CNG, H_2, CNG-H_2 Blends – Critical Fuel Properties and Behavior

Jay Keller,
Sandia National Laboratories

Keynote Lecture presented at:
Workshop on
Compressed Natural Gas and Hydrogen Fuels:
Lessons Learned for the Safe Deployment of Vehicles

December 10-11, 2009

Hydrogen Behavior – Myth Busting

Jay Keller,
Sandia National Laboratories

Topical Lecture
Progress in Hydrogen Safety: International Short Course Series

June 15-19, 2009

Hydrogen Myths

- Hydrogen Molecular Diffusivity is 3.8 times that of CH_4
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- Hydrogen is 14.4 times lighter than air
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- We just do not understand hydrogen combustion behavior
  - Hydrogen release is different than other fuels
  - Radiation is different than other fuels

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Momentum-Dominated Jets are within the Ignition Region

Unignited Jet Separation Distance Length Scales

Pressure = ~20 MPa (~3000 psig)

Hole Diameter	Flowrate	Xmax - Distance to 4% mole fraction	Start of Intermediate Region (Buoyancy)
1.5875 mm (1/16 inch)	2.430×10^{-2} Kg/sec (615.9 ft^3/min)*	7.40 m (24.28 ft)	14.6 m (48.0 ft)
0.794 mm (1/32 inch)	6.075×10^{-3} Kg/sec (154.1 ft^3/min)*	3.70 m (12.14 ft)	10.3 m (33.9 ft)

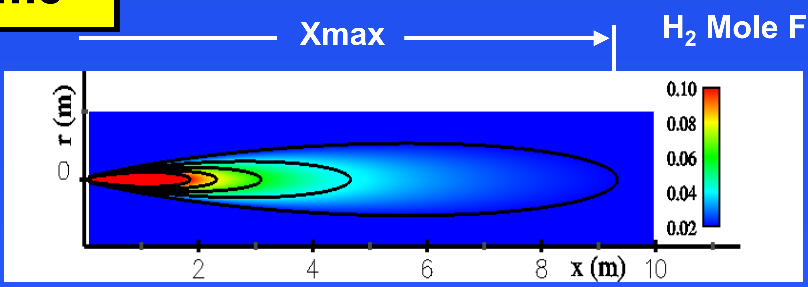
(2,463 ft^3/min)*

*@NTP = 21° C (70° F), 101 kPa (14.7 psia)

Flow between exit and 4% mole fraction is in the momentum dominated regime

- Start Intermediate Region
  $x/D = 0.5\, F^{1/2}(\rho_{exit}/\rho_{amb})^{1/4}$

