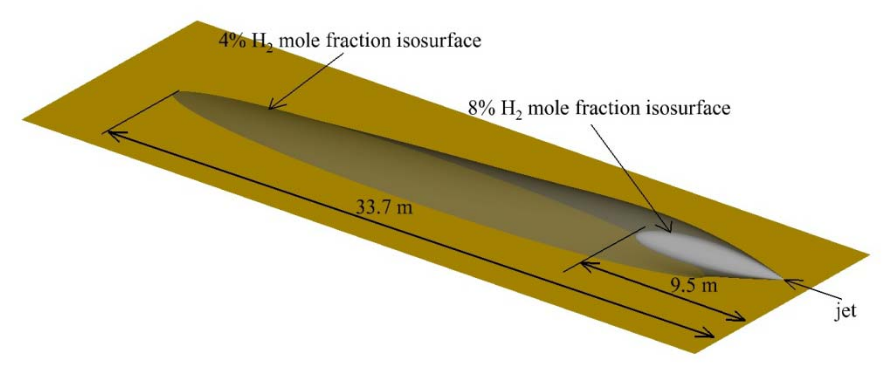
- Radiation Heat Flux Levels
  - 1.5 kW/m2 - Lot line
  - 4.7 kW/m2 - Employee exposure for 3 minutes
  - 20 kW/m2 - Combustible Equipment
  - 25 kW/m2 - Non-combustible Equipment
- Source Pressures
  - 1.8 MPa (250 psig)
  - 20.7 MPa (3000 psig)
  - 103.5 MPa (15,000 psig)
- Barriers reduce horizontal distances (all rad. Heat fluxes)
- Tables also generated for Codes and Standards Source Pressures
- 3-wall (135^o) most effective

Simulations of unignited hydrogen releases

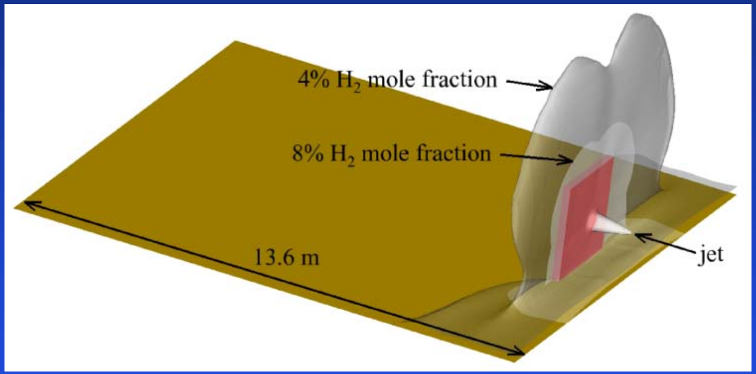
- Conditions of Sandia/SRI jet flame tests
- Barriers shorten concentration decay distances in direction of jet release

Simulations of 4% and 8% H_2 mole fraction surfaces

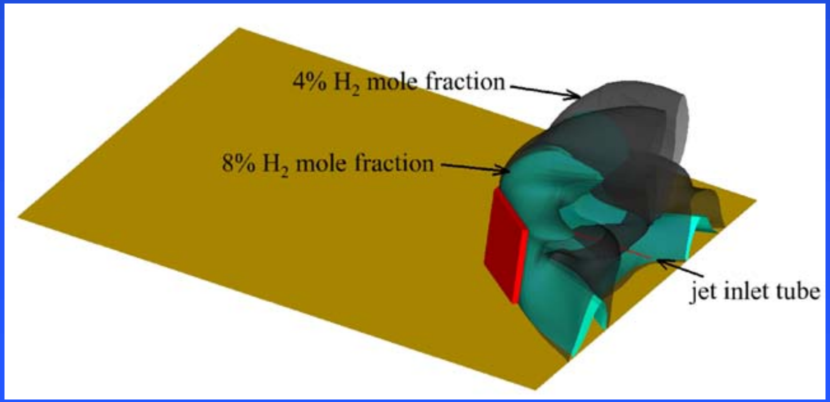
Free Jet Flame



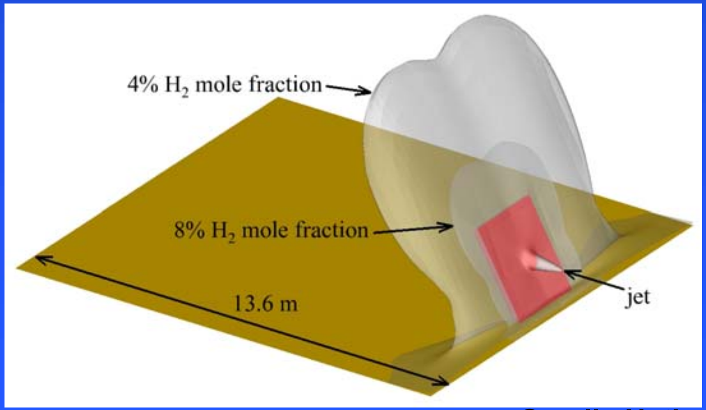
1-Wall Vertical Barrier



3-Wall Vertical Barrier



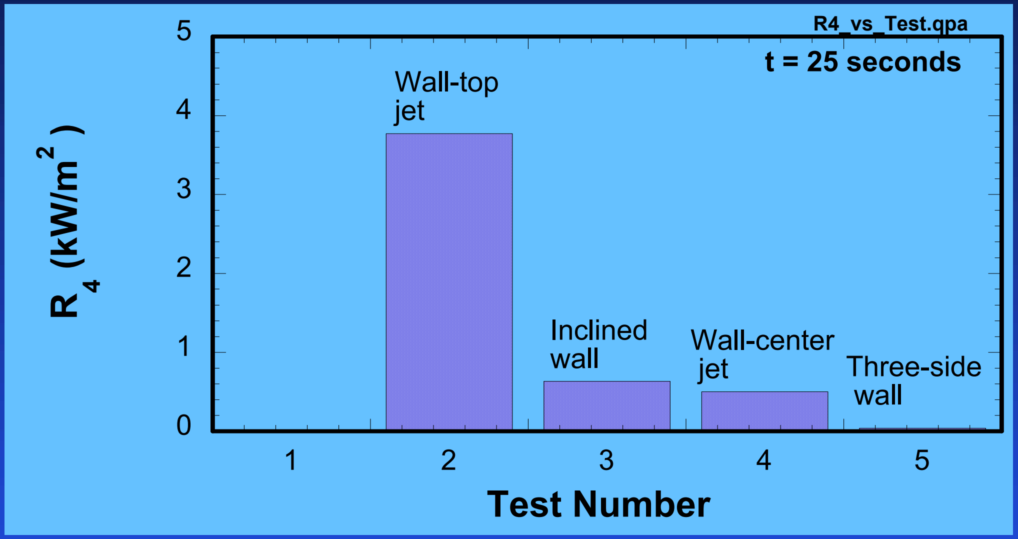
1-Wall Tilted Barrier



Sandia National Laboratories

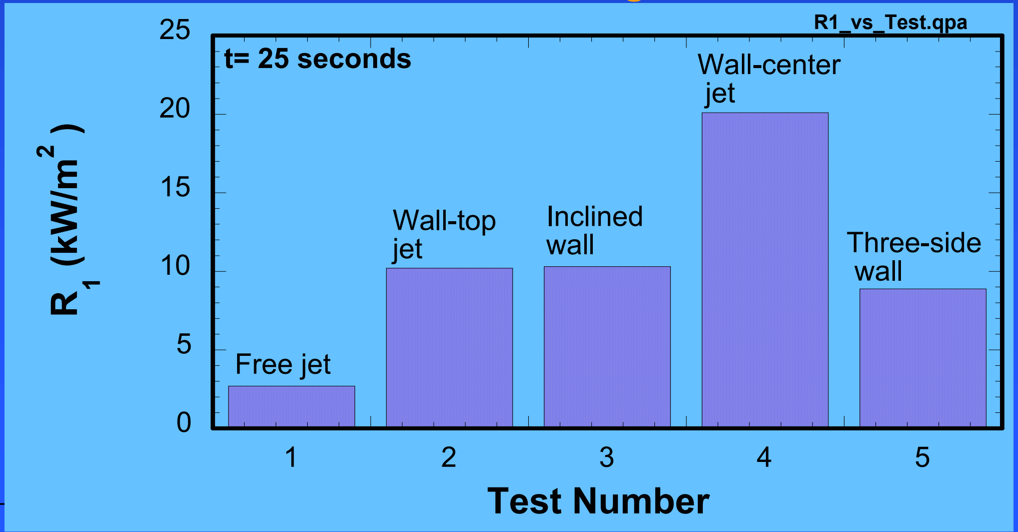
Barrier Wall Tests: Effect on Radiative Heat flux

Heat Flux Behind Wall



- Maximum radiative heat flux behind wall occurs with jet at top of wall jet configuration
- Heat flux levels with all walls are well below harmful levels.
- Walls are an effective mitigation strategy for radiative heat flux hazards as long as flame is confined by wall.

Heat Flux at Jet Origin



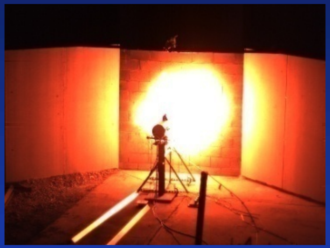
- Walls significantly increase heat flux levels at leak origin.
- Heat flux levels at leak origin for jet centered on wall exceed pain threshold limit (19.87 kW/m2 for 2 sec exposure time).

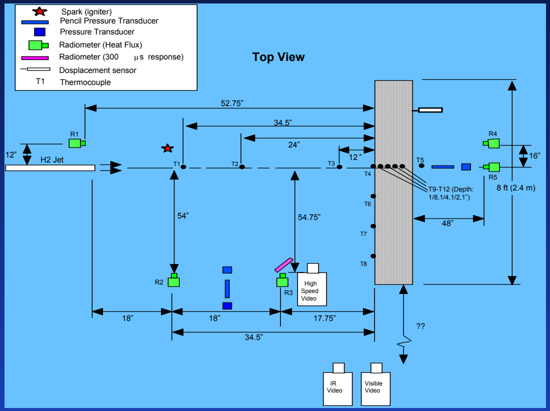
Overpressure from the ignition of impinging hydrogen jets

High-speed movie frames of H_2 ignition near barrier wall

Frame 1 (t = 137 msec)
Spark ignition

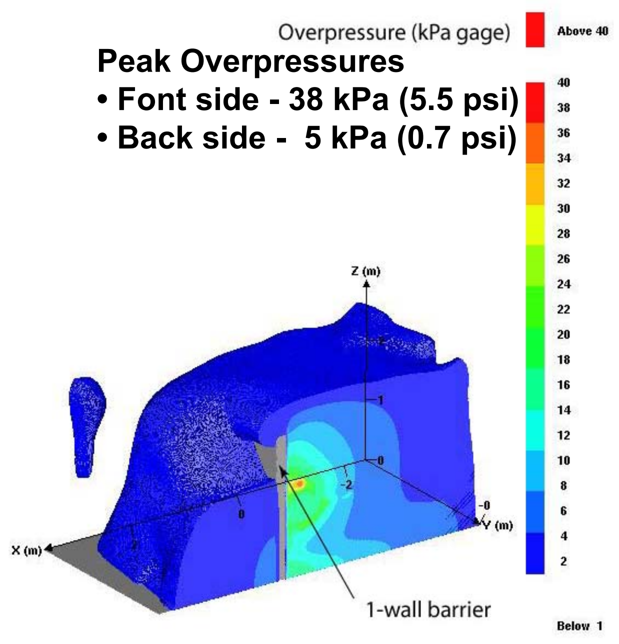
Frame 15 (t = 165 msec)



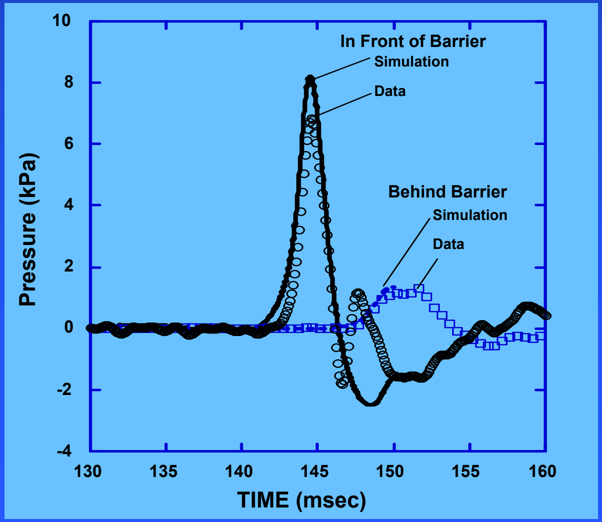


1-Wall Barrier
(Jet at Wall Center)

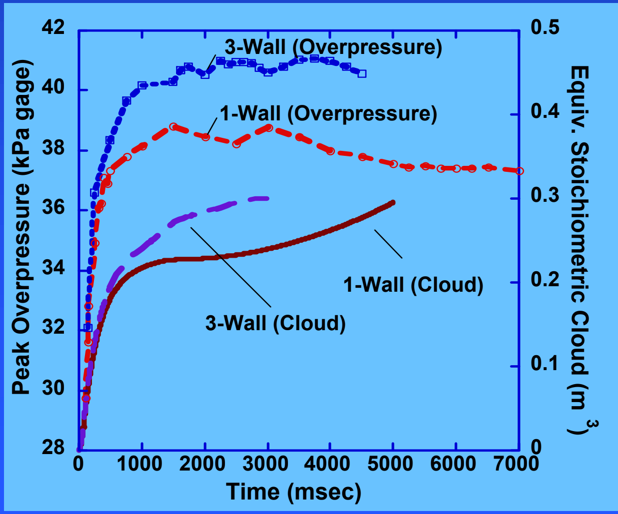
Peak Overpressures
- **Font side - 38 kPa (5.5 psi)**
- **Back side - 5 kPa (0.7 psi)**



Comparison of Simulation and Experiment for Overpressure Sandia/SRI 1-Wall Test



Simulation of Peak Overpressures For Different Ignition Times 1-Wall and 3-Wall

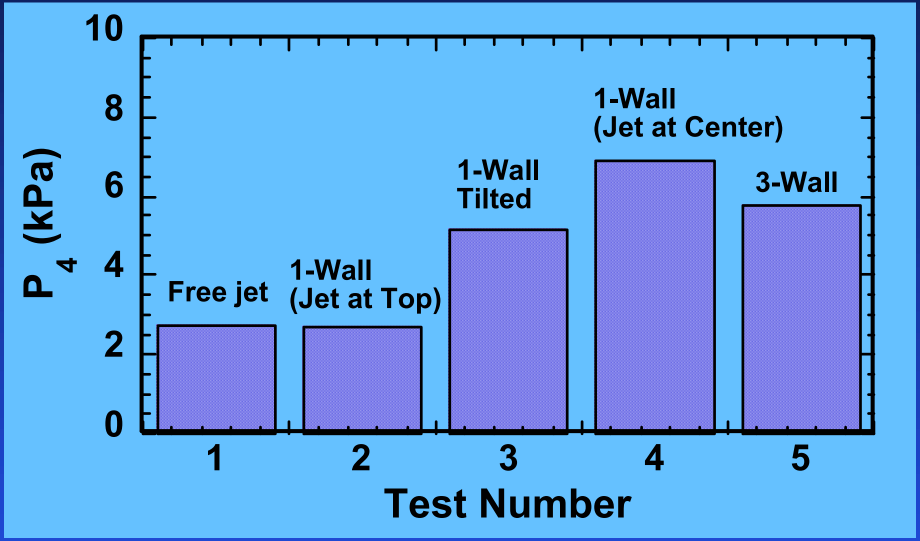


Tests performed at SRI Corral Hollow test site

Sandia National Laboratories

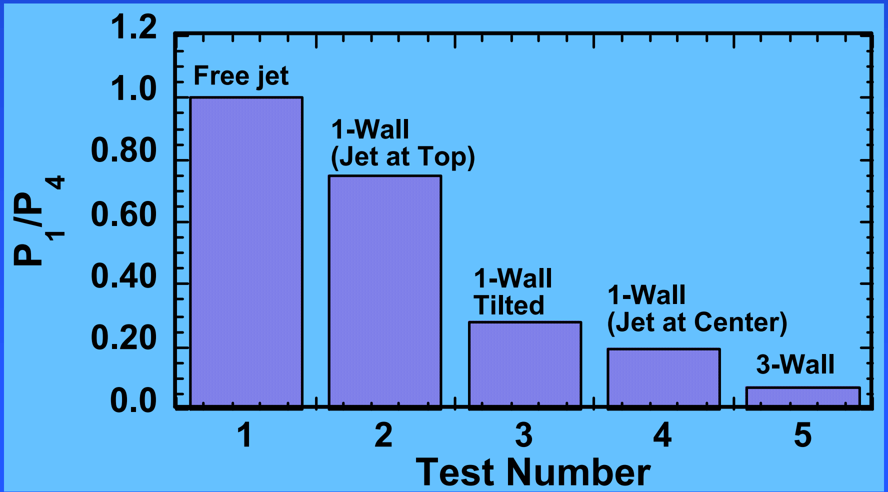
Barrier Wall Tests: Effect on Overpressure

Pressure Before Wall



- Wall-centered jet results in a factor of 2.5 increase in overpressure prior to wall.
- Maximum overpressure reduction achieved by three-sided wall (pressure behind wall reduced by a factor of 14).

