A Study of Barrier Walls for Mitigation of Unintended Releases of Hydrogen

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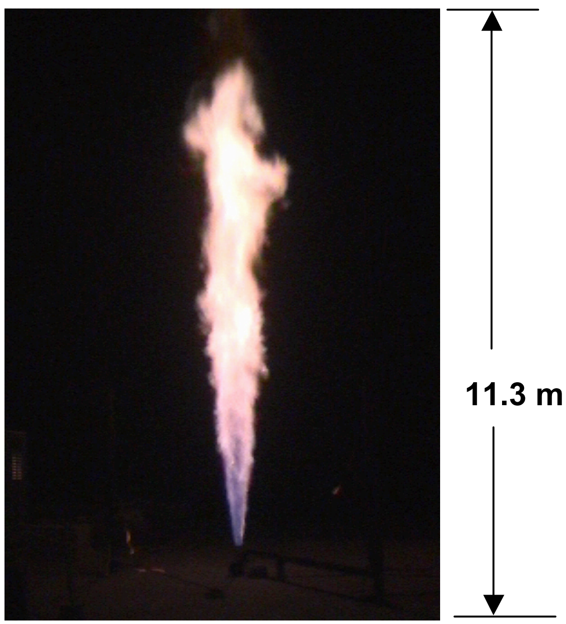
3rd International Conference on Hydrogen Safety
Ajaccio, Corsica
September 16-18, 2009

Session 16
Paper Reference Number: 146

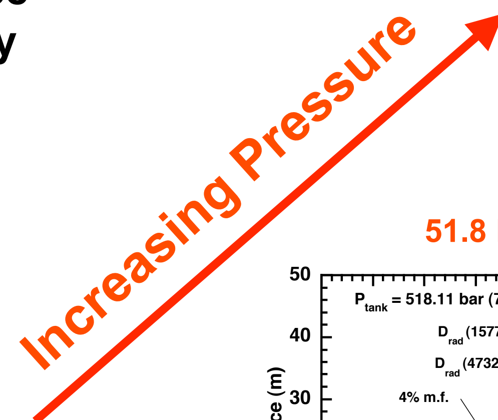
Experiments and calculations have shown that consequence distances increase as refueling pressure increases.

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

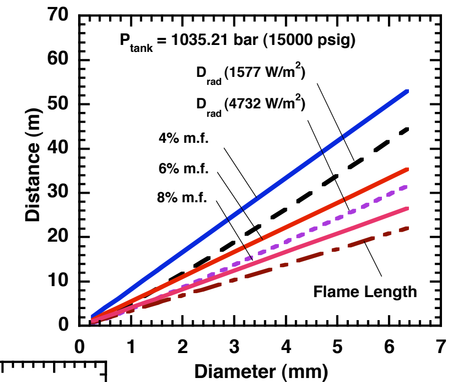


Nighttime Photo of H_2 Jet Flame Test
Source Press. = 41.3 MPa (6000 psig)
Dia. = 5.08 mm
L_{vis} = 10.6 m

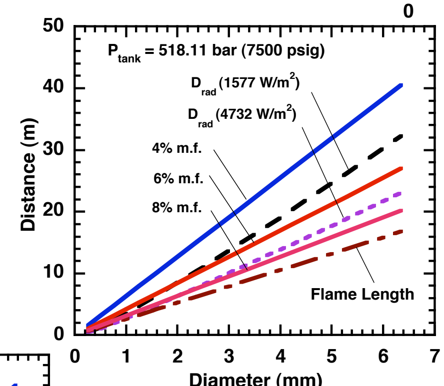
Consequence Distance Calculations



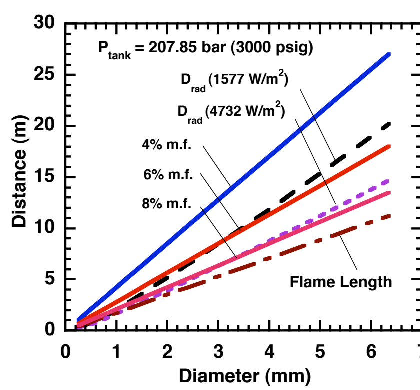
103.5 MPa



51.8 MPa



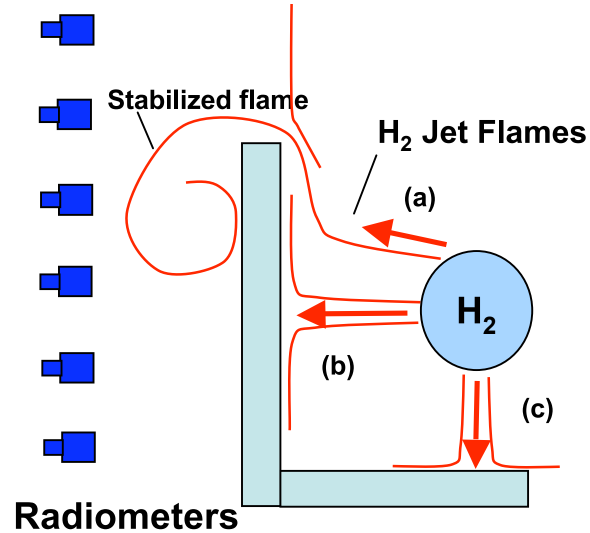
20.7 MPa



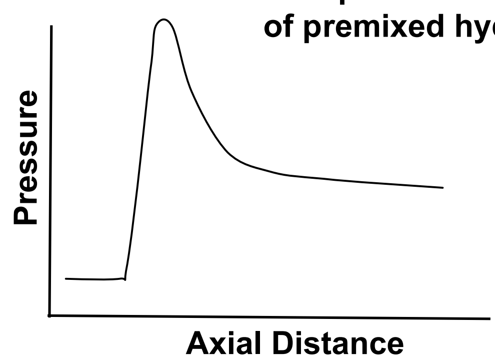
Sandia supports the development of Codes & Standards for commercial hydrogen use.

We have performed a study of barriers to determine if they are an effective mitigation strategy to reduce safety distances.

- **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 with HYSAFE for modeling**
- ***Combine data and analysis with quantitative risk assessment for barrier configuration guidance.***



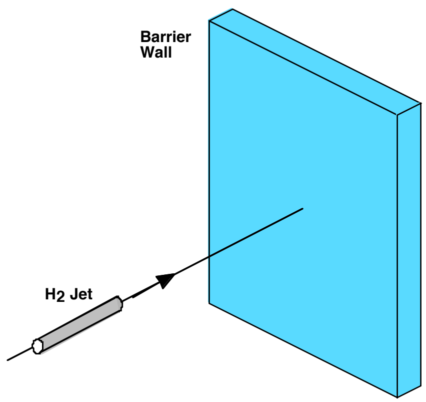
Sandia/SRI H_2 Jet Flame Barrier Test



We have looked at several barrier configurations for evaluation with experiments and modeling.

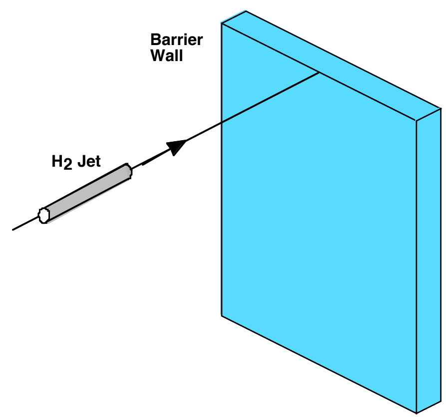
1-Wall Vertical Barrier

(Jet at Wall Center)



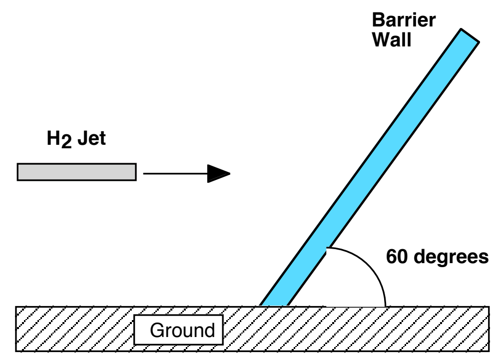
1-Wall Vertical Barrier

(Jet at Wall Top)



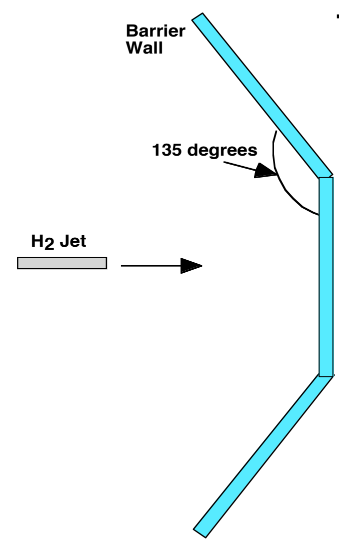
1-Wall Tilted Barrier[1]