F = Exit Froude No. = $U^2_{exit}\,\rho_{exit}/(gD(\rho_{amb} - \rho_{exit}))$



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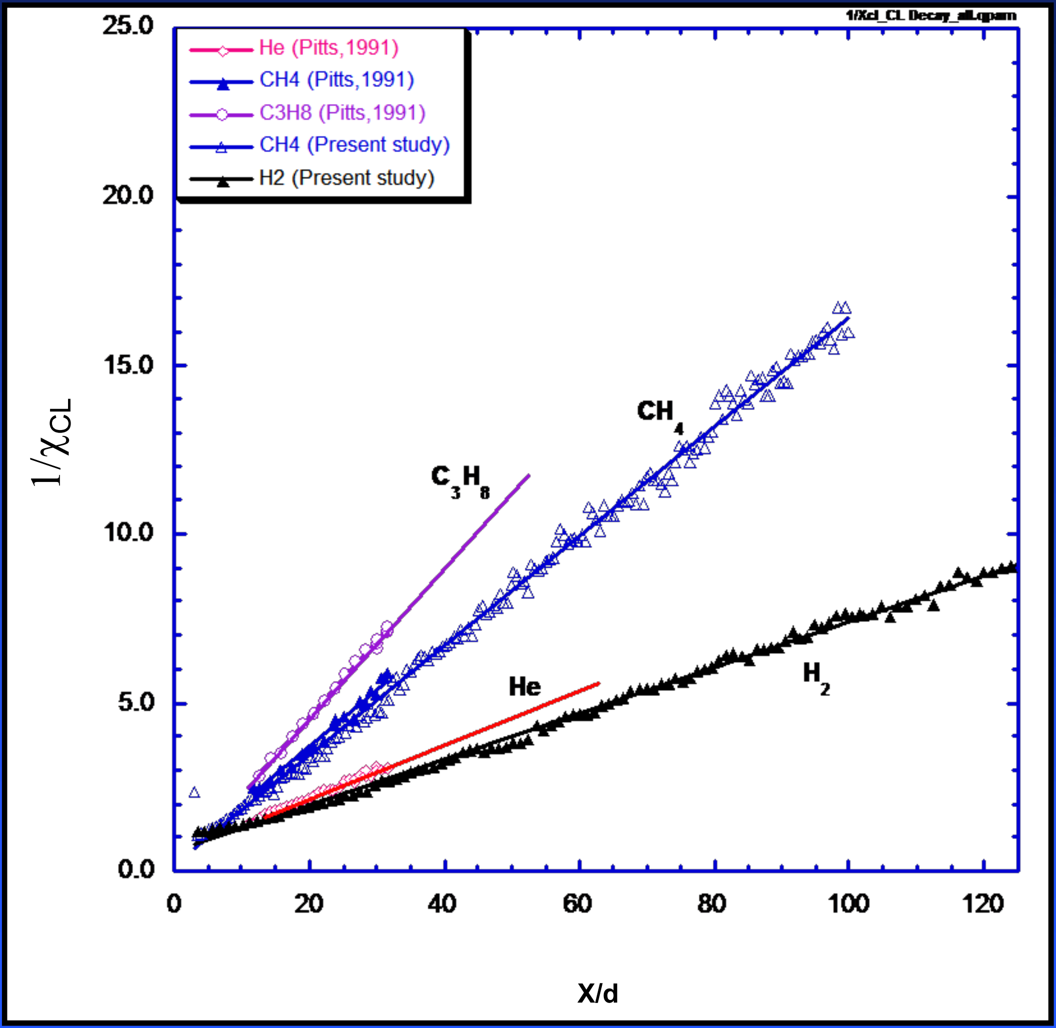
Small Unignited Releases: Momentum-Dominated Regime

Data for round turbulent jets



- In momentum-dominated regime, the centerline decay rate follows a $1/\chi_{CL}$ dependence for all gases.
- The mole fraction centerline decay rate increases with increasing molecular weight.

The decay rate for H_2 is significantly slower than for methane and propane.