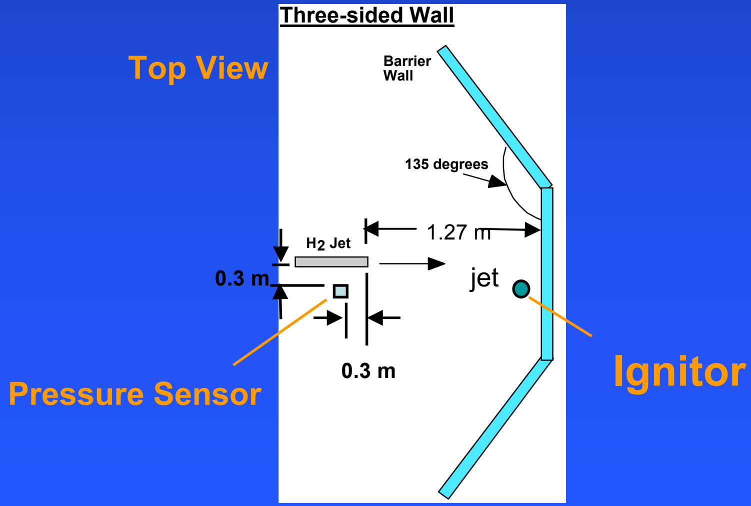
Pressure Attenuation



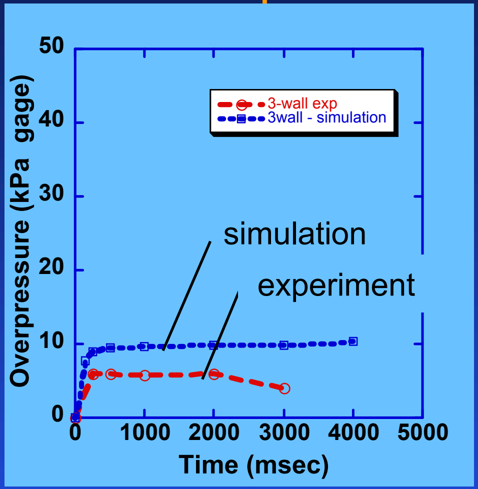
Overpressure does not increase with increasing time to ignition

High-speed movie frame of H_2 ignition near 3-wall barrier

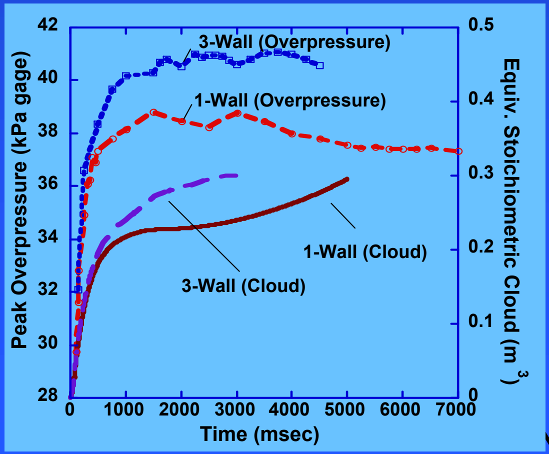
3-Wall Barrier



Comparison of Measurement and Simulations of Overpressure at Sensor

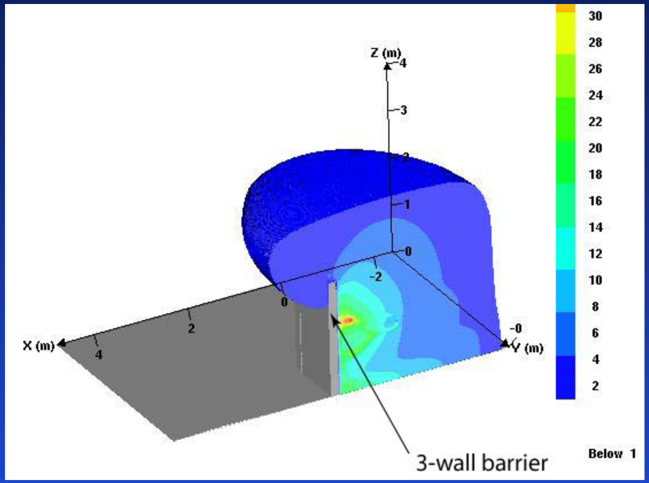


Comparison of Peak Overpressure and for 1-Wall and 3-Wall Tests (Simulations)



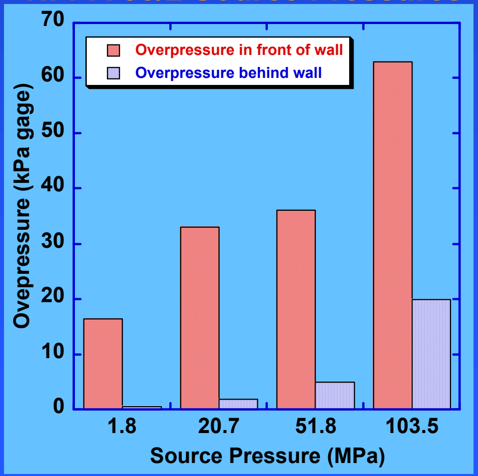
Validated simulations are used for code development basis

Simulation of Ignition Peak Overpressures around 3-Wall 135° Barrier*

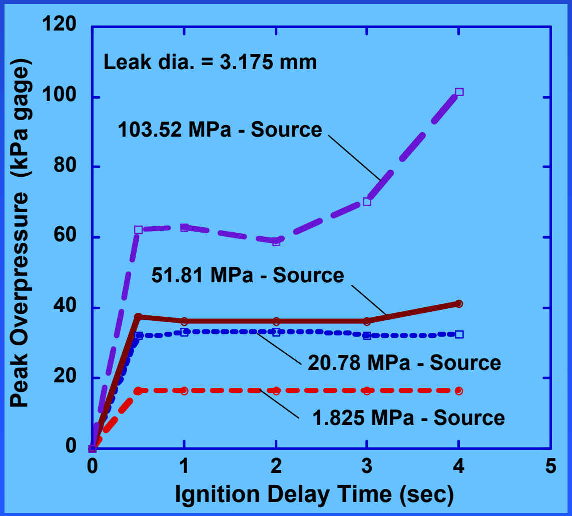


- Barriers reduce over-pressure behind wall
  - factor of 5x for 1-wall
  - factor of 20x for 3-wall configurations
- New NFPA 55/2 separation distance table incorporates credit of 50% reduction in distances for use of 2 hr fire barrier wall
- HYPER IPG incorporates experimental and modeling results for barrier design guidance

Simulations of Ignition Peak Overpressure Reduction by 1-Wall Barrier for NFPA 55/2 Source Pressures*



Simulations of Ignition Peak Overpressure for Different Delay Times for 1-Wall Barrier and NFPA 55/2 Source Pressures*



* Results for ignition 1 sec after release (dia. = 3.175 mm)

Sandia National Laboratories

Summary and Conclusions

- For Conditions Studied
  - Barriers reduce horizontal jet flame impingement hazard
  - Barriers reduce radiation hazard distances for horizontal jet flames
  - Barriers reduce horizontal unignited jet flammability hazard distances
  - Barriers attenuate ignition overpressure
- 3-Wall 135^o most effective at mitigation of overpressure, radiation, and unignited jet
- Overpressure relatively constant with ignition delay time for all barriers (1 - 6 sec)
- New NFPA 55/2 separation distance table incorporates credit of 50% reduction in distances for use of 2 hr fire barrier wall

Jet Centered on 1-Wall Barrier
Dia. = 3.175 mm (1/8 in); Source Press. = 13.8 MPa (2000 psi)

Jet Centered on Top of 1-Wall Barrier
Dia. = 3.175 mm (1/8 in); Source Press. = 13.8 MPa (2000 psi)

Publications & Presentations

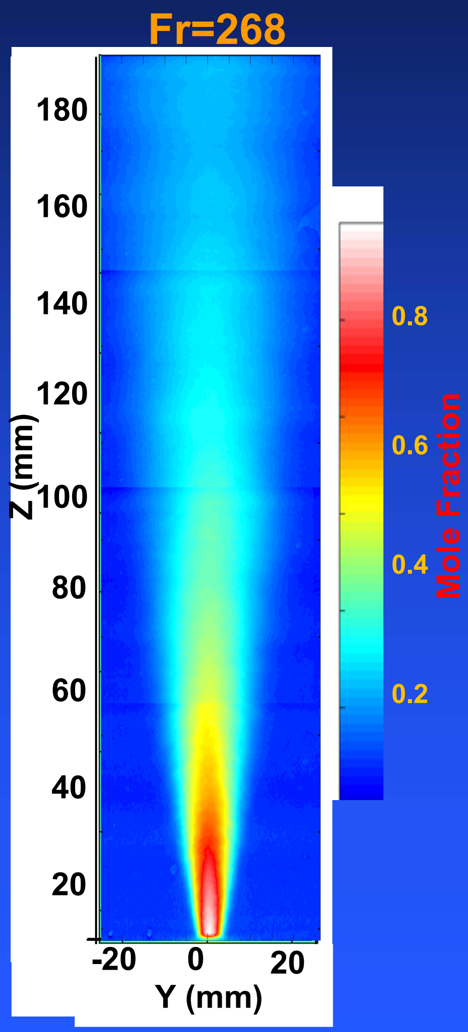
1. W. Houf, G. Evans, and R. Schefer, "Evaluation of Barrier Walls for Mitigation of Unintended Releases of Hydrogen", 2009 NHA Conference and Hydrogen Expo, Columbia, SC, March 30 - April 3, 2009.
2. R. Schefer, W. Houf, M. Groethe, G. Evans, M. Royle, D. Willoughby, "HYPER Report 5.4 - Report on Experimental Evaluation of Barrier Walls for Risk Reduction of Unintended Releases of Hydrogen," Sept. 30, 2008.
3. W. Houf, G. Evans, R. Schefer, "HYPER Report 4.3 - Releases, Fires, and Explosions Final Modelling Report, Chapter 6 - Effects of Barriers and Walls", Aug. 31, 2008.
4. W. Houf, G. Evans, R. Schefer, "Analysis of Jet Flames and Unignited Jets from Unintended Releases of Hydrogen," *International Journal of Hydrogen Energy*, in press February 24, 2009.
5. R. Schefer, M. Groethe, W. Houf, G. Evans, "Experimental Evaluation of Barrier Walls for Risk Reduction of Unintended Hydrogen Releases," *International Journal of Hydrogen Energy*, Volume 34, Issue 3, February 2009, pp. 1590—1606.
6. Schefer, R.W., Groethe, M., Houf, W.G. and Evans, G., "Experimental Evaluation of Barrier Walls for Risk Reduction of Unintended Hydrogen Releases," Sandia Report SAND2008-41411, October, 2008.
7. R.W. Schefer, W.G. Houf, T.C. Williams , "Investigation of small-scale unintended releases of hydrogen: momentum-dominated regime", *International Journal of Hydrogen Energy, Volume 33, Issue 21, November 2008, pp. 6373-6384.*
8. R.W. Schefer, W.G. Houf, T.C. Williams, "Investigation of small-scale unintended releases of hydrogen: Buoyancy effects", *International Journal of Hydrogen Energy, Volume 33, Issue 17, September 2008, pp.4702-4712.*
9. J. LaChance, W. Houf, B. Middleton, L. Fluer, "Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards," Technical Report SAND2009-0874, March 2009.
10. W. S. Winters and W. G. Houf, "Results from an Analytical Investigation of Small-Scale Releases from Liquid Hydrogen Storage Systems", 2009 NHA Conference and Hydrogen Expo, Columbia, SC, March 30 - April 3, 2009.

Lecture Outline

- Dispel some myths about hydrogen
  - We cannot build a safe hydrogen infrastructure on false perception
- Unintended release behavior
  - Momentum dominated flows
  - Buoyancy dominated flows
- Effect of barriers on:
  - Flame impingement, Radiation, Pressure effects
- Ignition
  - Spontaneous ignition (Not covered here)
  - Flammability limits (flame stability)
    - Quiescent flows, Turbulent jets, Detonation, Explosion
- Quantitative risk assessment

Flame Ignition Limits: Ignitable Gas Envelope Considerations

Vertical H_2 Jet (d_j=1.9 mm)

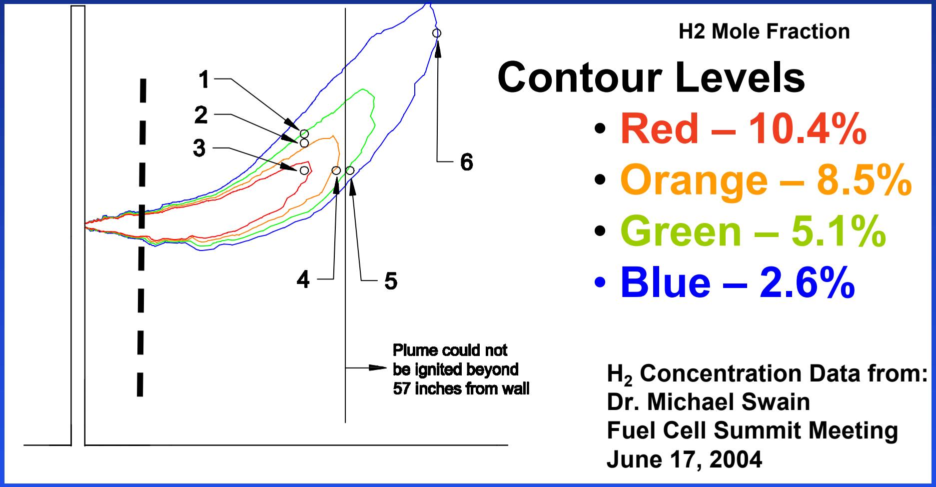


- The ignitable gas envelope is important to establishing separation distances for unintended releases.
- The extent of the ignitable gas envelope can be based on several criteria. Which is best for Codes & Standards development?
- For example:
  - Time-averaged H_2 concentration field reveals extent of cloud within traditional flammability limits (4% LFL to 75% RFL).
  - Do traditional (static) flammability limits provide a suitable measure of ignitability in turbulent flowing systems?

Sandia National Laboratories

Flame Ignition Limits: Motivation

Time-averaged concentration field



Jet Conditions:

Flowrate = 20 scfm, Hole Dia. = 9.44 mm

Exit Mach Number = 0.1 (Unchoked Flow)

- Swain determined that hydrogen in turbulent jets could not be ignited at concentrations less than 8%.
- Why does this ignition limit differ from the traditional LFL of H_2 of 4%?
- Possible explanations:
  - **The LFL of H_2 is not well known**
  - **Ignition limits in turbulent jets are not well-represented by the time-averaged concentration field**
- Which volume fraction contour is relevant:
  - **lean flammability limit? … 4% or 8%**
  - **detonation limit? … 18%**
  - **a fraction of the lowest lean flammability limit? … 1%**

***(Chen and Rodi, 1980)**

Flammability Limits for H_2: Are well known.