Side View



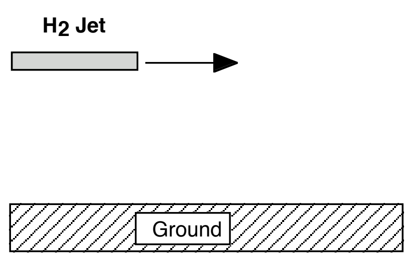
3-Wall Barrier[2]

Top View



Free Jet

Side View

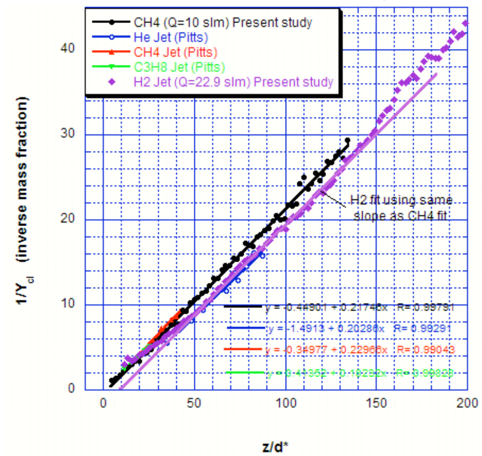


[1] Based of NFPA 68 guidelines for barrier walls.
[2] Recommended by IFC 2006.

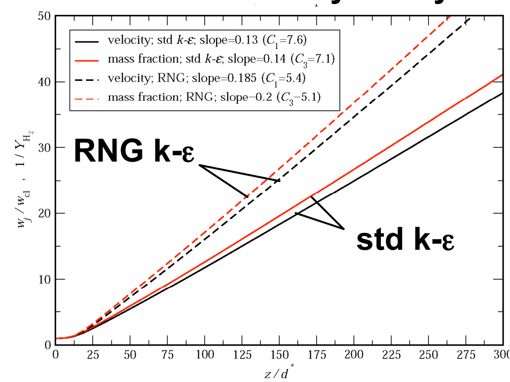
We initiated the barrier modeling effort by validating our in house CFD code to predict concentration decay in unignited H_2 free jets and temperatures in H_2 flames.

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

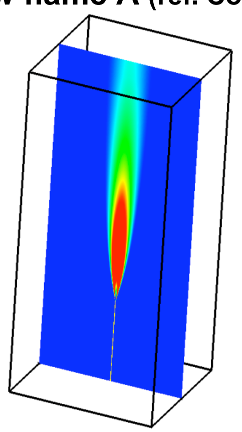
Concentration Decay Data

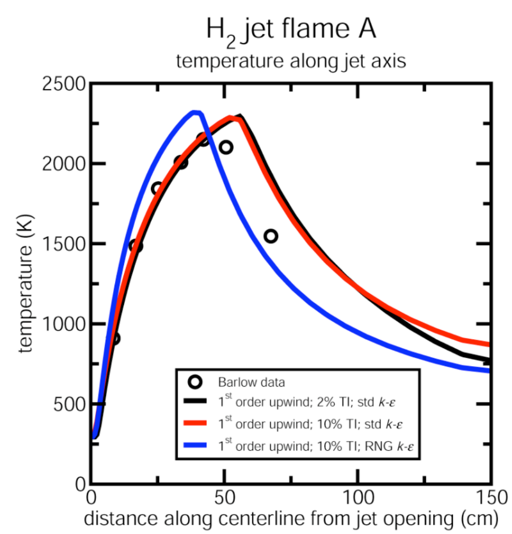


Concentration and Velocity Decay Simulations



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



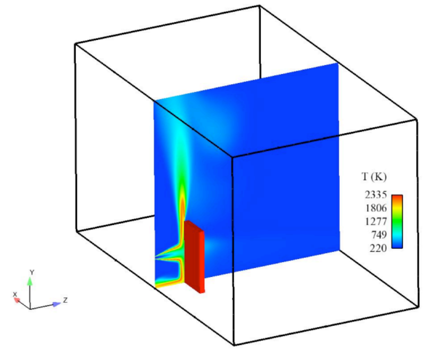


- Houf, Evans, and Schefer, “Analysis of Jet Flames and Unignited Jets from Unintended Releases of Hydrogen,” Inter. Jour. of Hydrogen Energy, Feb, 2009.

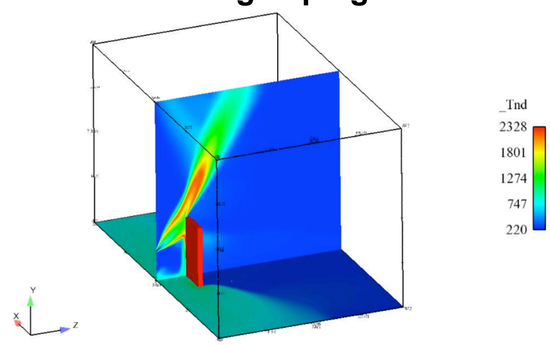
We investigated many different barrier jet flame impingement scenarios and barrier geometries with modeling and full-scale experiments.

Different Leak Scenarios

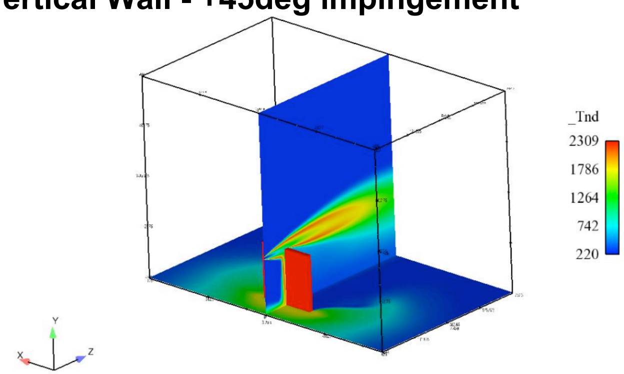
- Source pressure
- Leak to barrier spacing
- Leak trajectory
- Leak location
- Barrier geometry