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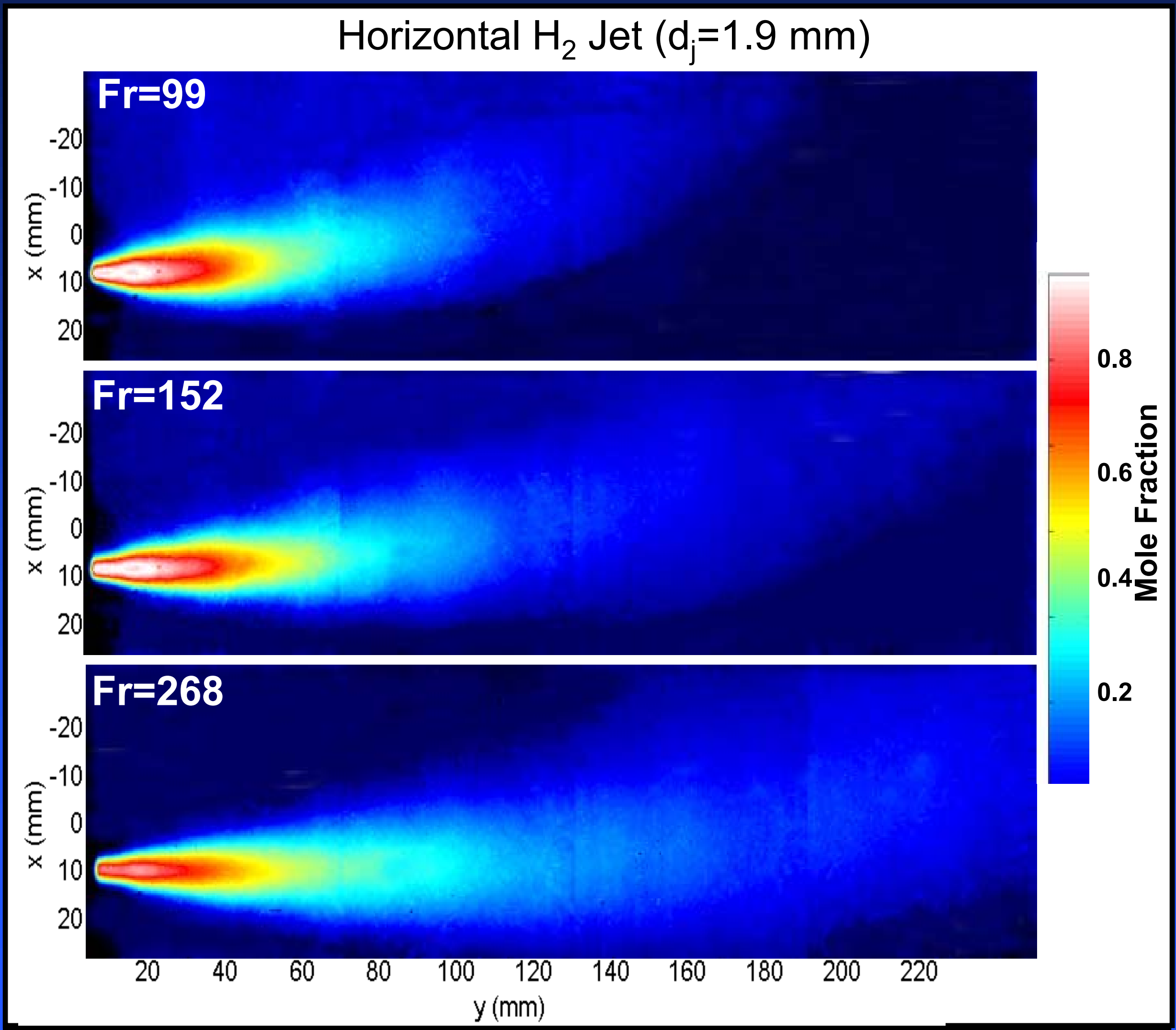
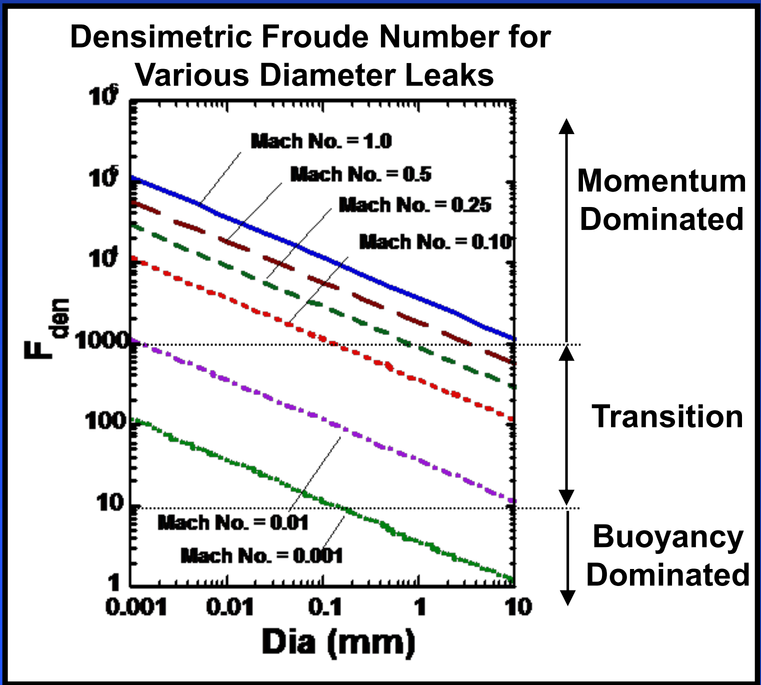
Buoyancy effects are characterized by Froude number