Upward Flame Propagation (4%)

Tube Dimensions, cm		Firing end	Limits, percent		Water Vapor Content	Reference
Diameter	Length		Lower	Higher		
7.5	150	Closed	4.15	75.0	Half-saturated	356
5.3	150	Open	4.19	74.0	Dried	94
5.3	150	Ņ	4.1			
5.3	150	Ņ	4.1			
5.0	150	Closed	4.1			
5.0	150	Open	4.0			
4.8	150	Ņ	4.0			
4.5	80	Closed	4.1			
4.5	80	Ņ	3.9			

Horizontal Flame Propagation (7.2%)

Tube Dimensions, cm		Firing end	Limits, percent		Water Vapor Content	Reference
Diameter	Length		Lower	Higher		
7.5	150	Closed	6.5	-----	Half-saturated	356
5.0	150	Ņ	6.7	-----	Ņ	356

Downward Flame Propagation (9.5%)

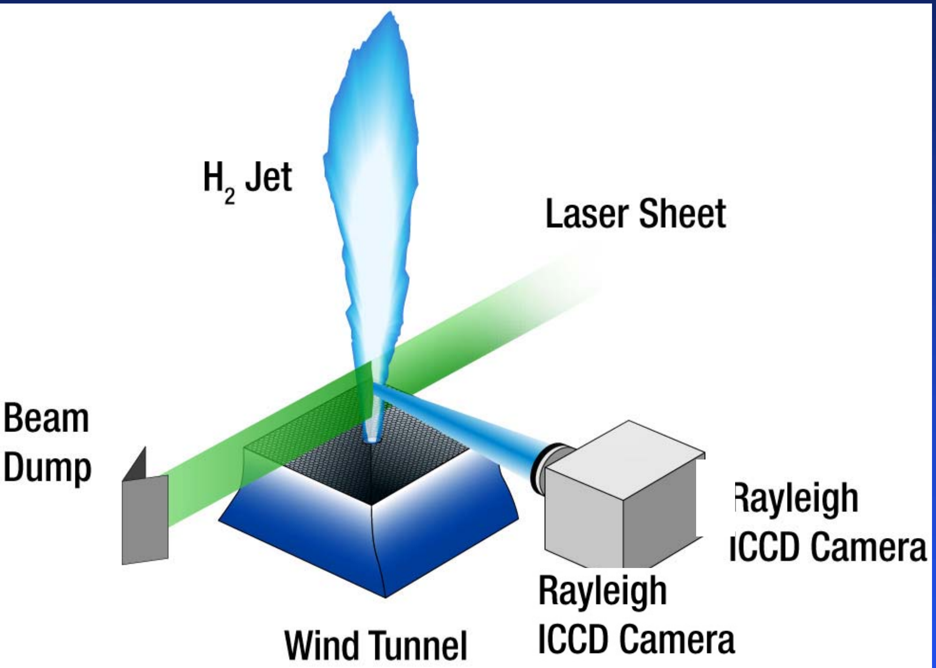
Tube Dimensions, cm		Firing end	Limits, percent			
Diameter	Length		Lower	Higher		
21.0	31	Open	9.3	----		
8.0	37	Closed	8.9	68.8		
7.5	150	Ņ	8.8	74.5		
7.0	150	Ņ	-----	74.5		
6.2	33	Open	8.5	----		
6.0	120	Ņ	9.45	----	Ņ	325

Propagation in a Spherical Vessel

Capacity, cc	Firing end	Limits, percent		Water Vapor Content	Reference
		Lower	Higher		
Not stated	Closed	9.2	----	Saturated	271
Not stated	Ņ	8.5	67.5	Ņ	82
1,000	Ņ	8.7	75.5	Ņ	95
810	Ņ	5.0	73.5	Ņ	349
350	Ņ	4.6	70.3	Ņ	368
35	Ņ	9.4	64.8	Ņ	297

- *Flammability limits of H_2 are sensitive to propagation direction but are well established*

Small Unignited Releases: Concentration Contours

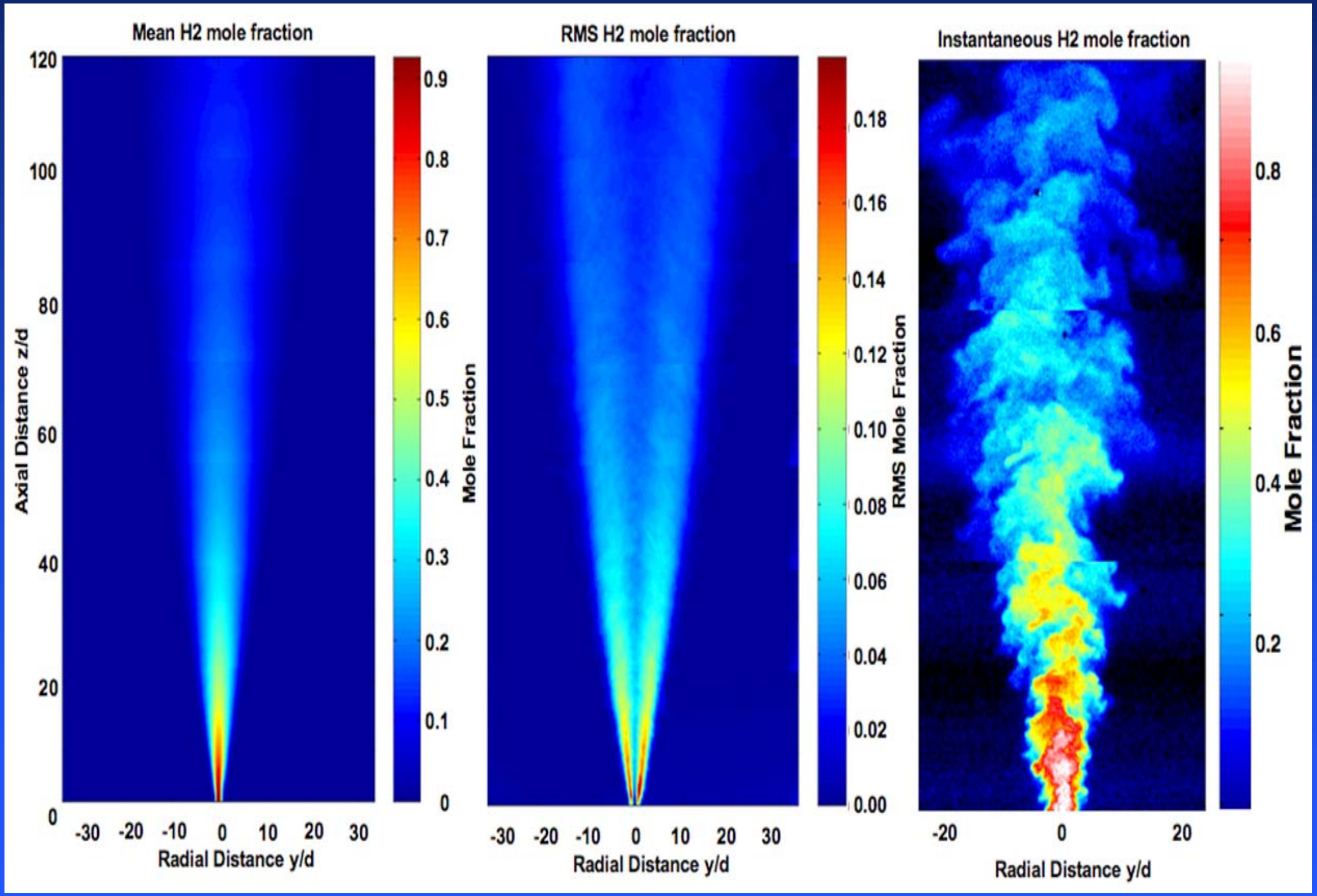


- Molecular (Rayleigh) scattering from laser sheet is imaged onto CCD camera.
- Rayleigh scattering signal is given by: I=C1n∑xi σI
  - where Ci = optical constant
  - n = gas number density
  - xi= species i mole fraction
  - σi= Rayleigh cross section.
- For an isothermal, two component mixture, the H2 mole fraction is linearly related to signal intensity.

Use Rayleigh imaging to characterize concentration field in H_2 leaks.

Small Unignited Releases: Vertical Jets

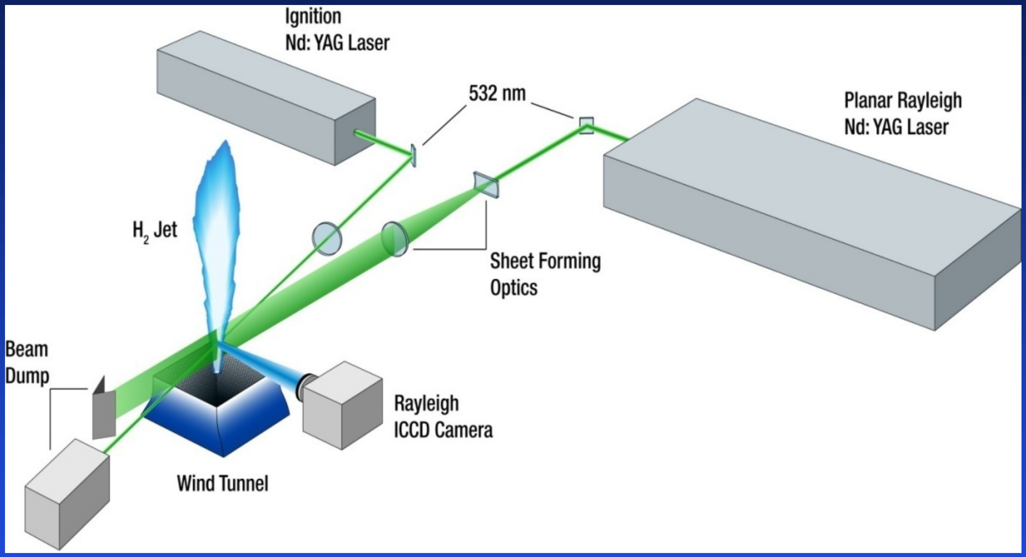
Vertical H_2 Jet (d_j=1.9 mm)



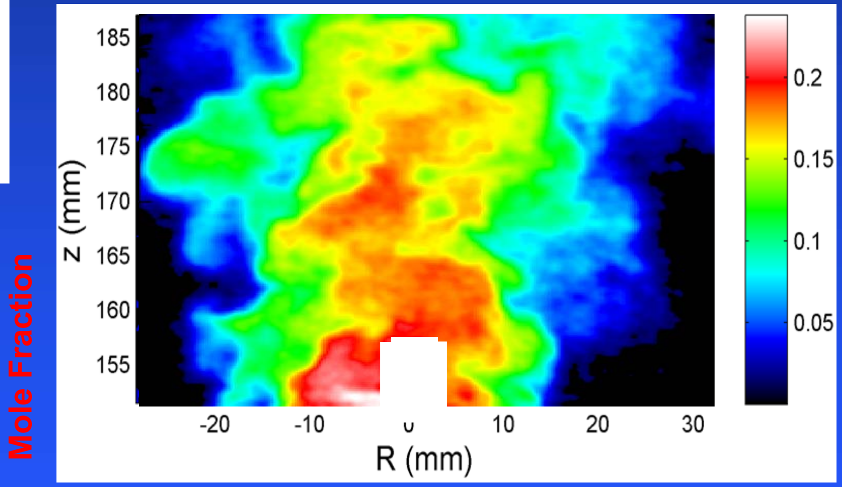
- Time-averaged mean and fluctuating concentration field provides validation data and link to CFD modeled quantities.
- Single-shot images reveal instantaneous flow structure.
- Significant temporal fluctuations in H_2 at all locations in flow.

Jet Ignition Probability: Ignition Point Concentration Contours

Simultaneous Planar Laser Rayleigh Scattering (PLRS) and laser ignition



H_2 distribution in ignition region

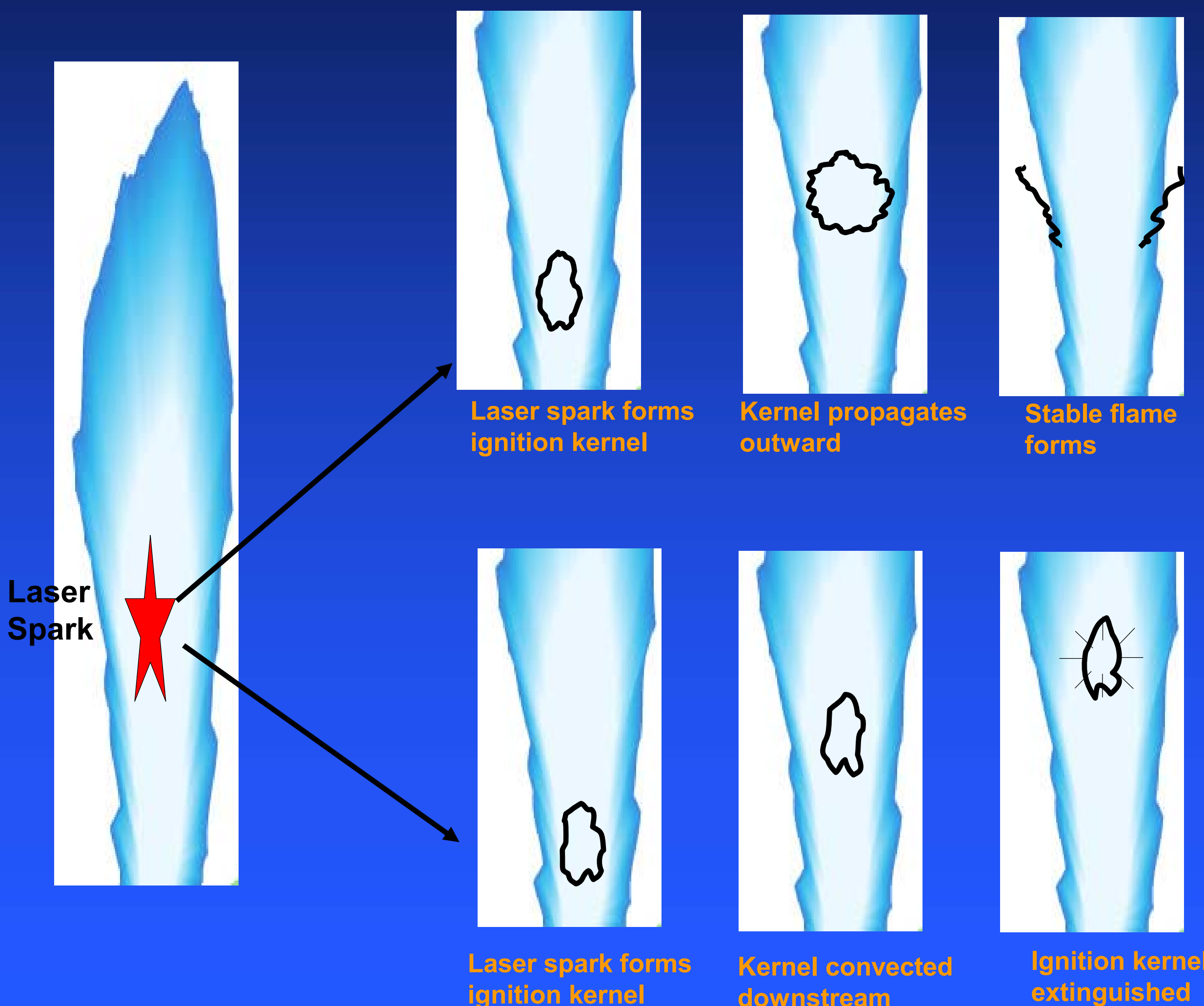


Rayleigh laser occurs 320 μsec before ignition laser pulse.

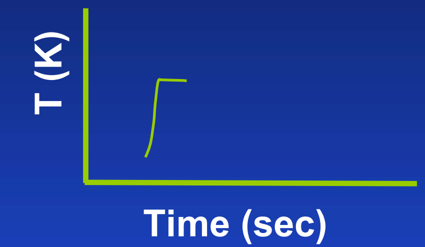
Use simultaneous Rayleigh imaging and laser ignition to characterize H_2 concentration distribution at ignition point.

Jet Ignition Probability: Definitions

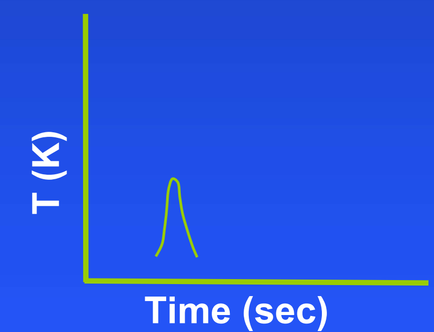
Methane jet studies revealed both local ignition and total flame lightup.