• Vertical Wall - 90 deg impingement



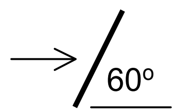
• Vertical Wall - +45deg impingement

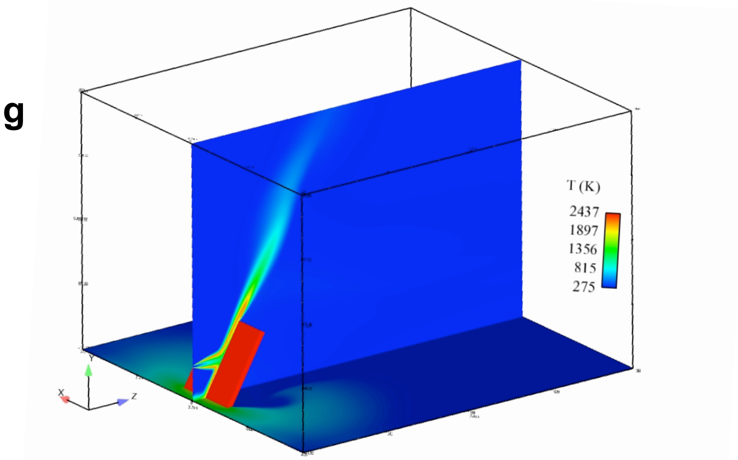


• Vertical Wall - Jet centerline aligned with top of wall

Different Barrier Geometries

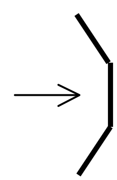
Side View

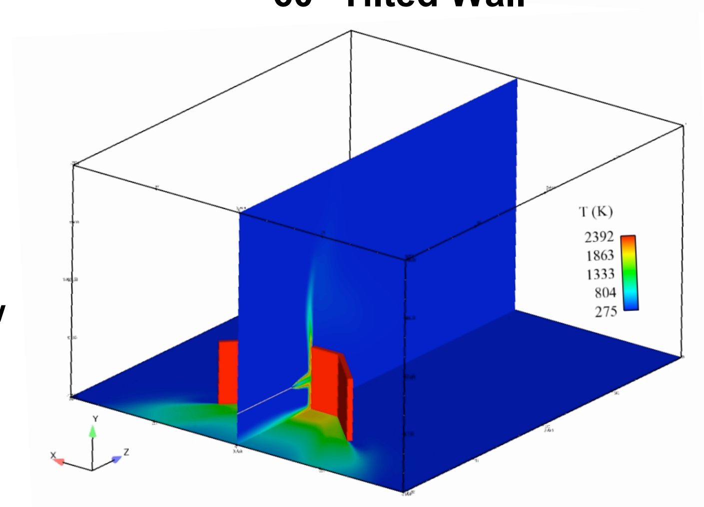




• 60° Tilted Wall

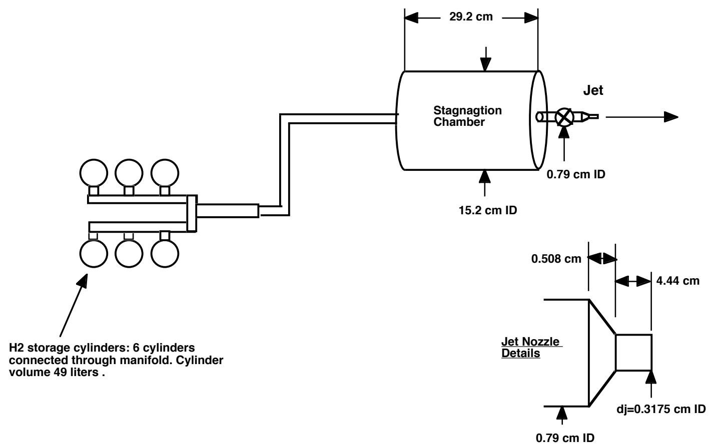
Top View

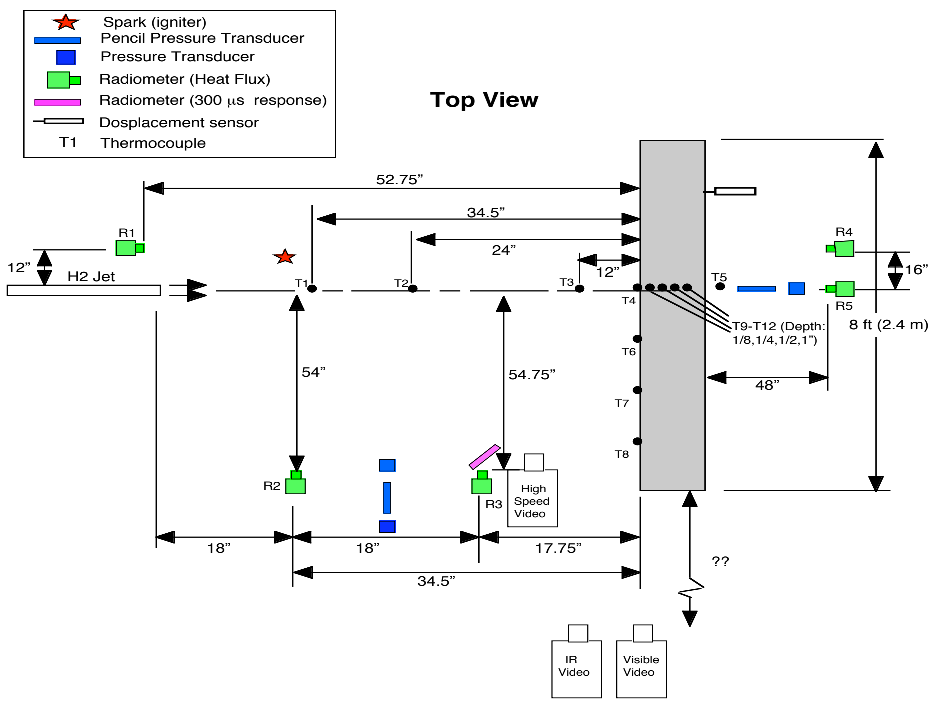




• 3 Wall Configuration (135° between walls)

Schematic of flow delivery system barrier wall test series and detector layout for single wall test.





Source Pressure = 13.79 MPa (2000 psig)
Jet Diameter = 3.175 mm

Hydrogen jet flame barrier wall impingement tests have been completed and used to assess the effectiveness of barriers.

Jet Centered on 1- Wall

Jet Centered on Top of 1-Wall

1-Wall Tilted at 60^0

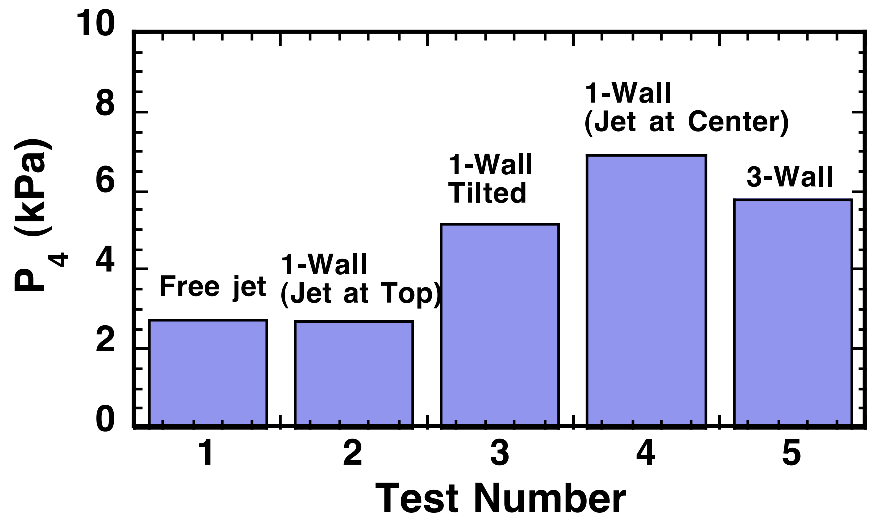
3-Wall (135°)

Vertical wall - 2.4 m x 2.4 m cinderblock
Tilted walls - backerboard (reinforced cement/concrete board)

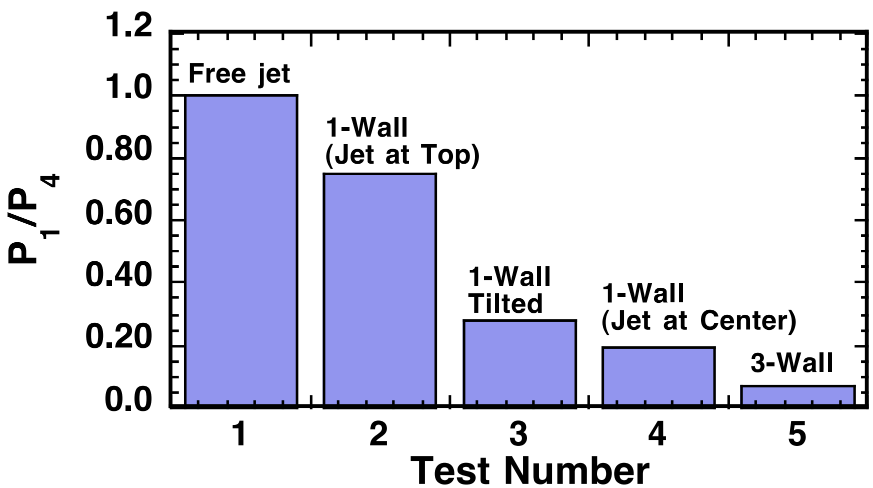
Barrier Wall Tests: Effect on Overpressure

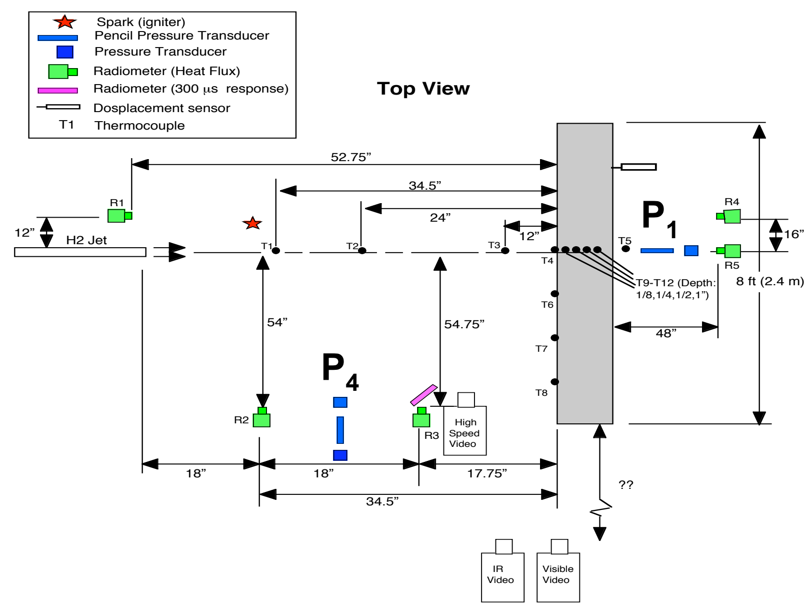
- Wall-centered jet results in a factor of 2.5 increase in overpressure prior to wall.
- Maximum overpressure reduction achieved by three-sided wall (pressure behind wall reduced by a factor of 14).