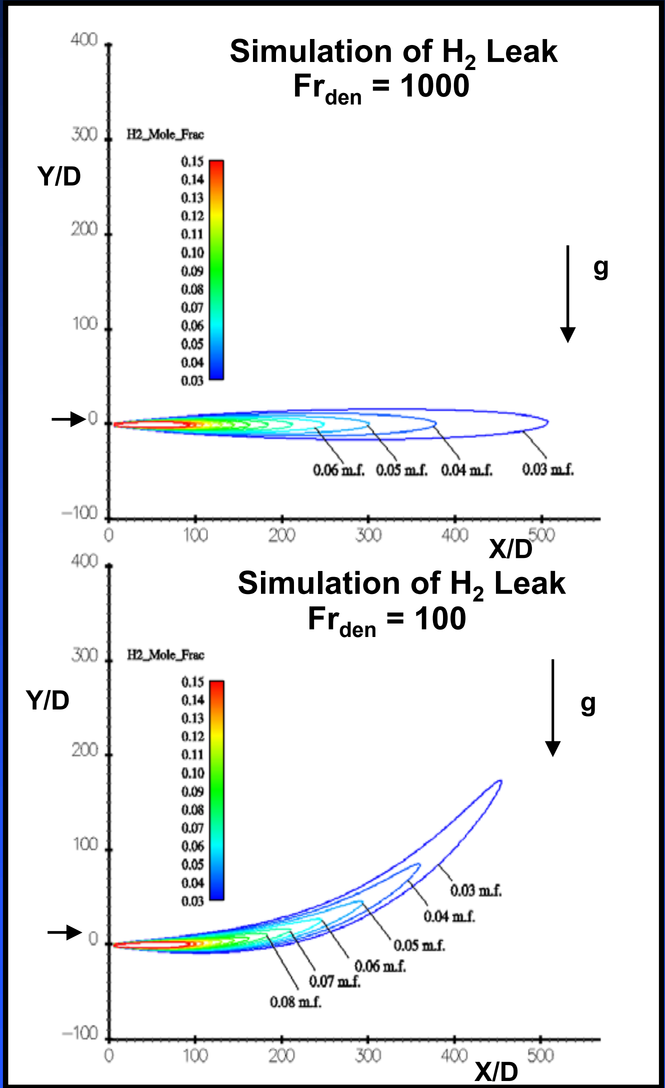
- Time-averaged H_2 mole fraction distributions.
- Froude number is a measure of strength of momentum force relative to the buoyant force
- Increased upward jet curvature is due to increased importance of buoyancy at lower Froude numbers.

Influence of buoyancy is quantified by the Froude number

- Jets from choked flows (Mach 1.0) are typically momentum-dominated ($P_{upstream}/P_{downstream}$>~2).
- Lower source pressures or very large pressure losses through cracks lead to subsonic, buoyancy-dominated plumes.