Downstream Temperature Sensor Readout.



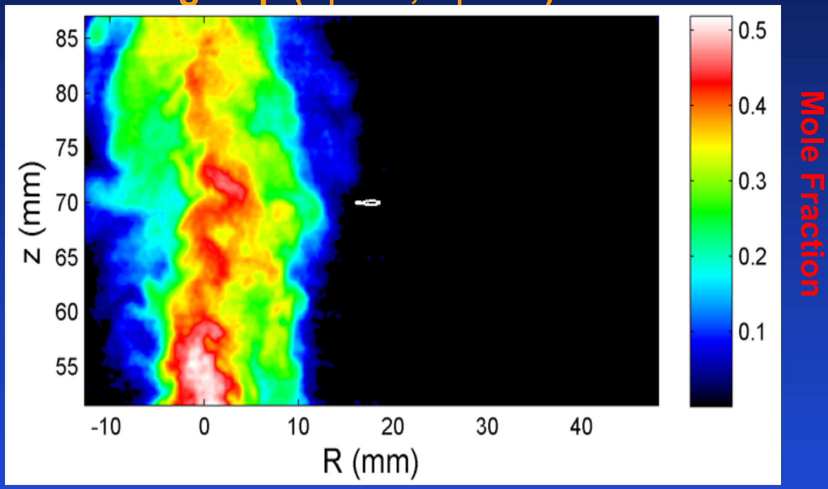
Define Lightup Probability, P_L, as probability stable jet flame forms.



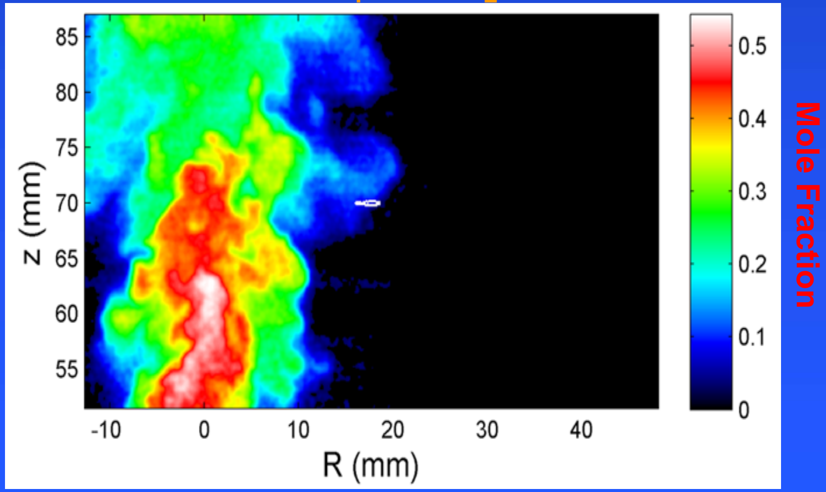
Define Ignition Probability, P_I, as probability of local ignition event.

Jet Ignition Probability: Ignition Point Concentration Contours

No Lightup (P_I=0.1; P_L =1.0)



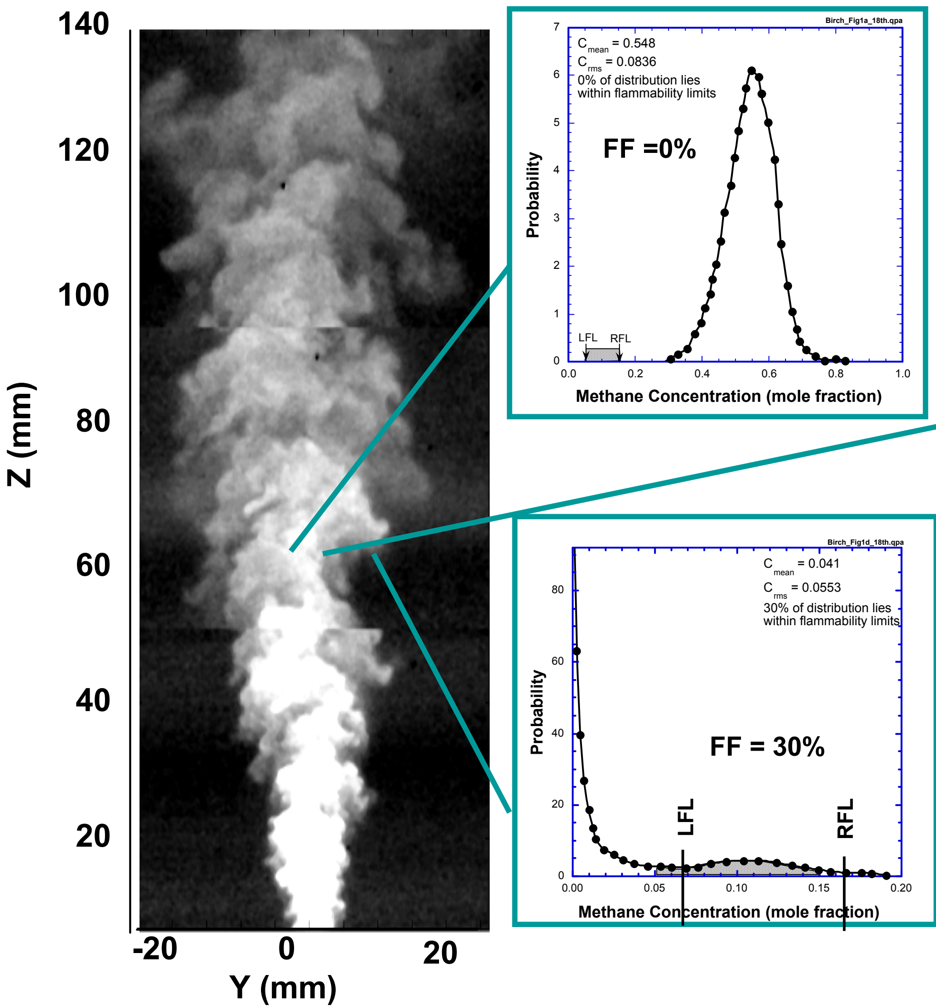
Jet Lightup (P_I=0.1; P_L=1.0)



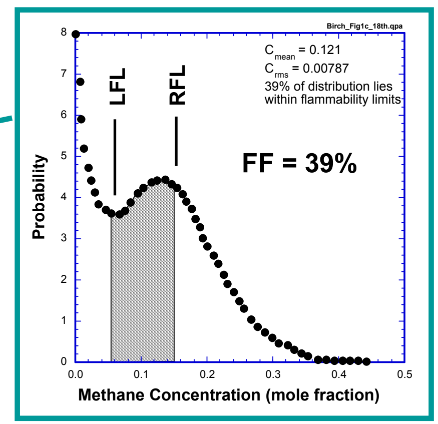
- Instantaneous concentration distribution near ignition point at radial location in outer jet shear layer.
- In the upper image no local ignition occurred since pure air occupied the ignition volume.
- In the lower image both local ignition and jet lightup occurred since mixed H_2/air was present at the ignition point and within the flammability limits.

Jet Ignition Probability: Definitions

Methane jet into ambient air (Birch et. al., 1981)

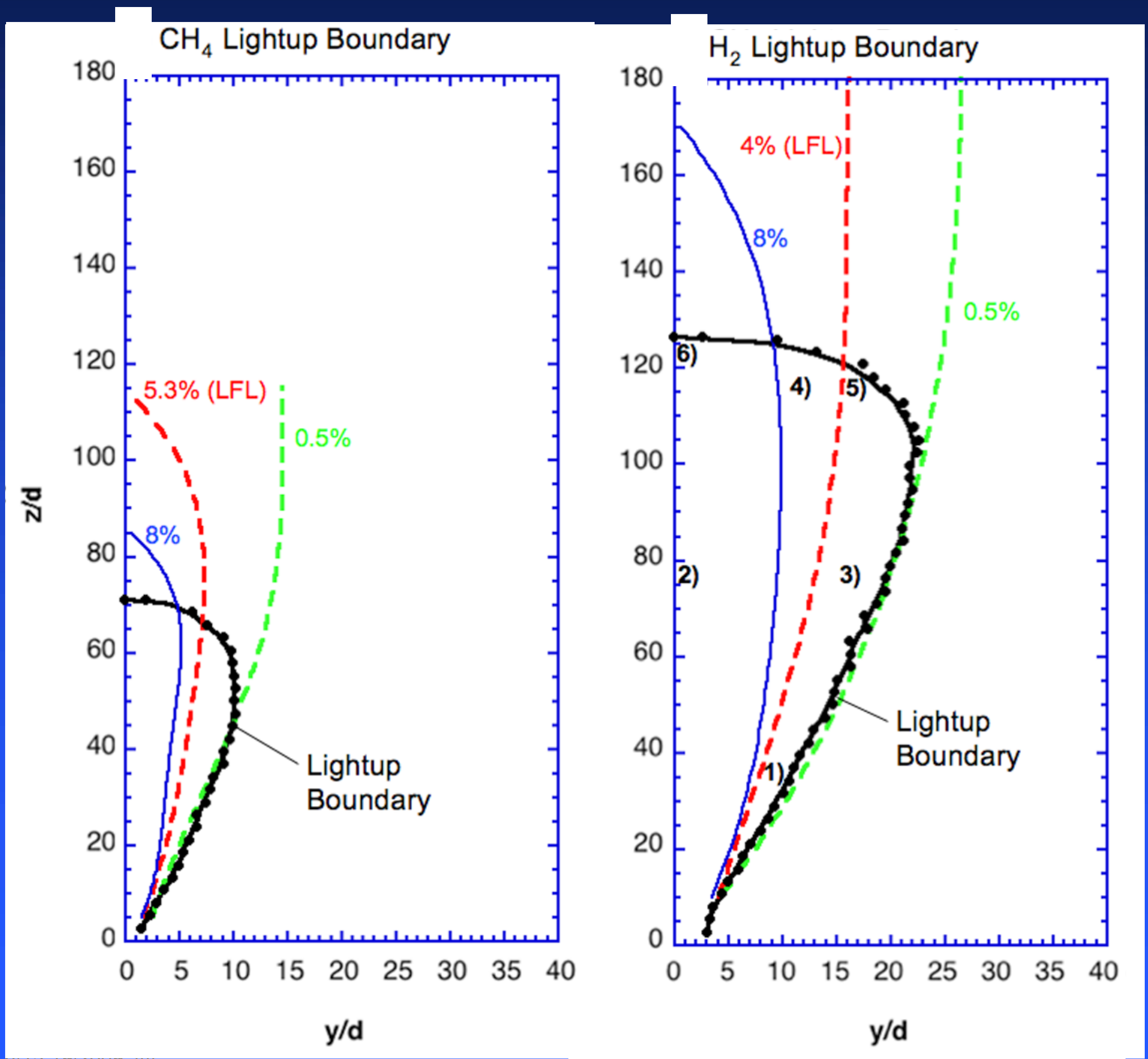


- Concluded time-averaged concentration data are not a good measure of ignitability in turbulent flows
- Probability distributions quantify intermittent nature of turbulent flows and must be used to



Flammability Factor is defined as the cumulative probability of a potentially flammable mixture occurring at a given point.

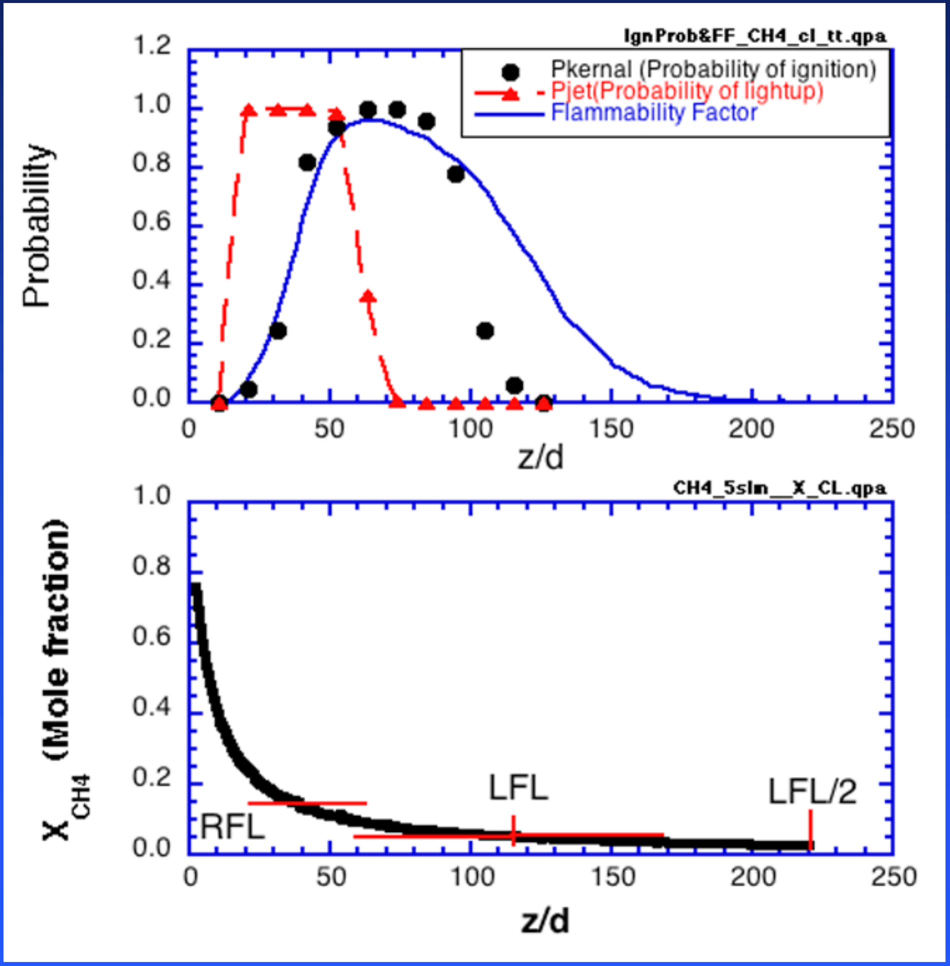
Jet Ignition Probability: Comparison Methane & H_2 Jets



- Jet Reynolds numbers are 2,384 and 3,406 for H_2 and CH_4 jets, respectively
- H_2 jet ignition characteristics are similar to CH_4 jet
- No flame lightup observed near jet centerline for H_2 volume fraction < 10% (in agreement with Swain).
- At outer radial locations flame lightup boundary closely follows 0.5% H_2 and CH_4 contour (<< LFLH_2 or CH_4).

Jet Ignition Probability: Centerline Profiles

Methane jet (d_j=1.91 mm)

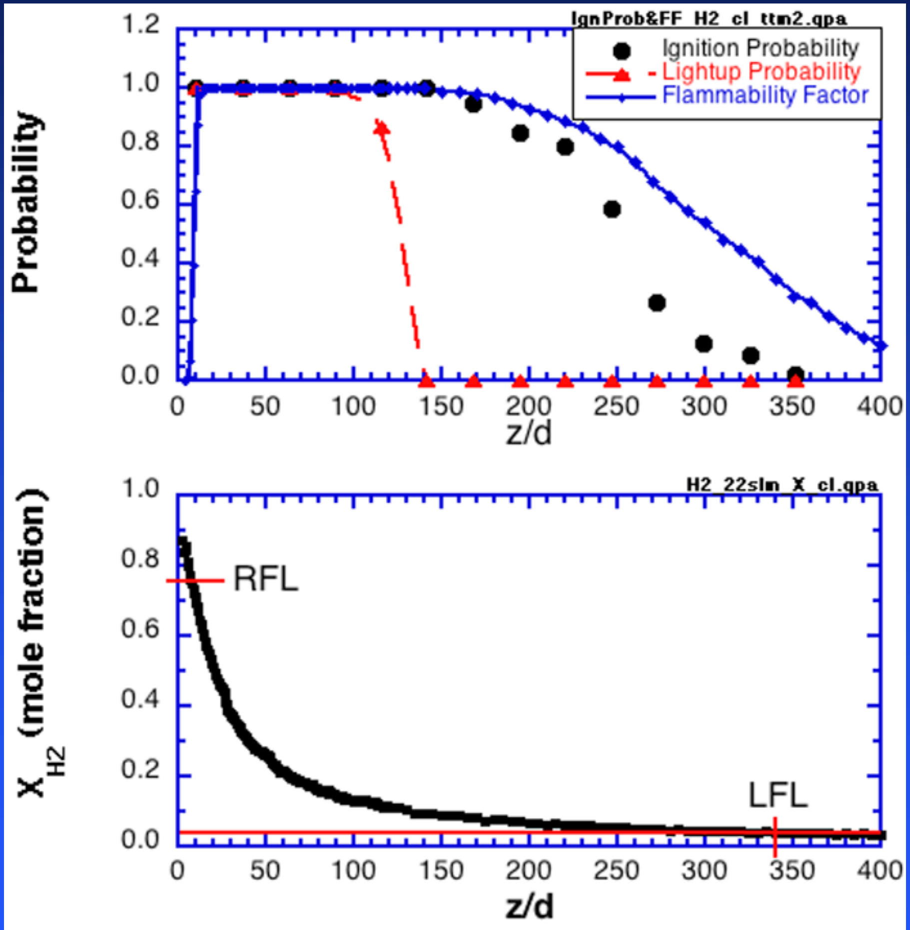


- P_L increases rapidly to unity while P_I increases more slowly than with H_2.
- Between 20 < z/d < 70, P_I and P_L are nonzero and some ignition events lead to lightup.
- Flammability factor provides reasonable measure of ignitability.
- Faster downstream fall off of P_I may indicate not all flame kernels are captured.