Pressure Before Wall

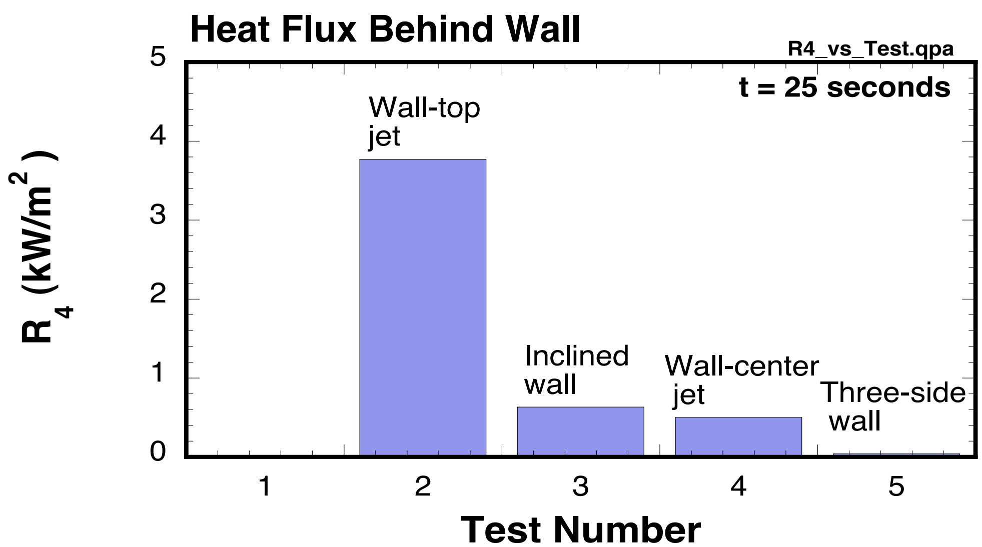


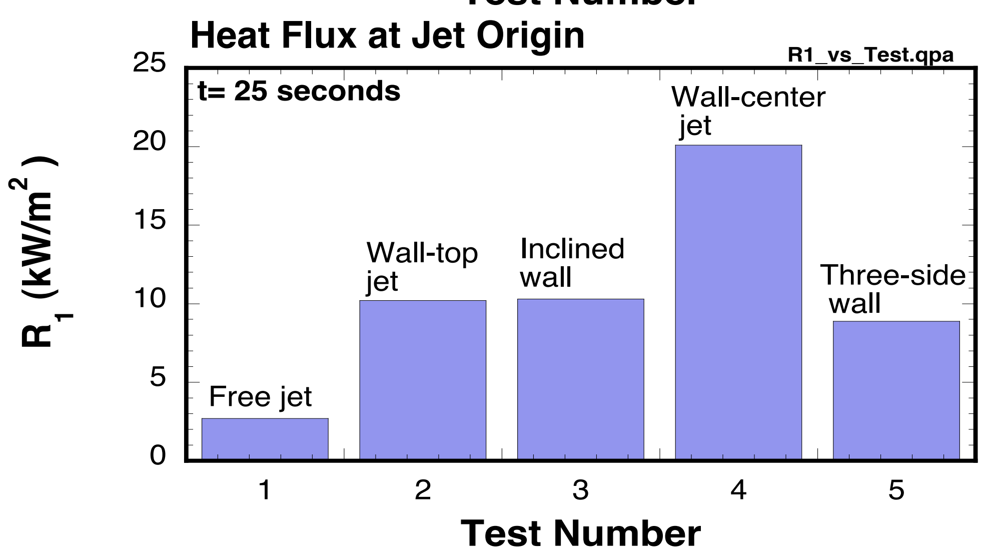
Pressure Attenuation



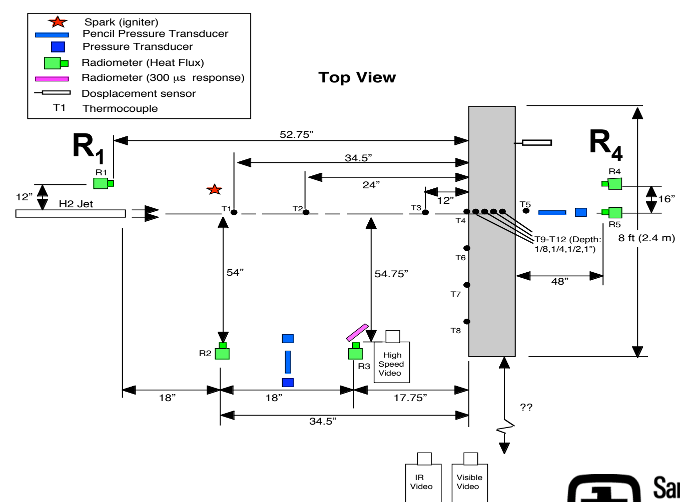


Barrier Wall Tests: Effect on Radiative Heat flux





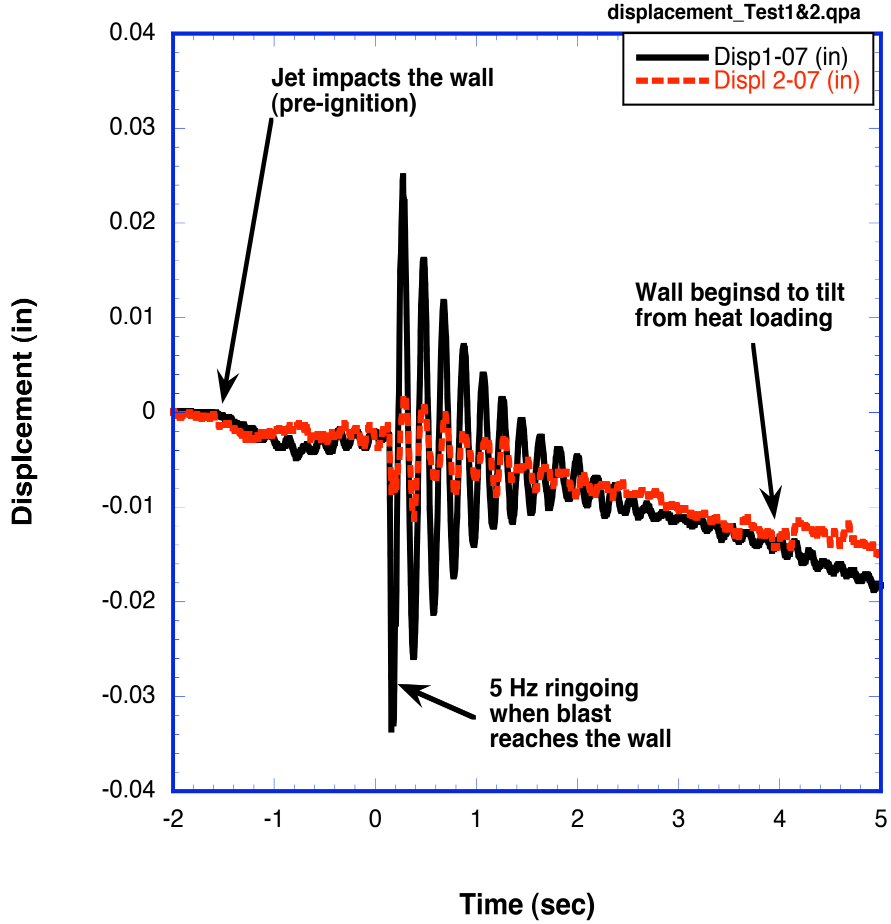
- Maximum radiative heat flux behind wall occurs with jet at top of wall jet configuration
- Heat flux levels with all walls are well below harmful levels.
- Walls are an effective mitigation strategy for radiative heat flux hazards as long as flame is confined by wall.
- Walls significantly increase heat flux levels at leak origin.
- Heat flux levels at leak origin for jet centered on wall exceed pain threshold limit (19.87 kW/m^2 for 2 sec exposure time).