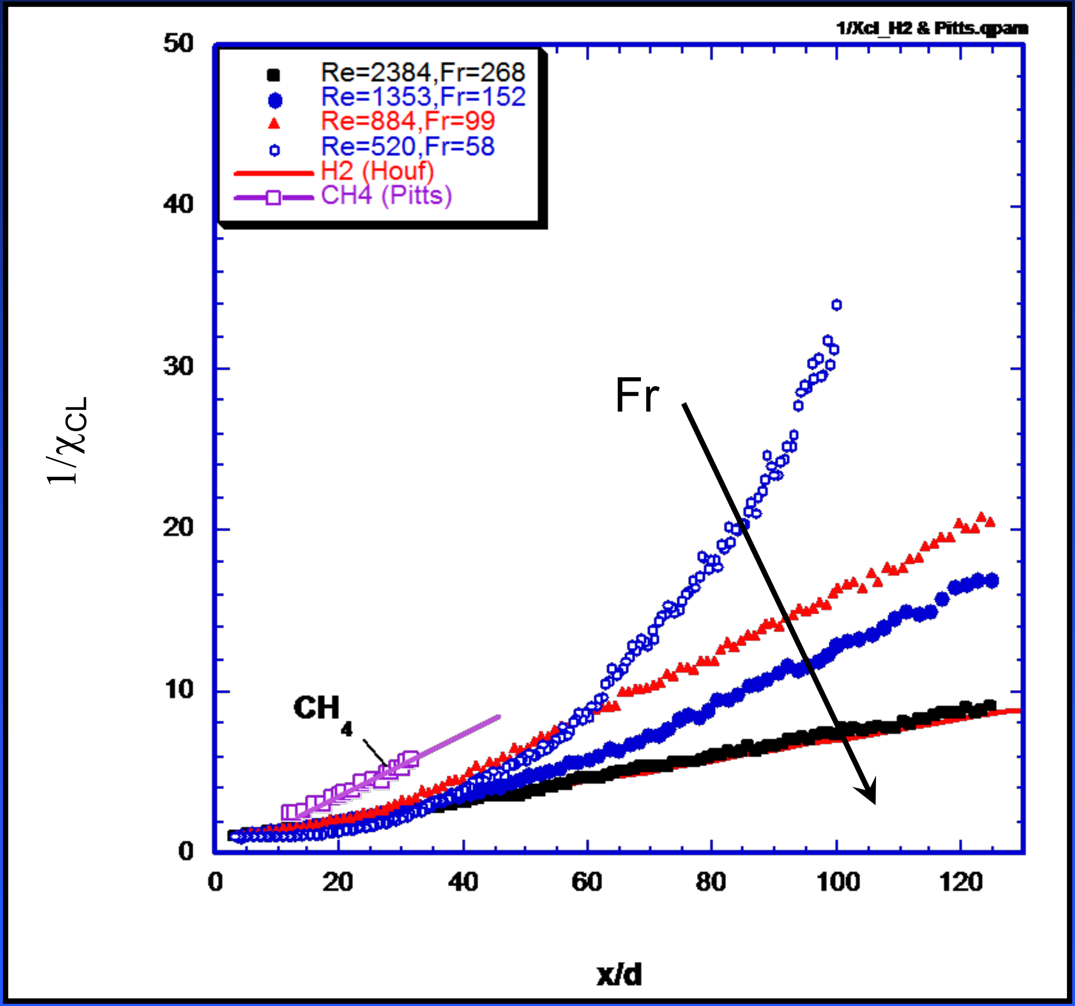
$$Fr_{den} = U_{exit}/(gD(\rho_{amb} - \rho_{exit})/\rho_{exit})^{1/2}$$



Ricou and Spalding entrainment law (J. Fluid Mechanics, 11, 1961)

Small Unignited Releases: Buoyancy Effects

- Data for round H_2 Jets (d_j=1.91 mm)