Laser ignition measurements show good agreement with spark ignition measurements in NG jets by Birch et al. 1981.

Jet Ignition Probability: Centerline Profiles

Hydrogen jet (d_j=1.91 mm)

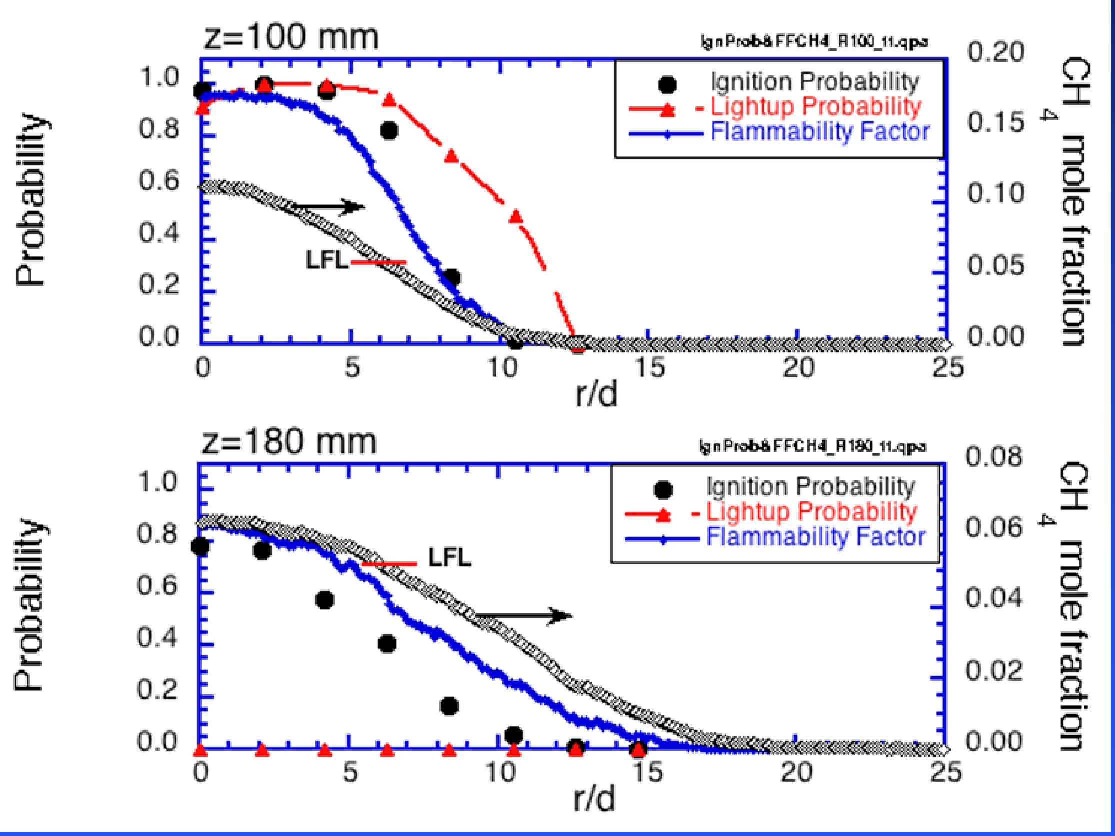


Ignition measurements based on 100 mJ spark at 3 sec intervals.

- Both P_L and P_I increase rapidly to unity downstream of jet exit.
- Between 5 < z/d < 120, both P_I and P_L are unity and every ignition leads to lightup.
- P_L decreases to zero at z/d=140 which corresponds to XH_2=0.10 (>2*LFL).
- Between 140 < z/d < 350 P_I is nonzero while P_L is zero and all ignitions are extinguished.
- Flammability Factor provides reasonable measure of ignitability upstream but falls off more gradually than P_I

Jet Ignition Probability: Radial Profiles

Methane jet (d_j=1.91 mm)



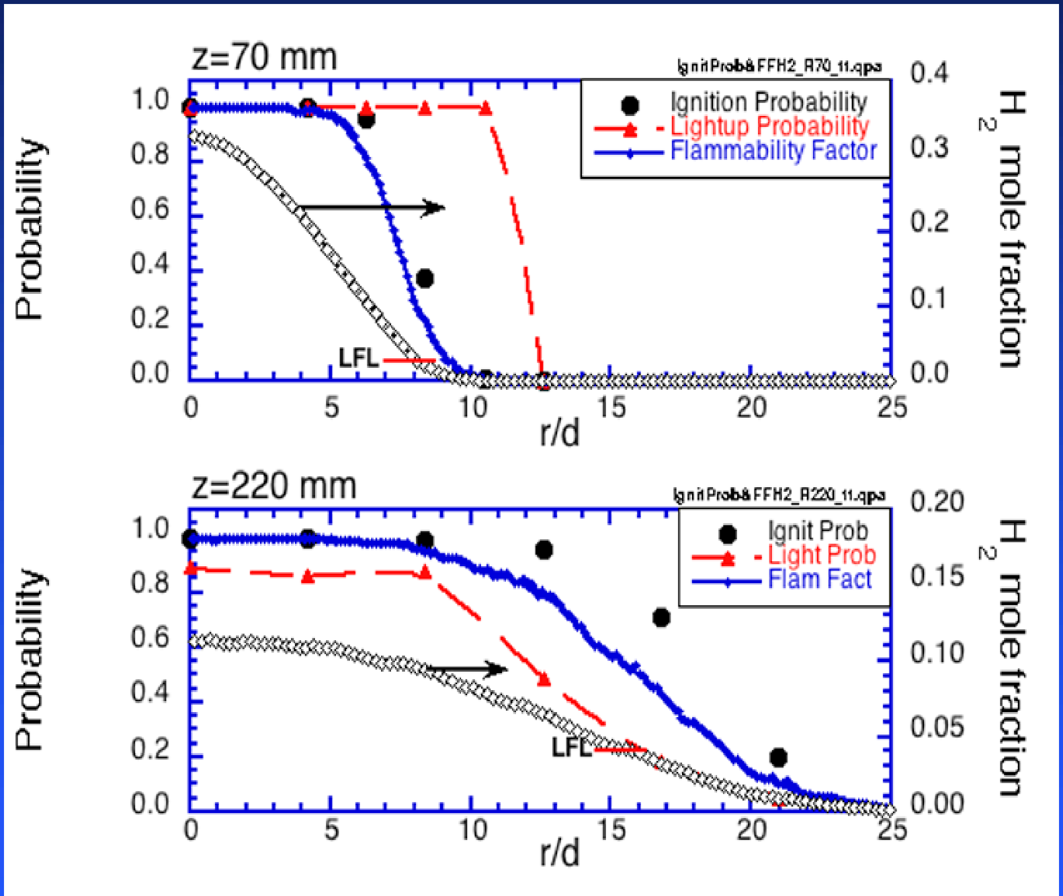
- At upstream locations PI is near unity in the central jet and most ignitions lead to jet lightup.
- Farther downstream PI is nonzero across most of central jet but no lightup is observed.
- Both ignition and lightup are observed at radial locations where concentration is below static flammability limits.
- Flammability factor again provides good measure of ignitability.

Ignition measurements based on 100 mJ spark at 3 sec intervals.

Sandia National Laboratories

Jet Ignition Probability: Radial Profiles

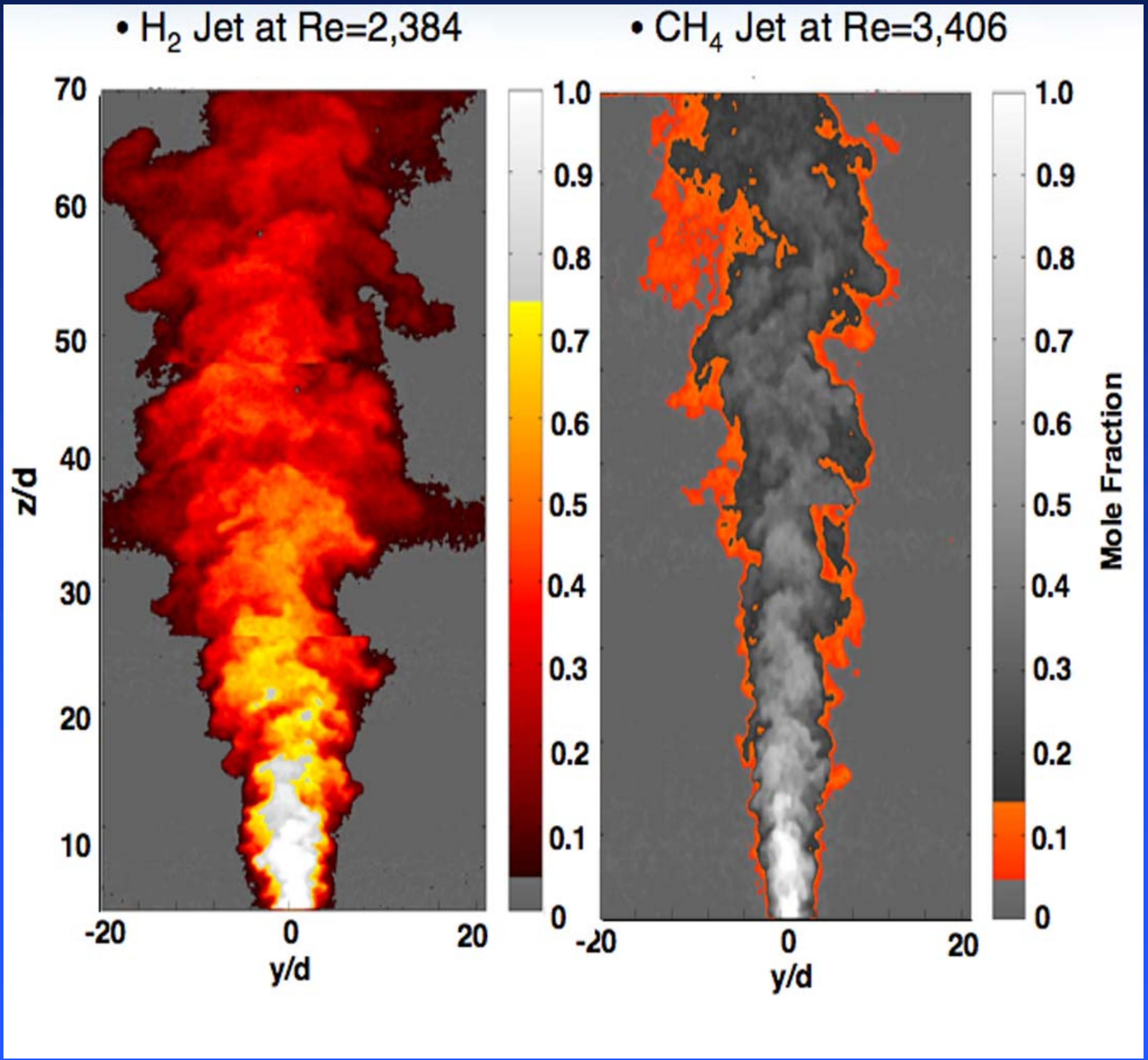
Hydrogen jet (d_j=1.91 mm)



Ignition measurements based on 100 mJ spark at 3 sec intervals.

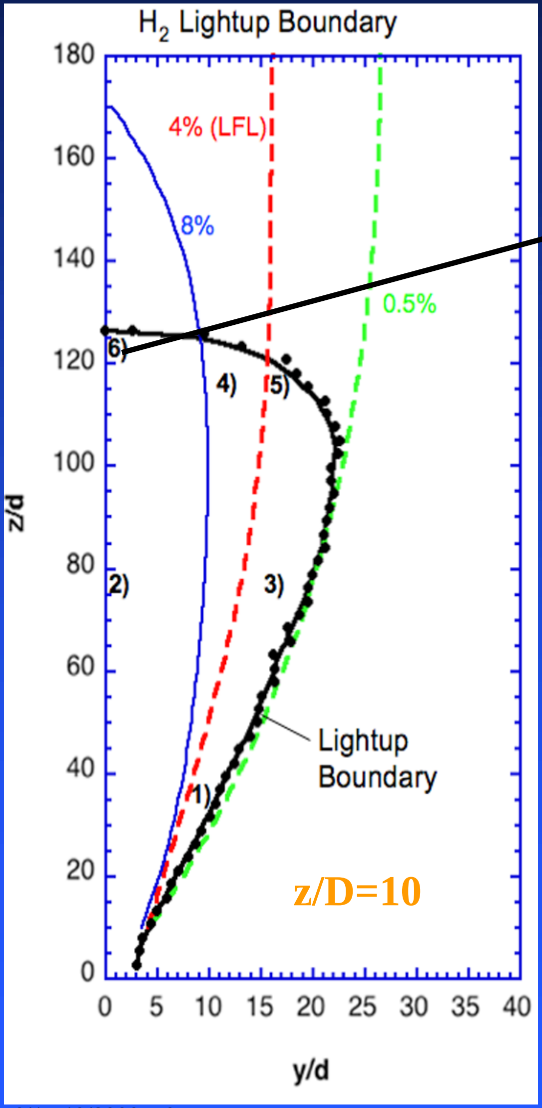
- P_I and P_L are both unity in central jet and decrease to zero at outer radial locations due to mixing with excess air.
- Width of region where ignition occurs increases with downstream distance.
- Both ignition and lightup are observed at radial locations where mean H_2 concentration is below static flammability limits.
- Flammability factor provides a good measure of ignitability at outer radial locations.

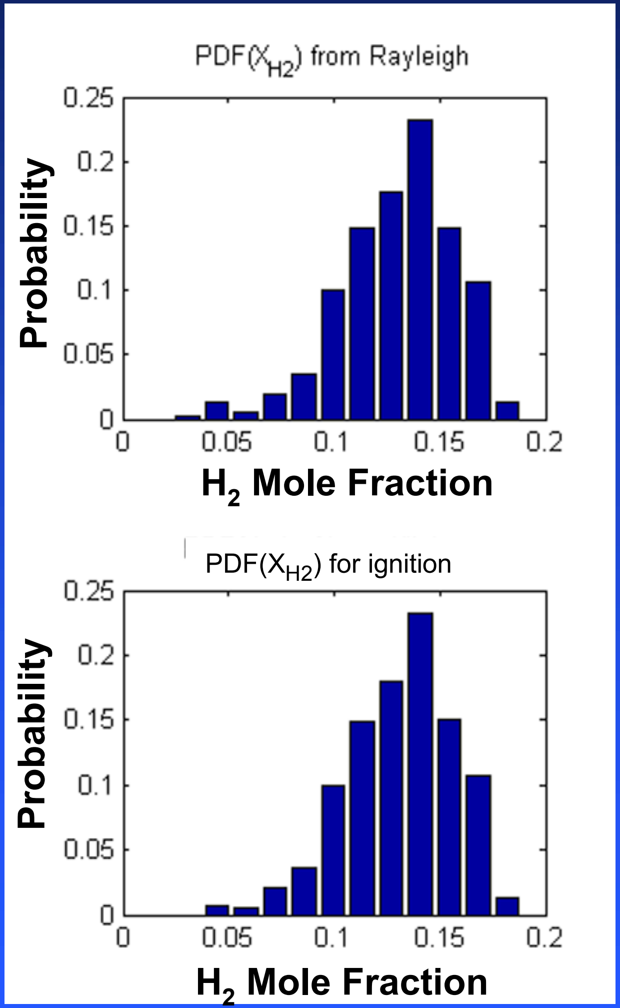
Jet Ignition Probability: Ignition Occur at Locations Outside LFL, why?