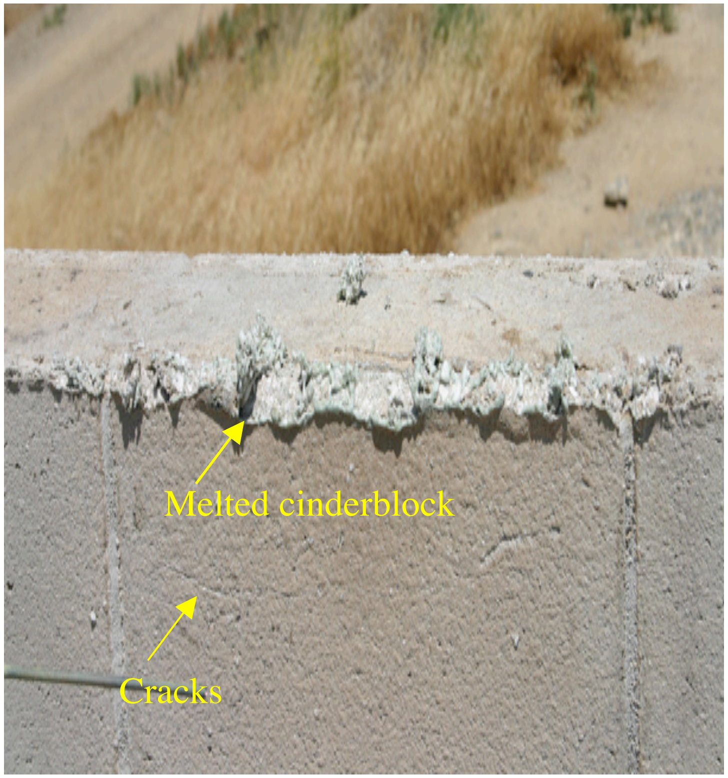
BARRIER WALL TESTS

- Jet centered at top of wall

- Wall Displacement



- Melted Cinderblock Wall

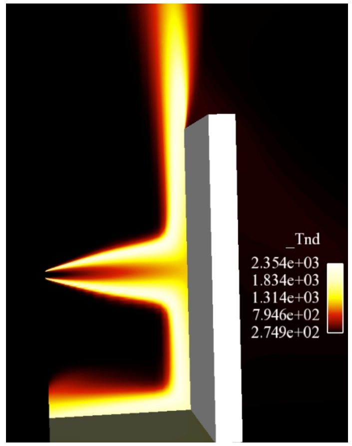


Full-scale jet flame impingement experiments provided valuable insight on barrier behavior as well as modeling validation data.

Jet Centerline Aligned with Center of Barrier

Experiment

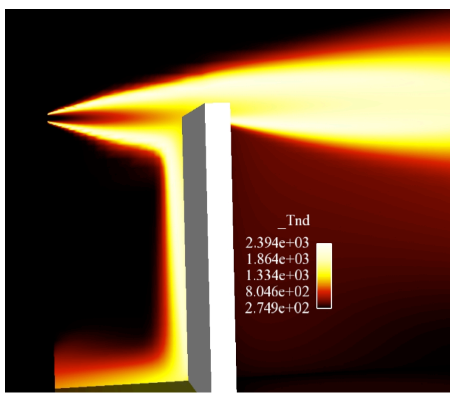
Simulation



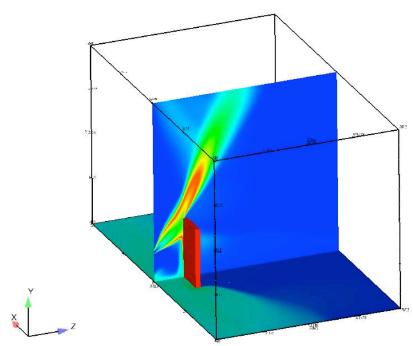
Jet Centerline Aligned with Top of Barrier

Experiment

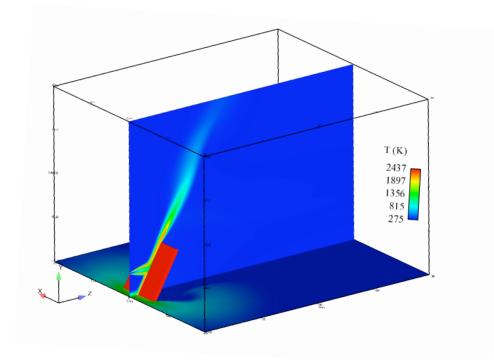
Simulation



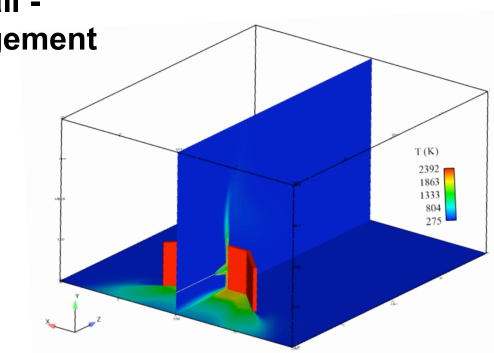
- **Full-scale experiments provide model validation data for simulations of jet flames**
- **Barriers reduce downstream flame impingement hazard**
- **No flame stabilization behind barrier (top of wall configuration)**
- **Validated model is used to predict flame deflection for barrier and leak configurations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



Vertical Wall - +45° impingement



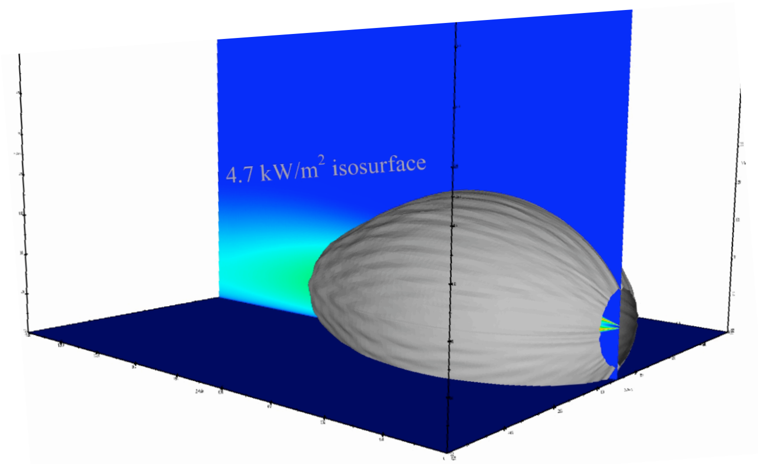
60° Tilted Wall



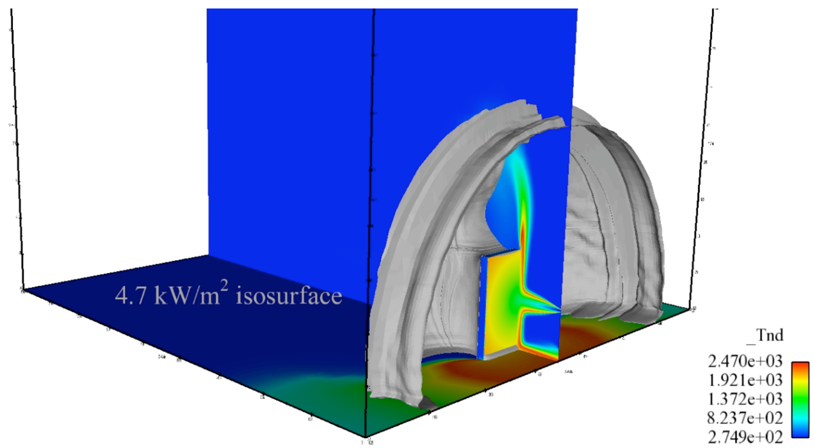
3 Wall Configuration (135° between walls)

Barriers can reduce the exposure from jet flame radiation heat flux as well as reduce jet flame impingement hazard.

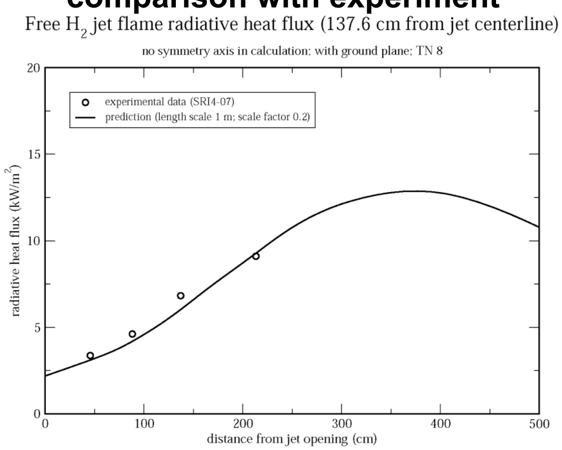
Free H_2 jet flame 4.7 Kw/m² surface



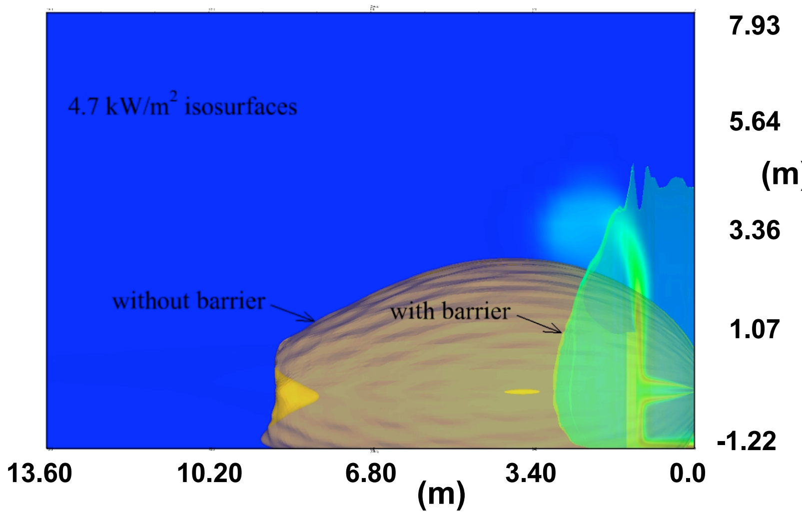
H_2 Jet Flame Impinging on Barrier 4.7 Kw/m² surface