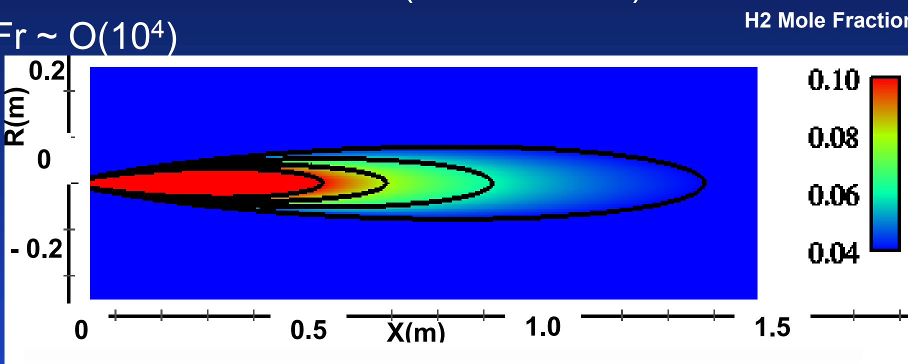
- At the highest Fr, 1 / χ_{CL} increases linearly with axial distance, indicating momentum dominates.
- As Fr increases buoyancy forces become less important and the centerline decay rate decreases.
- The transition to buoyancy-dominated regime moves downstream with increasing Fr.

Choked & Unchoked Flows at 20 SCFM

Tank Pressure = 3000 psig, Hole Dia. = 0.297 mm

Exit Mach Number = 1.0 (Choked Flow)

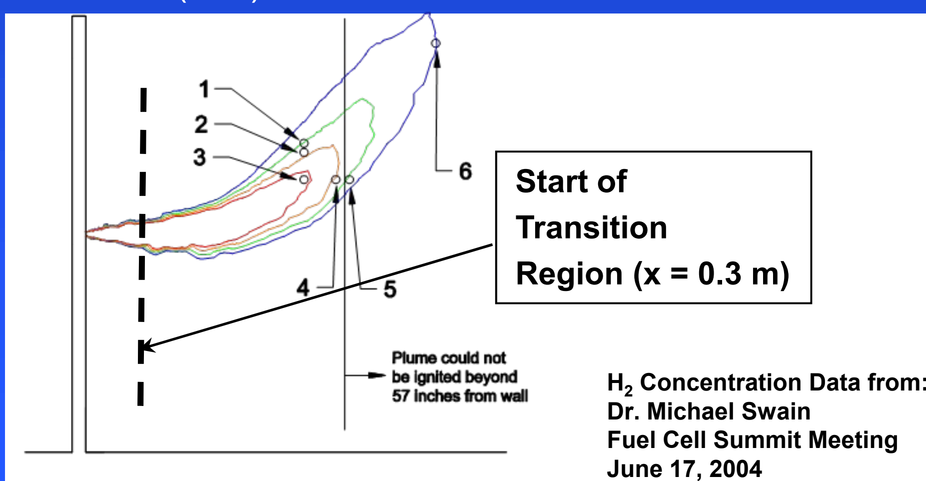
Fr ~ $O(10^4)$



Flowrate = 20 scfm, Hole Dia. = 9.44 mm

Exit Mach Number = 0.1 (Unchoked Flow)

Fr ~ O(100)



- Correlations based on experimental data
- Start Intermediate Region
  - $x/D = 0.5\, F^{1/2}(\rho_{exit}/\rho_{amb})^{1/4}$
- End Intermediate Region
  - $x/D = 5.0\, F^{1/2}(\rho_{exit}/\rho_{amb})^{1/4}$
- F = Exit Froude No.

  $= U^2_{exit}\, \rho_{exit}/(gD(\rho_{amb} - \rho_{exit}))$

Start Transition Region -> x = 6.3 m

- Assuming gases at 1 Atm, 294K (NTP)
  - Red – 10.4%
  - Orange – 8.5%
  - Green – 5.1%
  - Blue – 2.6%

*(Chen and Rodi, 1980)

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Flammability Limits for H_2

Upward Flame Propagation

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					
5.3	150					
5.3	150					
5.0	150					
5.0	150					
4.8	150					
4.5	80					
4.5	80					

Horizontal Flame Propagation

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

Downward Flame Propagation

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

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	N̦	8.5	67.5	N̦	82
1,000	N̦	8.7	75.5	N̦	95
810	N̦	5.0	73.5	N̦	349
350	N̦	4.6	70.3	N̦	368
35	N̦	9.4	64.8	N̦	297

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- 78 investigations of hydrogen flammability limits were identified between 1920 and 1950.
- Hydrogen flammability limits are well established.