- Ignitable gas envelope wider in H_2 jets due to broader flammability limits:
  - H_2: LFL 4.0%; UFL 75%
  - CH_4: LFL 5.2%; UFL 15%
- Ignition at locations where concentration less than LFL consistent with “intermittency”.
- At outer radial locations highly irregular interface exists between jet and ambient air.
- At fixed point, concentration varies between mixed H_2/air and pure air.
- Time-averaged concentration is low due to pure air contribution but finite probability that flammable mixture will sometimes exist.

Jet Ignition: Conditional Probabilities

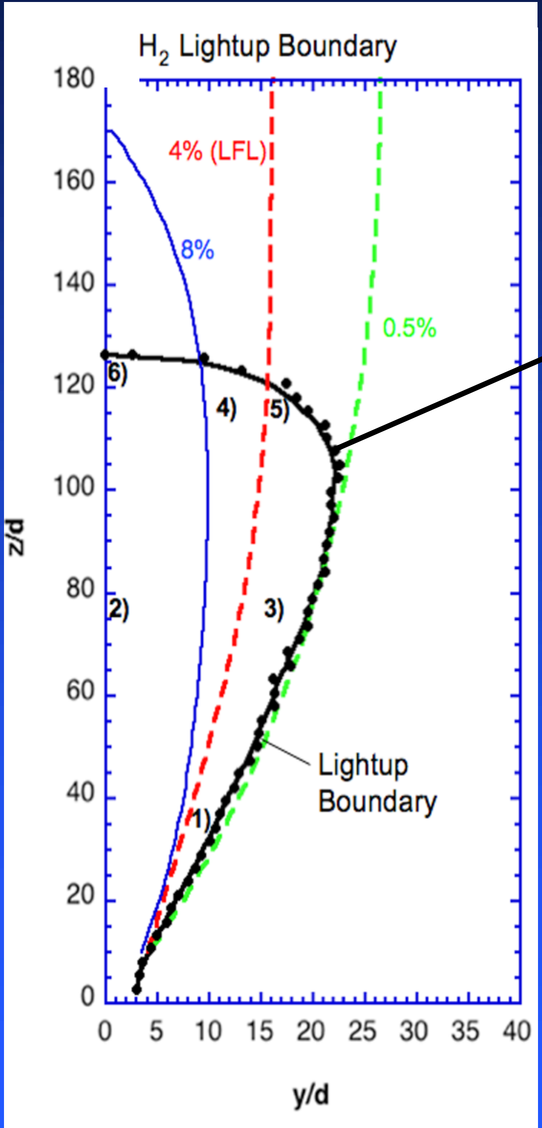


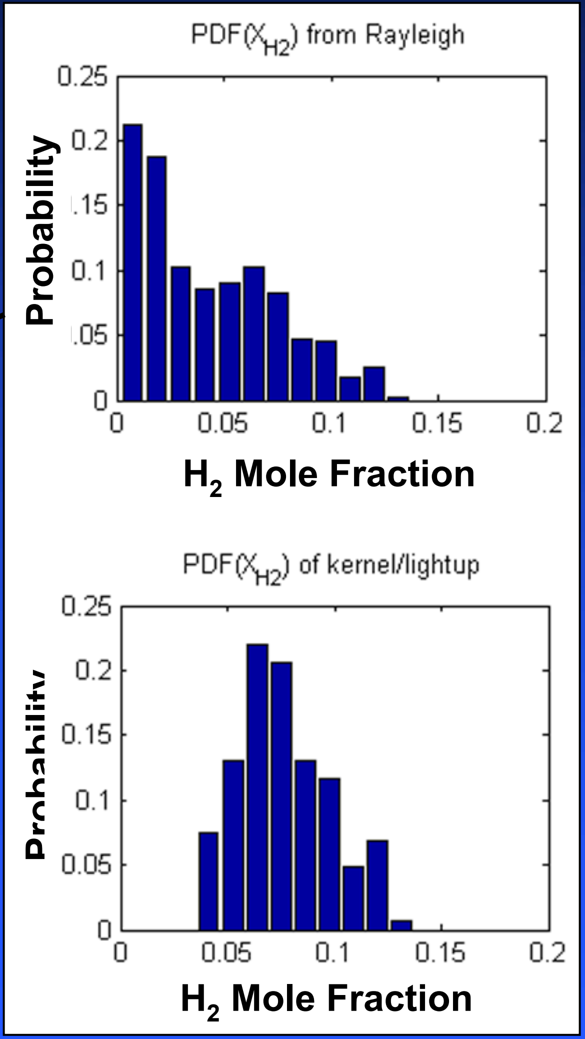


- Unconditional PDF's of H_2 concentration near centerline show wide range of H_2/air mixtures but no pure air.
- PDF's conditional on ignition show that ignition only occurs when the concentration is within the H_2 flammability limits.
- *Static flammability limit concepts valid at the location and time of ignition, but cannot be applied based on mean concentrations in turbulent flows.*

Sandia National Laboratories

Jet Ignition: Conditional probabilities





- Unconditional PDF's of H_2 concentration at outer radial locations show significant contribution from pure air.
- Since at most times pure air occupies ignition location, time-averaged H_2 concentration is well below LFL.
- PDF's conditional on ignition show that ignition only occurs when the local concentration is within the H_2 flammability limits
- Similar findings at other flow locations.

Lecture Outline

- Dispel some myths about hydrogen
  - We cannot build a safe hydrogen infrastructure on false perception
- Unintended release behavior
  - Momentum dominated flows
  - Buoyancy dominated flows
- Effect of barriers on:
  - Flame impingement, Radiation, Pressure effects
- Ignition
  - Spontaneous ignition
  - Flammability limits (flame stability)
    - Quiescent flows, Turbulent jets, Detonation, Explosion
- Quantitative risk assessment

Risk-Informed Codes and Standards

- Use of a risk-informed process is one way to establish the requirements necessary to ensure public safety
  - Endorsed by Fire Protection Research Foundation ("Guidance Document for Incorporating Risk Concepts into NFPA Codes & Standards")
  - Comprehensive QRA used to identify and quantify scenarios leading to hydrogen release and ignition
  - Accident prevention and mitigation requirements identified based on QRA
  - Results combined with other considerations to establish minimum code and standard requirements needed for an established risk level

Separation Distances

- Specified distances between a hazard source and a target (e.g., human, equipment, structures, other hazardous materials, ignition sources) which will mitigate the effect of a likely foreseeable incident involving the hazard source that results in an acceptable level of risk to the public and prevents a minor incident escalating into a larger one
  - Current distances do not reflect high pressures (70 MPa) being used in refueling stations
  - Documented basis for current distances not found

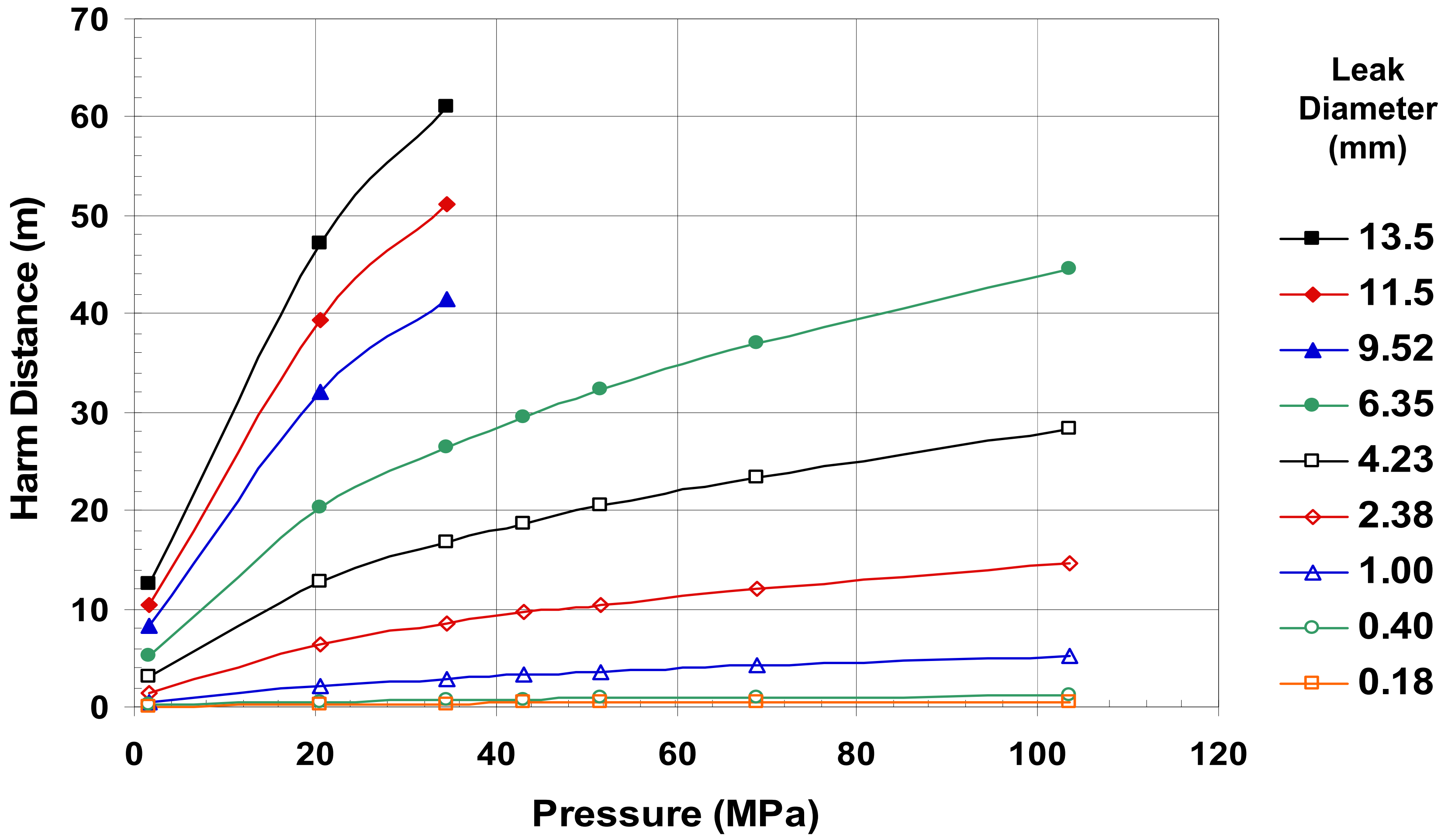
- Several options possible to help establish new separation distances
  - Subjective determination (expert judgment)
  - Deterministically determined based on selected break size (e.g., 20% flow area)
  - Based only on risk evaluation as suggested by the European Industrial Gas Association (IGC Doc 75/07/E)
  - Risk-informed process that combines risk information, deterministic analyses, and other considerations to make decisions

Deterministic (Consequence-Based) Approach

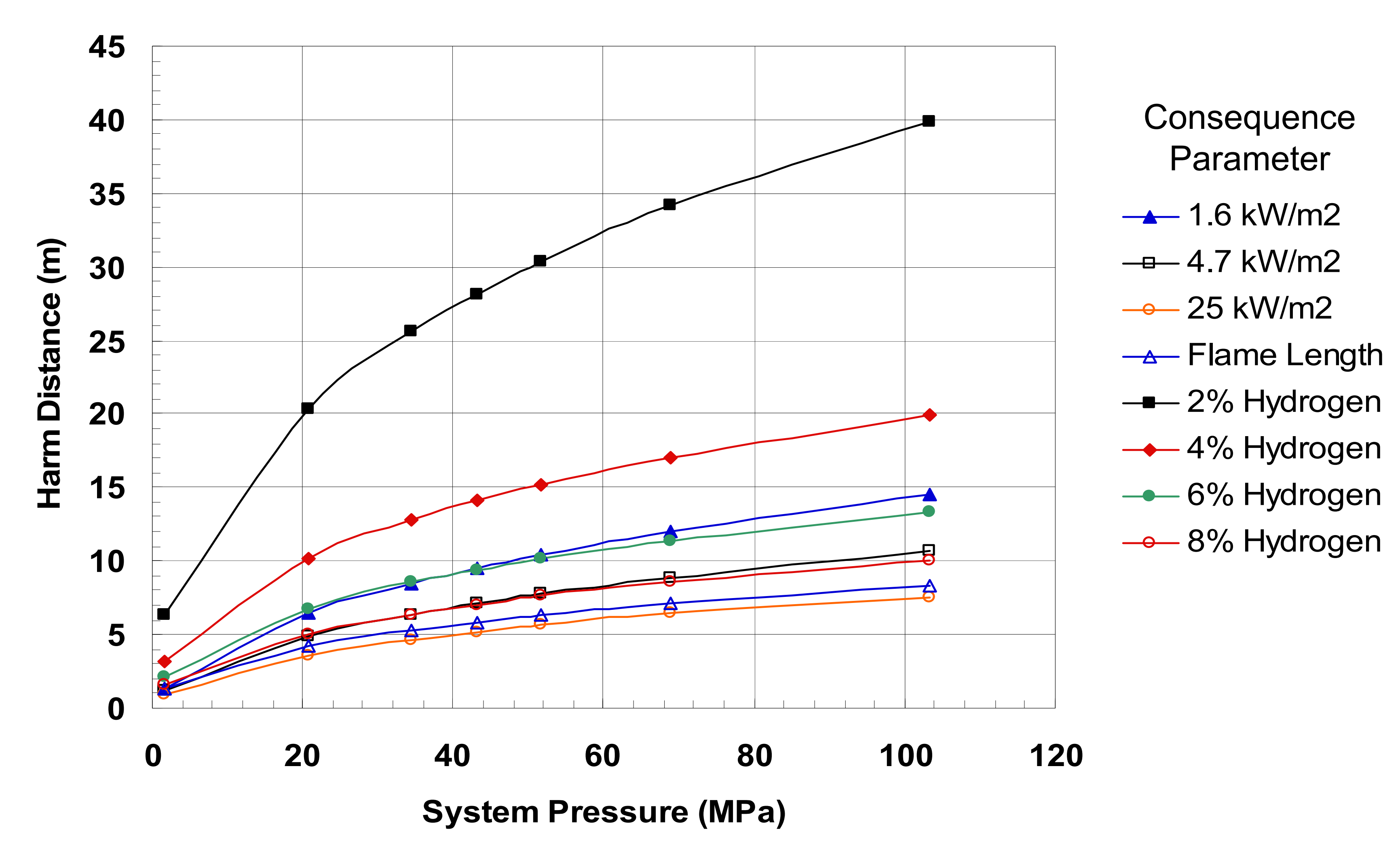
Used Sandia Hydrogen Leak Model

- Used to evaluate separation distances for hydrogen jets
- Model predicts (as function of system volume, pressure, and leak size):
  - Radiant heat flux from hydrogen jet flames
  - Visible flame length for ignited jets
  - Hydrogen concentrations in jets
- Assumes circular orifice for leak geometry and constant pressure - conservative
- Model validated against Sandia/SRI experiments

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



Harm Distances for Different Consequence Measures – 2.38 mm Leak



Example Consequence-Based Separation Distances

Consequence Bases	Separation Distance			
	>0.10 to 1.72 MPa (>15 to 250 psig)	>1.72 to 20.68 MPa (>250 to 3000 psig)	>20.68 to 51.71 MPa (>3000 to 7500 psig)	>51.71 to 103.43 MPa (>7500 to 15000 psig)
Un-ignited jet concentration – 4% mole fraction of hydrogen	31.2 m (20% Area) 22.1 m (10% Area) 15.7 m (5% Area) 12.1 m (3% Area) 7.0 m (1% Area)	36.1m (20% Area) 25.6 m (10%Area) 18.1 m (5% Area) 14.0 m (3% Area) 8.1 m (1% Area)	22.6 m (20% Area) 16.0 m (10% Area) 11.3 m (5% Area) 8.8m (3% Area) 5.0 m (1% Area)	26.8 m (20% Area) 19.0 m (10% Area) 13.4 m (5% Area) 10.4 m (3% Area) 6.0 m (1% Area)
Radiation heat flux level of 1577 W/m^2 (500 Btu/hr-ft^2)	23.4 m (20% Area) 15.9 m (10% Area) 10.7 m (5% Area) 7.9m (3% Area) 4.1 m (1% Area)	28.1 m (20% Area) 19.0 m (10% Area) 12.8m (5% Area) 9.5 m (3% Area) 4.8 m (1% Area)	16.6 m (20% Area) 11.2 m (10% Area) 7.8 m (5% Area) 5.5 m (3% Area) 2.6 m (1% Area)	20.5 m (20% Area) 13.8 m (10% Area) 9.6 m (5% Area) 6.8 m (3% Area) 3.3 m (1% Area)
Radiation heat flux level of 4.7 kW/m^2 (1500 Btu/hr-ft^2)	17.0 m (20% Area) 11.6 m (10% Area) 7.9 m (5% Area) 5.9 m (3% Area) 3.1 m (1% Area)	20.2m (20% Area) 13.8m (10% Area) 9.4m (5% Area) 7.0 m (3% Area) 3.7m (1% Area)	12.2 m (20% Area) 8.2 m (10% Area) 5.5 m (5% Area) 4.1 m (3% Area) 2.1 m (1% Area)	14.9 m (20% Area) 10.0 m (10% Area) 6.7 m (5% Area) 5.1 m (3% Area) 2.6 m (1% Area)
Greater of radiation heat flux level of 25237 W/m^2 (8000 Btu/hr-ft^2) or visible flame length Similar entry for 20kW/m^2 or visible flame length	13.0 m (20% Area) 9.2 m (10% Area) 6.5 m (5% Area) 5.0 m (3% Area) 2.9 m (1% Area)	15.0 m (20% Area) 10.6 m (10% Area) 7.5m (5% Area) 5.8 m (3% Area) 3.4 m (1% Area)	9.4 m (20% Area) 6.7 m (10% Area) 4.7 m (5% Area) 3.6m (3% Area) 2.1 m (1% Area)	11.1 m (20% Area) 7.9 m (10% Area) 5.6 m (5% Area) 4.3m (3% Area) 2.5 m (1% Area)

How Do You Select Leak Diameter?