Free jet flame radiation heat flux comparison with experiment



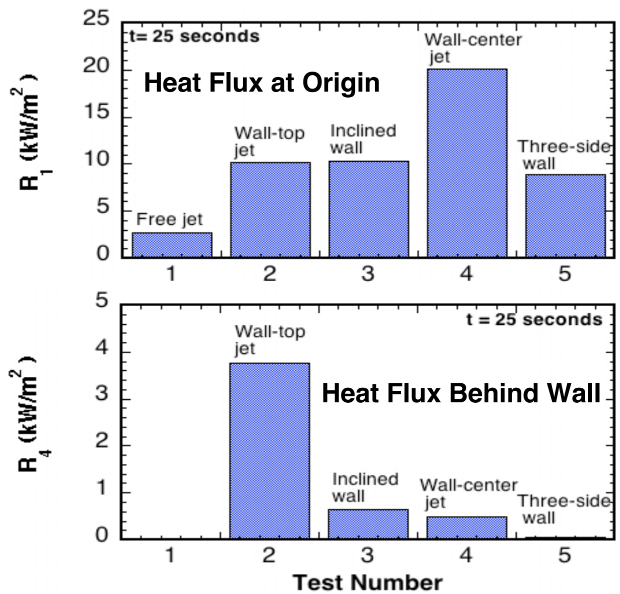
Comparison free jet and barrier



Horizontal distances to hazardous levels of radiative heat flux from hydrogen jet flames can be reduced with barriers.

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

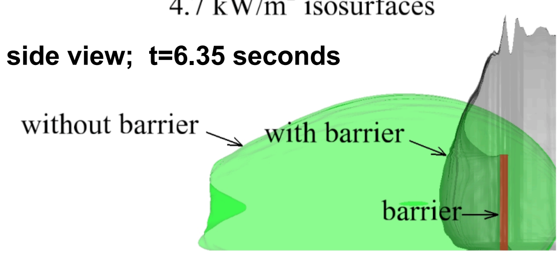
experiment



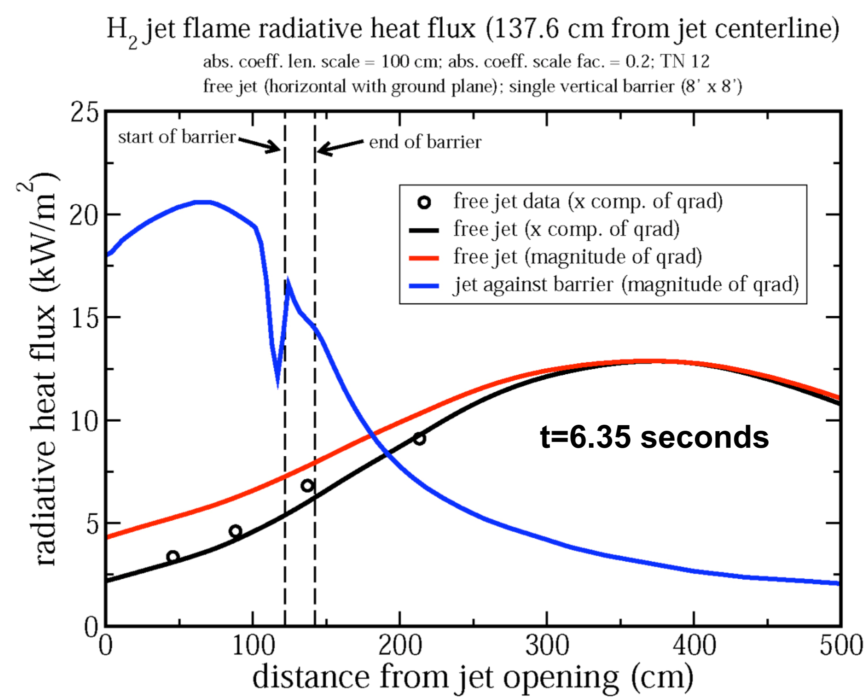
simulation

Horizontal and Vertical Extent of Radiation Heat Flux with and without a Barrier

4.7 kW/m^2 isosurfaces



comparison of experiment and simulation

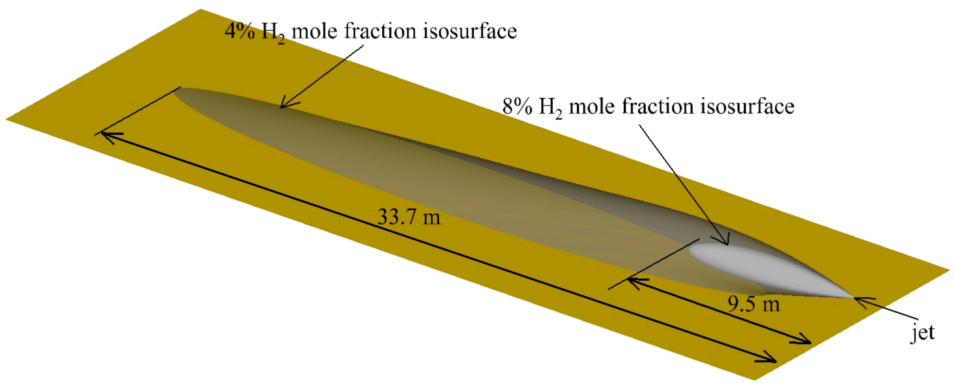


We have performed simulations of unignited H_2 releases around barrier to assess how barriers effect concentration decay distances.

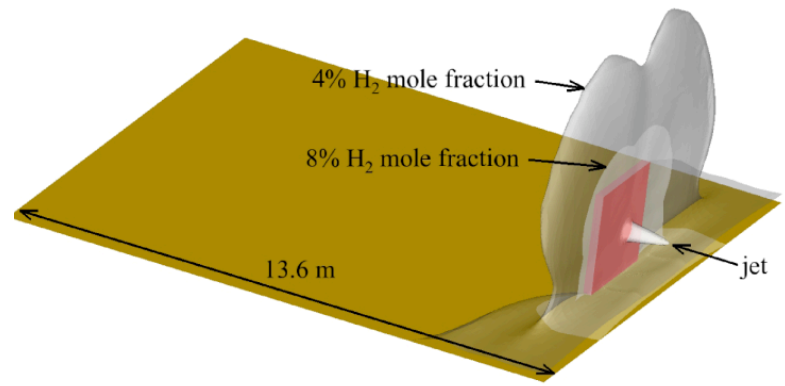
- Conditions of Sandia/SRI jet flame tests
- Barriers shorten concentration decay distances in direction of jet release

Simulations of 4% and 8% H_2 mole fraction surfaces

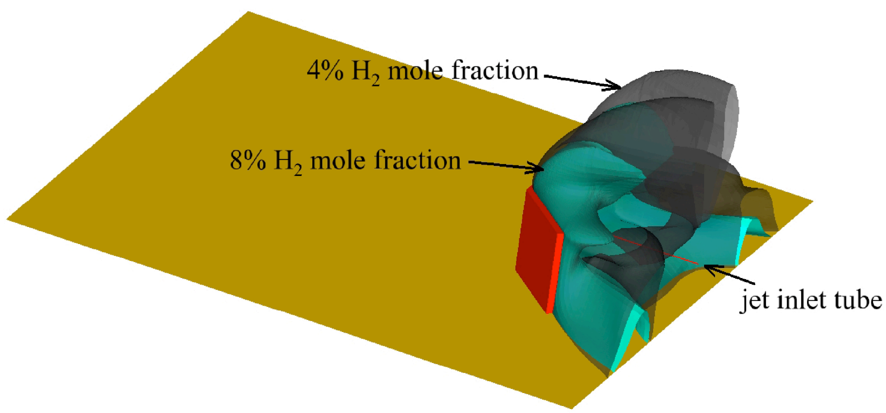
Free Jet Flame



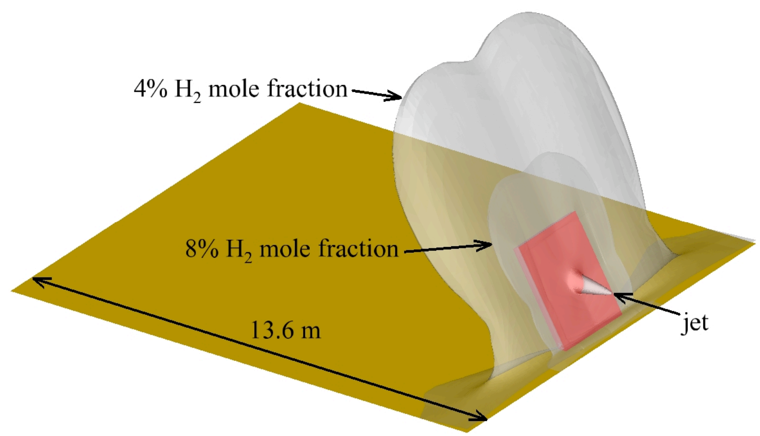
1-Wall Vertical Barrier



3-Wall Vertical Barrier



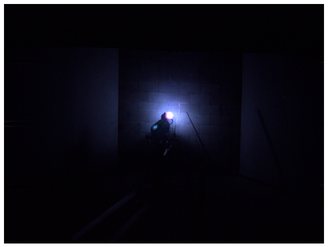
1-Wall Tilted Barrier



We have investigated the overpressure from the ignition of impinging hydrogen jet releases on barriers.

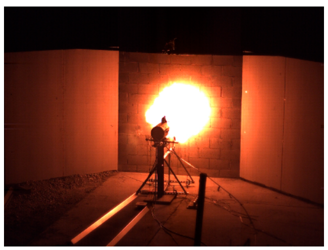
High-speed movie frames of H_2 ignition near barrier wall

Frame 1 (t = 137 msec)
Spark ignition

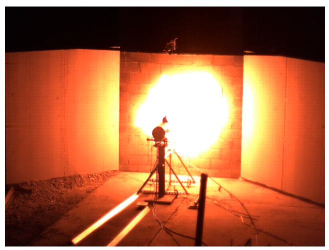


Frame 5 (t = 145 msec)

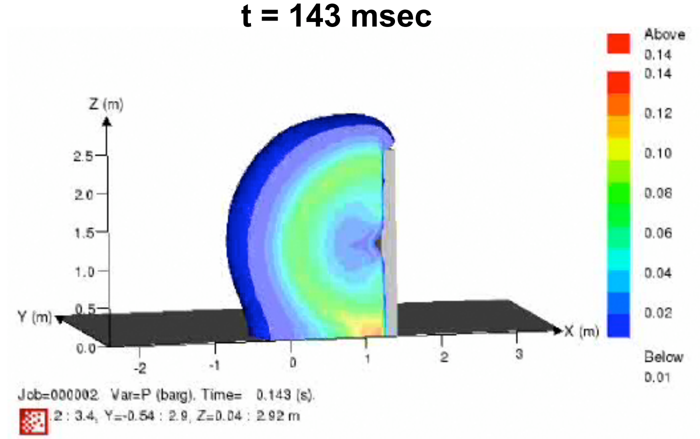
Frame 10 (t = 155 msec)



Frame 15 (t = 165 msec)

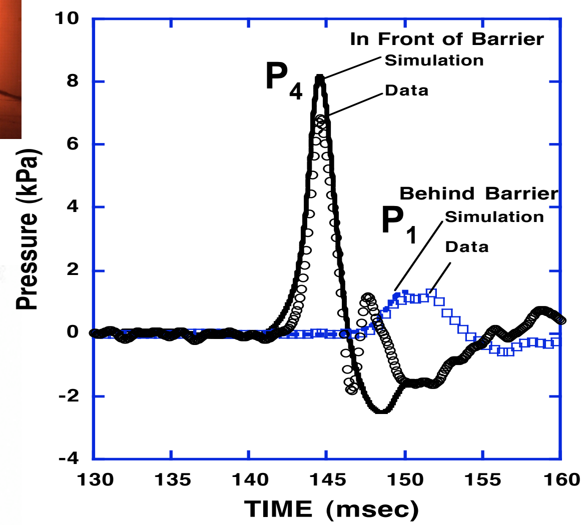


Single Wall Test
Simulation - Overpressure (barg)
t = 143 msec



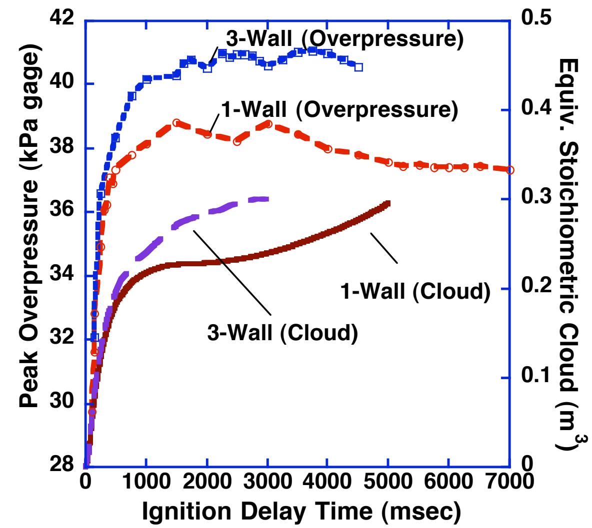
- We have investigated overpressure around barriers from H_2 ignition
  - Measurements of overpressure on front and back of barrier
  - Different barrier configurations
  - Time of release before ignition
  - Point of ignition
- Combined experimental and modeling approach
- Simulations are used to guide large-scale experiments

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



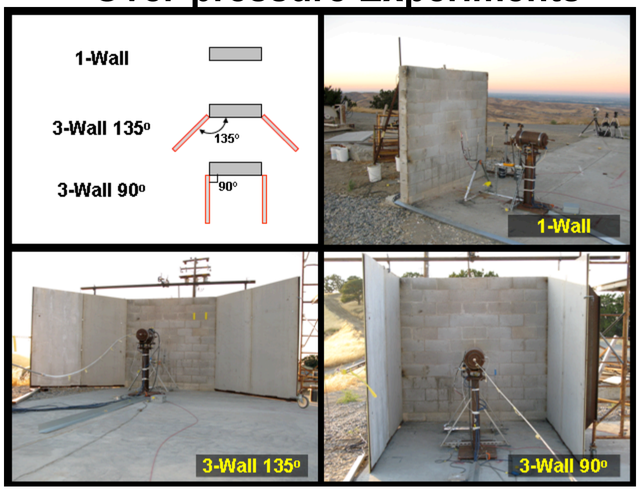
- Tests performed at SRI Corral Hollow test site

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



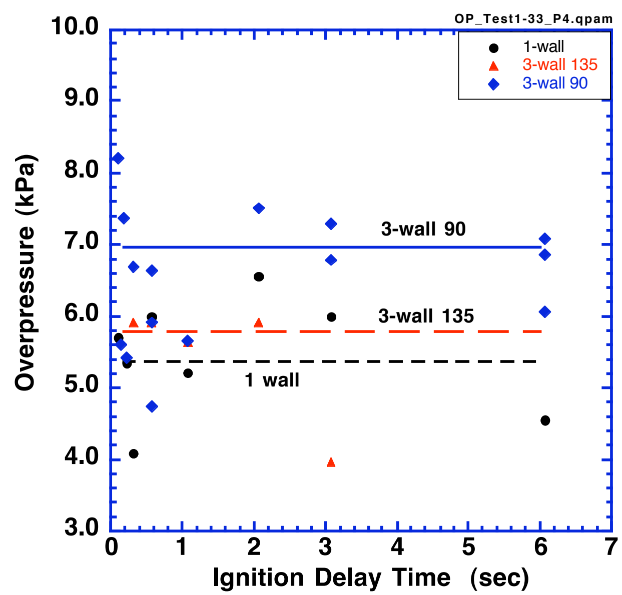
We have performed addition barrier tests to look at the effect of ignition delay time and confinement.