Risk-Informed Approach Selected

- 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
- Other considerations
  - Other code requirements
  - Other issues deemed important to SDO members

Hydrogen Leakage Data

- Approach 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
- So what data do you use?
- Traditionally, representative values are selected from available sources from other industries
- Problems with this approach:
  - Data is not necessarily reflective of hydrogen components and environments
  - Parameter uncertainty distribution is not characterized

Alternative Approach

- Use Bayesian statistics to generate leakage frequencies
  - Used to combine multiple sources of generic data
    - Can give equal weight to all sources
    - Can exclude some sources (e.g., nuclear data) or specific data (e.g., outliers)
    - Can give variable weight to sources
  - Update results (prior distribution) with hydrogen-specific data (posterior distribution)
- Hierarchical Bayesian approach used in our work allows one to attach different “layers” of significance to all the data that are used in the modeling process

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

Component Leakage Data

- Generic leakage data is available from multiple sources covering different industries
  - Some data is provided as a function of leak size (i.e., small leaks, large leaks, and ruptures)
    - Actual data from offshore oil industry substantiates that leak frequency is a power function of leak size
  - Data is not generally differentiated based on operating pressure
- Some limited hydrogen-specific data was obtained for this analysis
  - More hydrogen data is needed to provide more robust leakage frequencies

Important Data Uncertainties

- Little hydrogen data is available
- Exposure data is estimated
- Categorization of data into leak ranges
- Inclusion of very small leaks that present no important consequence
- Generic data source applicability
- Bayesian prior distribution selection
- Use of generic facility configuration
- Only random leakage events included
- **Sensitivity studies were performed for most of these uncertainties – must account for them in decision process**
  - **E.g., safety margin can be added to leak diameter to account for uncertainties or code requirements can be specified to reduce/eliminate uncertainty**

Hydrogen Leak Size Definitions

- Very small - Leak area is <0.1% of total flow area
- Minor – Leak area is 0.1% of total flow area
- Medium – Leak area is 1.0% of total flow area
- Major – Leak area is 10% of total flow area
- Rupture – Leak area is 100% of total flow area

Example: Sources for generic Leakage Data

- Center for Chemical Process Safety of the American Institute of Chemical Engineers, “Guidelines for Process Equipment Reliability Data with Data Tables,” 1989.
- Cox, A.W., Lees, F.P., Ang, M.L., “Classifications of Hazardous Locations,” Institution of Chemical Engineers, 2003.
- CPR 18E ed. 1, “Guidelines for Quantitative Risk Assessment: The Purple Book,” 1999.
- Eide, S.A, Khericha, S.T., Calley, M.B., Johnson, D.A., Marteeny, M.L., “Component External Leakage and Rupture Frequency Estimates,” EGG-SSRE-9639, Nov 1991.
- EIGA, “Determination of Safety Distances,” IGC Doc 75/01/E/rev, 2001.
- NUREG/CR-6928, “Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants,” February 2007.
- NUREG-75/014, “Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants,” WASH-1400, Oct 1975.
- Rijnmond, Openbaar Lichaam; “Risk Analysis of Six Potentially Hazardous Industrial Objects in the Rijnmond Area, A Pilot Study,” COVO, 1982.
- Savannah River Site, “Generic Data Base Development,” WSRC-TR-93-263, June 1993

Hydrogen Leakage Summary

- Limited data on hydrogen component leakage is currently available
  - Leakage events are generally very small in size (i.e., <0.1% Flow Area)
- Statistical analysis of data indicates frequency of leaks >1% Area is <1E-4/yr for most components
  - Generally lower than generic frequencies used in past QRA efforts
- Data and sensitivity studies supports selection of small leak area as bases for separation distances

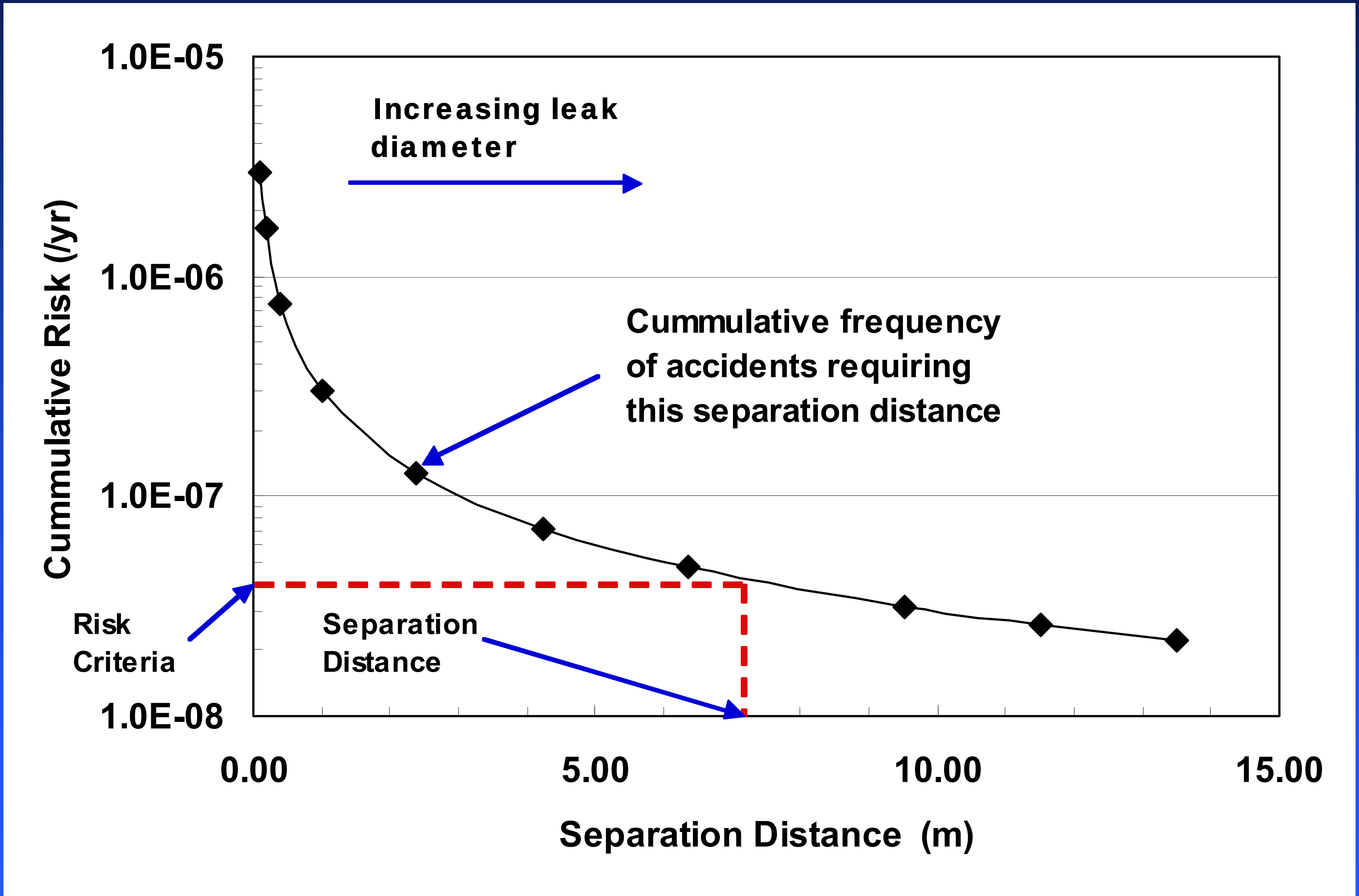
3% of system flow area selected in NFPA-55 as leak area for separation distance evaluation. Associated risk of larger leaks was evaluated.

Risk Evaluation

Risk = Frequency X
Consequence from all accidents

- Requires definition of important consequences
- Requires definition of acceptable risk levels
- Requires comprehensive evaluation of all possible accidents
- Requires data analysis for quantification of QRA models
- Accounts for parameter and modeling uncertainty present in analysis

Risk Approach for Establishing Adequacy of Safety Distances



Risk Acceptance Guideline

- Uniform risk acceptance guideline is required for development of risk-informed codes and standards
- Options for selecting risk guideline:
  - Based on statistics from existing stations (gasoline and CNG)
    - limited data available
    - data includes accidents other than accidental releases
    - NFPA data for gasoline stations in U.S. suggests frequency of deaths and injuries are ~$2x10^{-5}$/yr and ~$3x10^{-4}$/yr, respectively
  - Based on estimated risk for existing stations
    - limited analyses are available
    - differences in facilities affects comparison of data
  - Comparing with general risk in society – hydrogen should not increase the general risk level in society
    - Risk of death ~ $2\text{-}4x10^{-4}$/yr; risk of injury ~ 0.09/yr in U.S.
    - Fraction of total risk from just fires ($1.3x10^{-5}$/yr in the U.S.) and explosions ($6x10^{-7}$/yr in the U.S.)

Selected Risk Guideline

- Individual fatality risk to most exposed person at facility boundary selected for use in risk evaluation
- 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
    - Comparison of mean risk to guideline is usually done
    - Sensitivity studies and uncertainty analysis used to determine importance of assumptions

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

Basis – 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

Consequence Measures

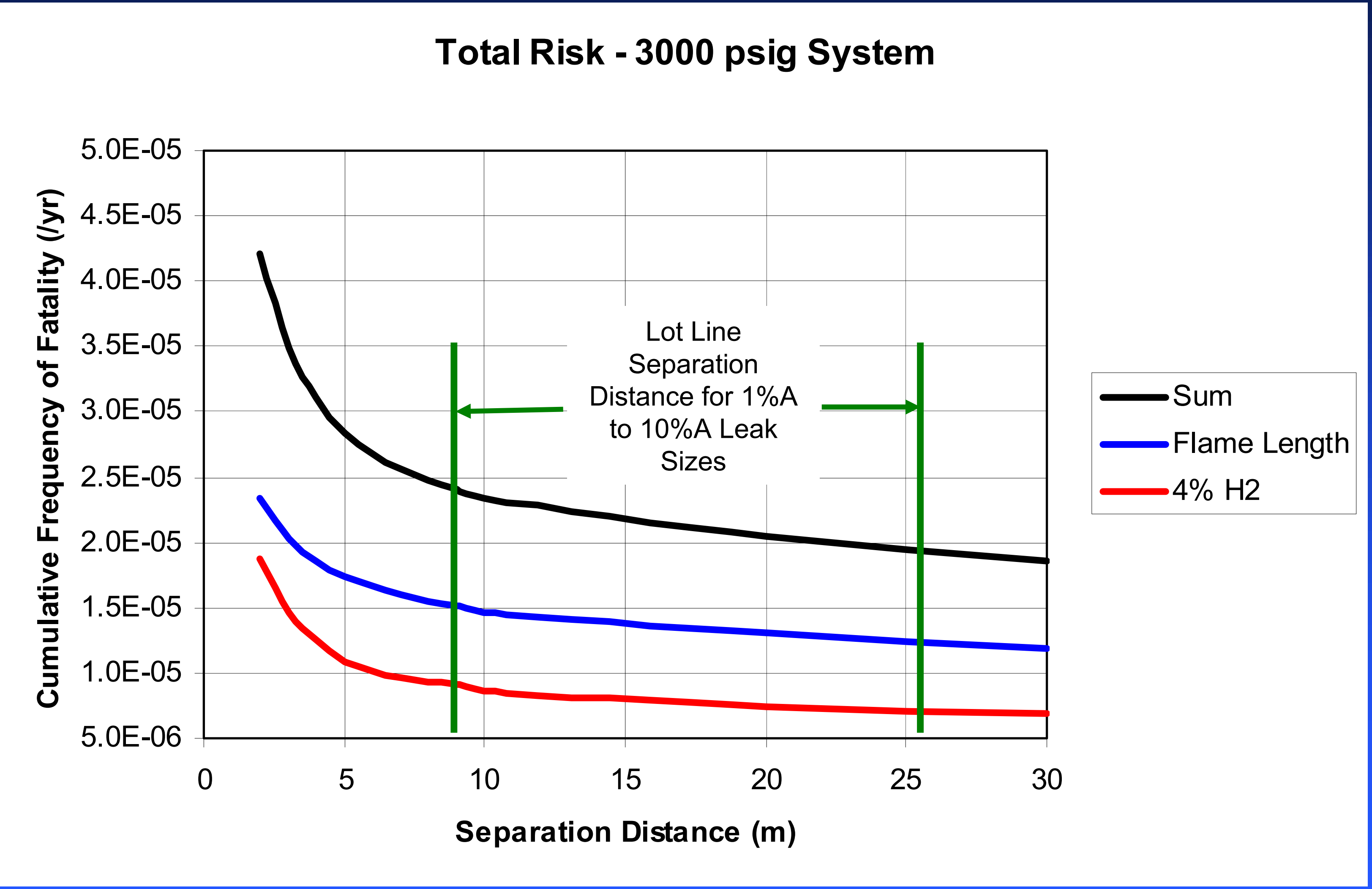
- Consequence measures are required for full range of hydrogen gas accidents modeled in QRA
  - Jet fires, flash fires, pool fires, vapor cloud explosions (VCEs), and detonations
- Consequence measures
  - Hydrogen concentration (4% mole fraction)
  - Thermal effects (radiation heat flux or direct flame contact)
  - Overpressure effects (direct and indirect)
- Consequences in analysis limited to jet and flash fires from hydrogen jets
  - Gas storage assumed unconfined

Risk Analysis Facts – Conservative Assumptions

- Used leak frequencies from Bayesian analysis incorporating hydrogen data (probably best available estimates)
- Uses Sandia hydrogen leak model (uncertainty~18%)
- Assumes circular orifice leaks
- Surface influences on hydrogen jets not included (preliminary Canadian work indicates could be important)
- Used DNV ignition probabilities ('reasonable values')
- Used Tsao and Perry Probit function (most appropriate)
- Currently only includes random leakage events (common to all facilities)
- No VCEs included (sensitivity study indicates not important)
- No volume effects have been incorporated
- No mitigation systems (e.g., detection) have been included
- Scenario propagation not included (not analyzed but believed not important)
- Maximum exposed individual assumed on lot line 24/7