Barrier Wall Configurations for Over-pressure Experiments

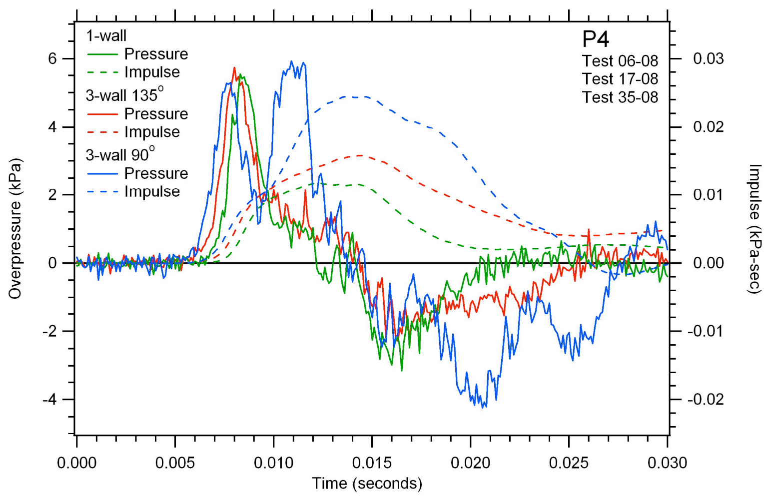


- Peak over-pressures (P_4) are between 5 - 7kPa near leak source for all wall configurations
- Over-pressure is approximately constant with respect to ignition delay time (> 100 msec)
- Over-pressure not sensitive to ignition location

Effect of Ignition Delay Time on Overpressure (P_4) for Different Barrier Configurations (Experimental Data)



Comparison of Overpressure and Impulse Time-Traces for Different Barrier Configurations



Model simulations allow evaluations to be made at conditions where experimental measurements were not taken.

Model Simulations for Comparison of Radiation Heat Flux Levels for Various Barrier Configurations with Free Jet Flame

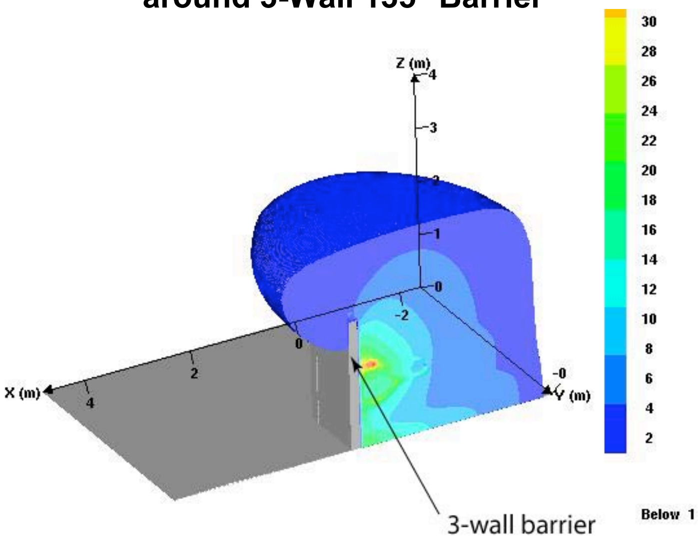
(Dia = 3.175mm, Source Pressure = 13.8 MPa)

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/m^2 - Lot line**
  - **4.7 kW/m^2 - Employee exposure for 3 minutes**
  - **20 kW/m^2 - Combustible Equipment**
  - **25 kW/m^2 - Non-combustible Equipment**
- **Source Pressures**
  - **1.8 MPa (250 psig)**
  - **20.7 MPa (3000 psig)**
  - **51.8 MPa (7500 psig)**
  - **103.5 MPa (15,000 psig)**
- **Barriers reduce horizontal distances (all rad. Heat fluxes)**
- **Tables also generated for Codes and Standards Source Pressures and diameters**
- **3-wall (135°) most effective**

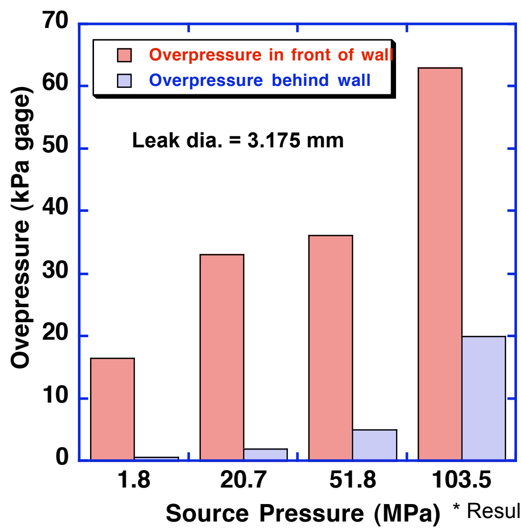
Validated barrier wall simulations are used for code development basis.

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

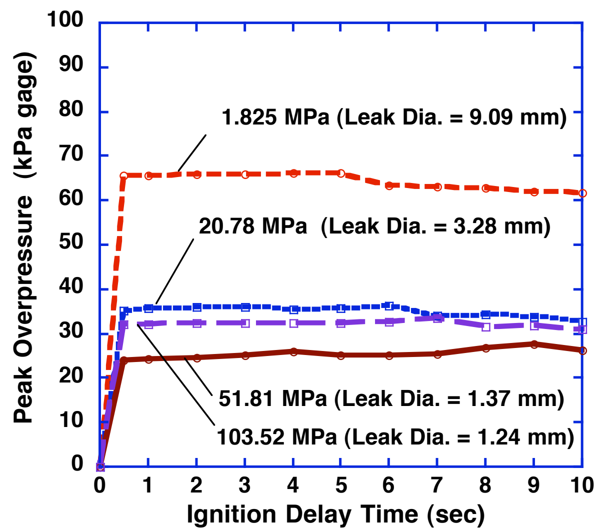


- **Barriers reduce over-pressure behind wall**
  - **factor of 5x for 1-wall**
  - **factor of 20x for 3-wall configurations**
- **New NFPA 55/2 separation distance table incorporates credit of 50% reduction in distances for use of 2 hr fire barrier wall**
- **HYPER IPG incorporates experimental and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



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

We provided valuable experimental and simulation results to the (EU) HYPER Project, IEA Task 19 and ISO Standard.

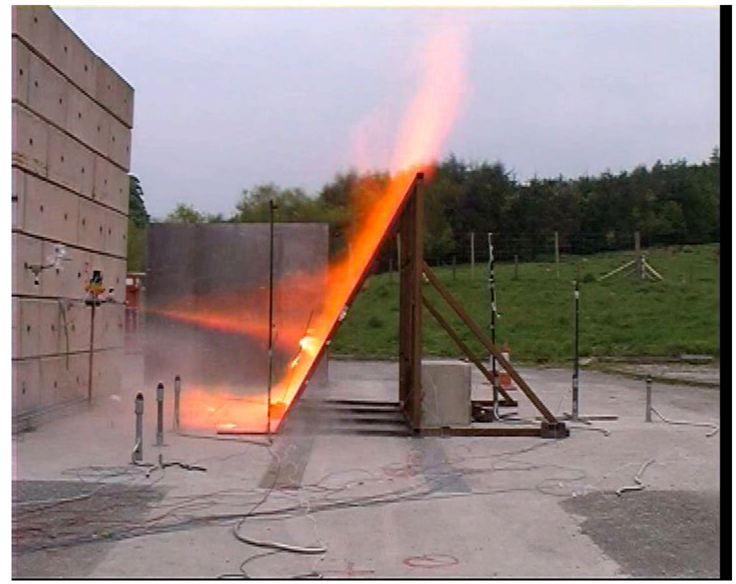
• **HYPER Project - EU Project to create permitting guidance for stationary fuel cells**

<u>Scenario A</u>: High Pressure Releases

- Sandia providing free jet flame data and simulations
- Simulation of data from Sandia/SRI 6000 psi vertical H2 jet flame by University of Ulster

<u>Scenario E</u>: Effects of barriers and walls on releases

- Sandia leading Scenario E
- Chapter 6 of WP4 HYPER Report on effects of barriers
- Sandia provided barrier simulations and experiments for barrier wall interactions
- Sandia/SRI large-scale free and impinging jet flame experiments modeled as part of HYSAFE (coordinated through FZK)
- Collaborated with HSE/HSL
  - HSE/HSL performed additional barrier tests
  - Joint HYPER WP5 Report on Barrier Exper. - Sandia / HSL



Barrier Test Performed by HSL (UK) as part of HYPER Project

• **IEA Task 19, NFPA 2, ISO Standard**

- Engineering Models for Separation Distances, Quantitative Risk Assessment Guidelines with incorporation of hydrogen specific leak frequency data (NFPA 2)
- Collaboration with HSL on autoignition work at Princeton
- Sharing information with Canadians on simplified underexpanded jet source models

Summary and Conclusions

- For Conditions Studied
  (1) Barriers reduce horizontal jet flame impingement hazard
  (2) Barriers reduce radiation hazard distances for horizontal jet flames
  (3) Barriers reduce horizontal unignited jet flammability hazard distances
  (4) Barriers attenuate ignition overpressure
- 3-Wall 135^{o} most effective at mitigation of overpressure, radiation, and unignited release
- Ignition 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.

Extra Slides

Summary and Conclusions

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Barrier

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