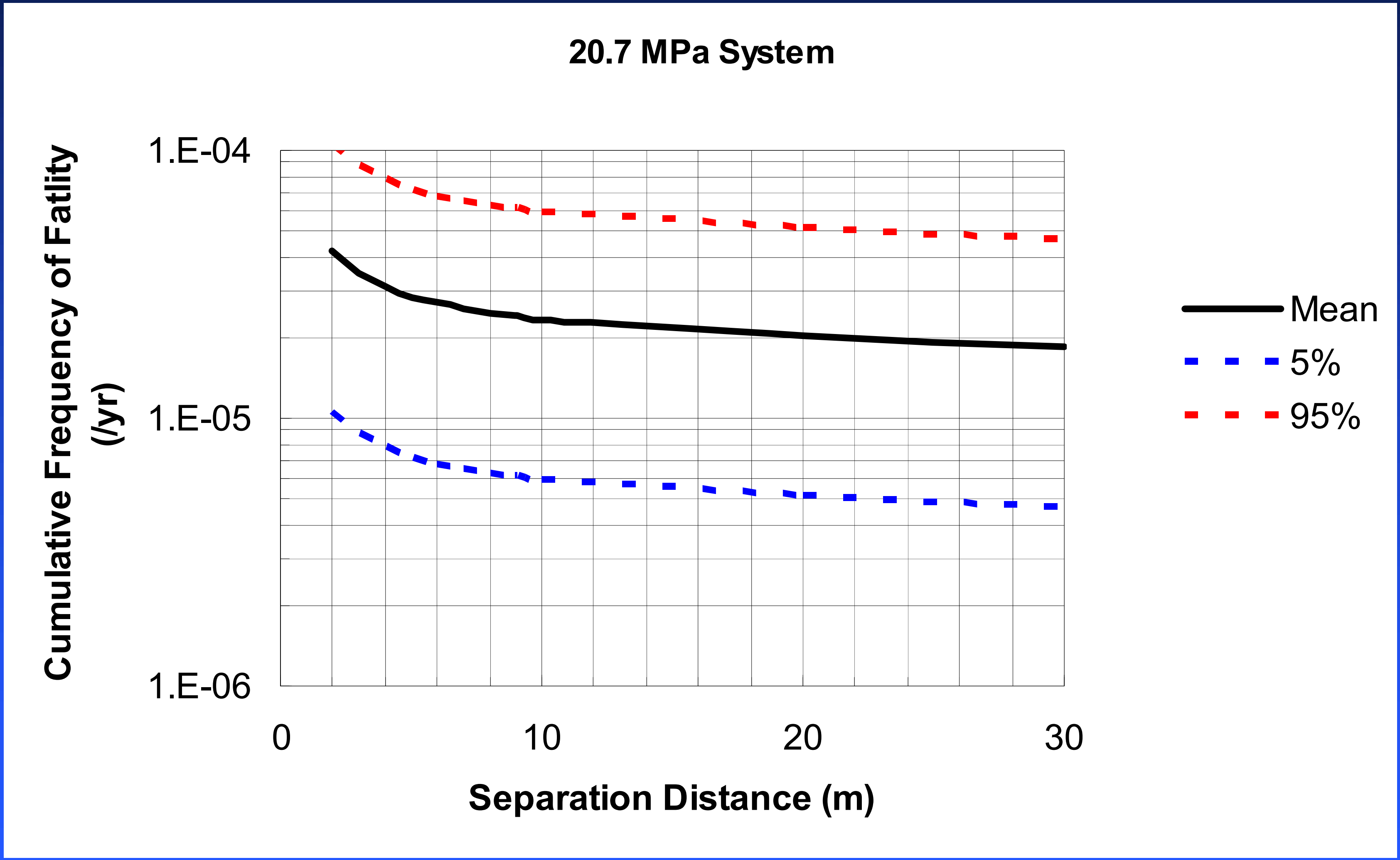
Sandia National Laboratories

Risk Results – 20.7 MPa

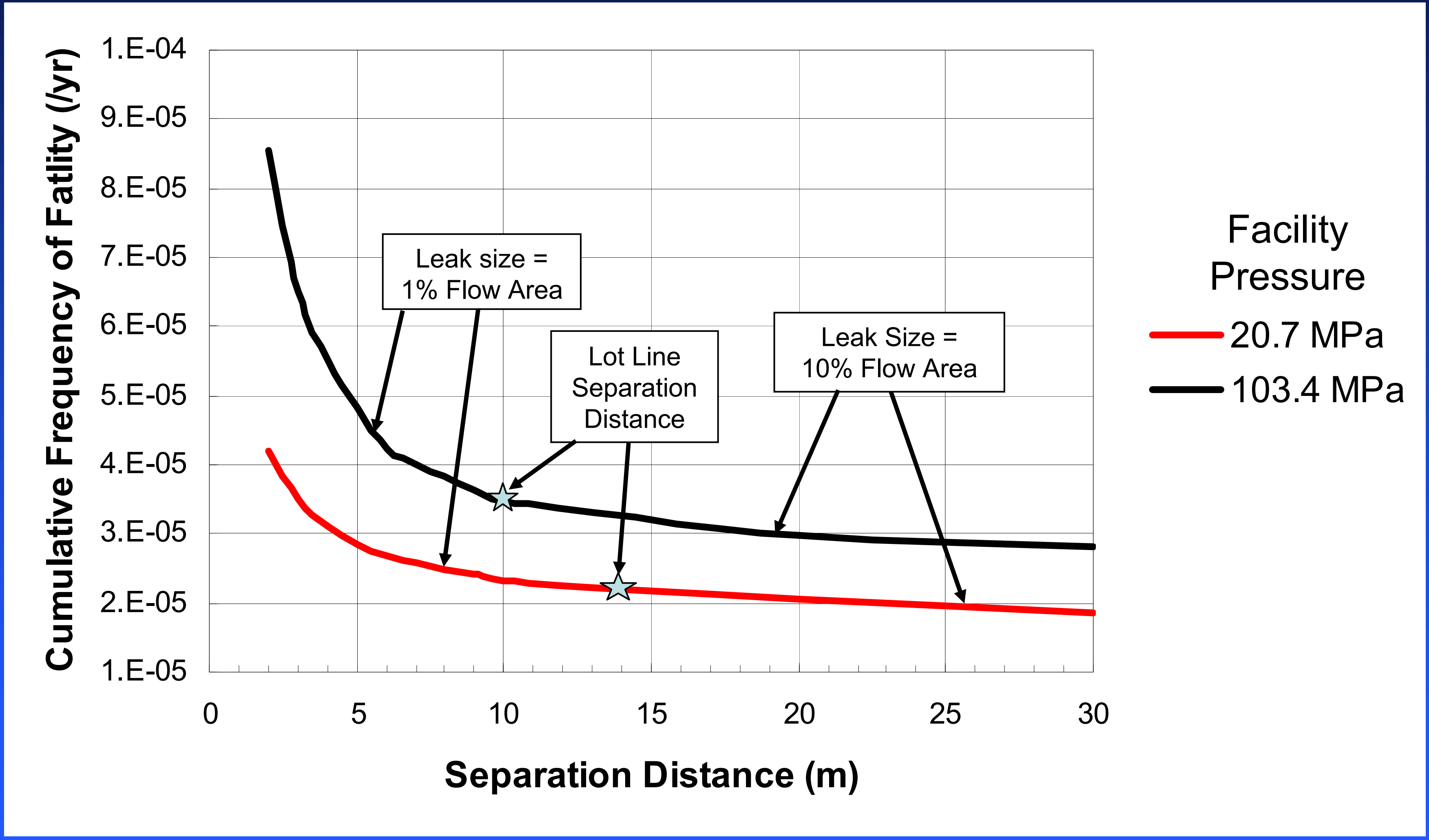


Sandia National Laboratories

Parameter Uncertainty Impact on Risk



Risk Results for Example Facilities



Summary- Risk-Informed Separation Distance Analysis

- Separation distances are significantly affected by facility operating parameters (H_2 pressure and volume)
- Consequence-based separation distances can be prohibitively long for large leak diameters
- If small leak diameters can be justified, short separation distances even for high pressures can be justified
- Data analysis can be used to help justify short separation distances
- Risk analysis can also be used as a basis to help justify selection of leak diameter and separation distances
- Risk-informed separation distances are significantly affected by component leakage frequency data and selected consequence parameters and risk criteria
- There are many uncertainties in both data and risk evaluations which have been addressed through sensitivity analysis

Hydrogen Leakage Summary

- Limited data on hydrogen component leakage is currently available
  - Leakage events are generally very small in size (i.e., <0.1% Flow Area)
- Statistical analysis of data indicates frequency of leaks >1% Area is <1E-4/yr for most components
  - Generally lower than generic frequencies used in past QRA efforts
- Data supports selection of small leak area as bases for consequence-based distances

3% of flow are selected as leak area for separation distance evaluation

Associated risk of larger leaks was evaluated

Risk Measures

- Human injury or fatality
  - Individual risk – frequency that an average unprotected person, located at most exposed location, is killed or injured due to an accident
  - Societal risk – frequency that multiple people within an area are killed or injured due to an accident (typically represented on an FN curve)
- Others
  - Economic loss – typically expressed in terms of loss value (lost income and replacement cost)
  - Environmental damage – can be expressed in terms of time required to recover damage to ecosystem

Individual fatality risk deemed most appropriate for establishing generic code requirements

Risk Exposed Persons

- Public – people located outside the facility boundary (used in this assessment)
  - People living and working near the facility
  - People visiting or traveling near the facility
- Customers – people using the facility
  - Limited exposure period
- Facility operators – personnel involved in operation, inspection, and maintenance of the facility
  - Generally assumed these people accept higher risk levels than for customers and outside public

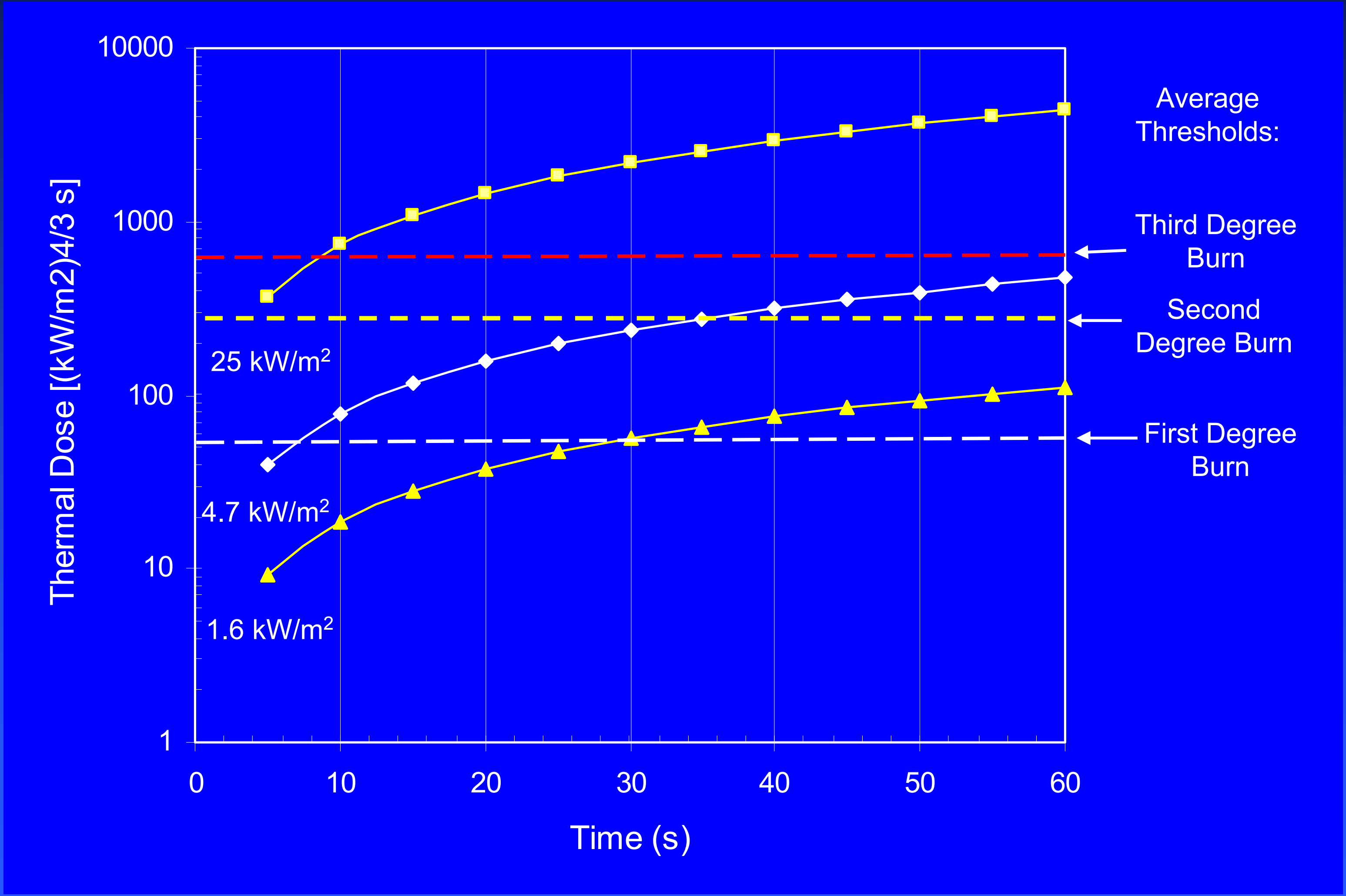
Risk to person at lot line selected for use in risk analysis

Radiation Heat Flux

- Potential for harm or facility damage is a function of heat flux level and exposure time
- Wide variation in criteria (assumes exposed skin):
  - 1.6 kW/m^2 – no harm for long exposures
  - 4 to 5 kW/m^2 - pain for 20 second exposure
  - 9.5 kW/m^2 -Second degree burns within 20 seconds
  - 12.5 to 15 kW/m^2 - 1% lethality in 1 minute, piloted ignition of wood
  - 25 kW/m^2 - 100% lethality in 1 minute, injury within 10 seconds, ignite wood (long exposure)
  - 35 to 37.5 kW/m^2 - 1% lethality in 10 seconds, damage steel structures (long exposure)

Potential of Injury from Jet Fires

Reduced time of exposure to heat flux reduces the magnitude of injury.



Sandia National Laboratories

Mitigation Features

- Plans were to perform risk-informed evaluation of following mitigation features:
  - Leak detection and isolation systems-reduces risk from leaks downstream of isolation valve
  - Fire suppression systems ??
  - Administrative controls (e.g., maintenance frequency and training)
  - Construction features (e.g., barriers)- type of joint and valve can be important
  - System location (e.g., underground, roof mounted)- impacts view factor

Key Accomplishments

Results:

Technical Basis Established for NFPA 55 Separation Distances (Sandia)

For purposes of illustration a system with the following basic parameters will be chosen:
Pressure Range: 250-3000 psig
ID: 0.25 in. (like a cell site fuel cell system)
Volume: <3500 scf
Using these assumed parameters the following results are obtained:

Exposure	NFPA 2005 Separation Distance	NFPA 2009 Separation Distance
Lot Lines	5ft	10 ft
Air intakes (HVAC, compressors, other)	50 ft	10 ft
Fire barrier walls or structures used to shield the bulk system from exposures	0 ft	5 ft
Unclassified electrical equipment	Not addressed	15 ft
Utilities (overhead) power,	5 ft	5 ft
Flammable Gas storage		

This new approach to specifying separation distances was accepted by the NFPA 55 Technical Committee and is scheduled to be issued in the 2009 edition of NFPA 55.

Summary

- Separation distances are significantly affected by facility operating parameters (H_2 pressure and volume)
- Consequence-based separation distances can be prohibitively long for large leak diameters
- If small leak diameters can be justified, short separation distances even for high pressures can be justified
- Data analysis was used to select leak diameter used to determine separation distances (>95% leaks included)
- Risk analysis was used to show that risk for larger leaks is acceptable
- Selection of 3% flow area as leak size can be justified based both on leak frequency and risk bases

Presentation End