Propagation

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Diameter	Length		Lower
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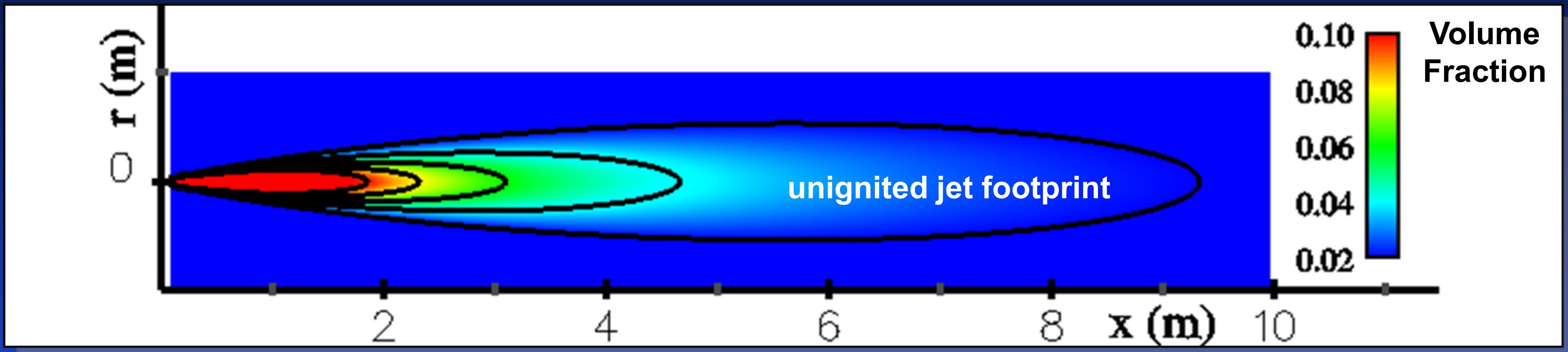
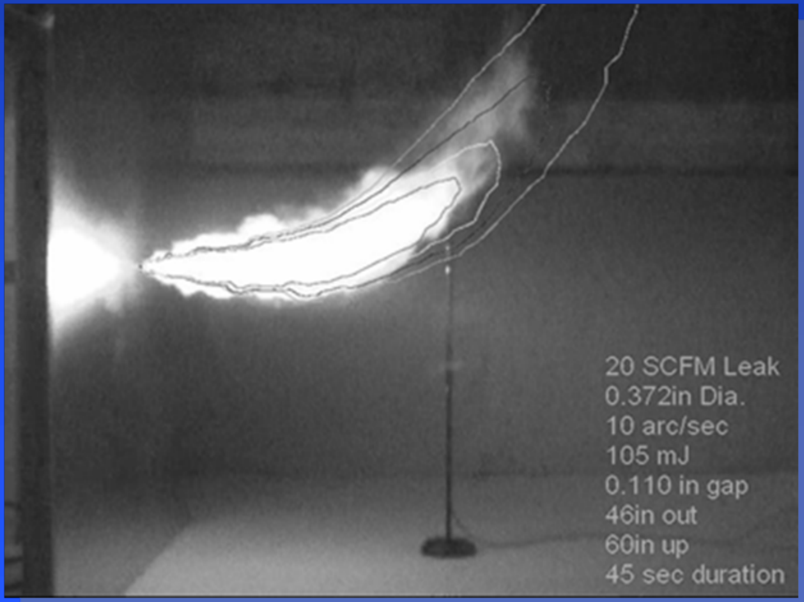
What is a Reasonable Flame Stabilization Limit?



- Which volume fraction contour is relevant:
  - lean flammability limit? … 4% or 8%
  - detonation limit? … 18%
  - a fraction of the lowest lean flammability limit? … 1%
- ***Ignition of hydrogen in turbulent jets occurs around 8% as measured by Swain.***
  - This is consistent with the downward propagating limit of 8%



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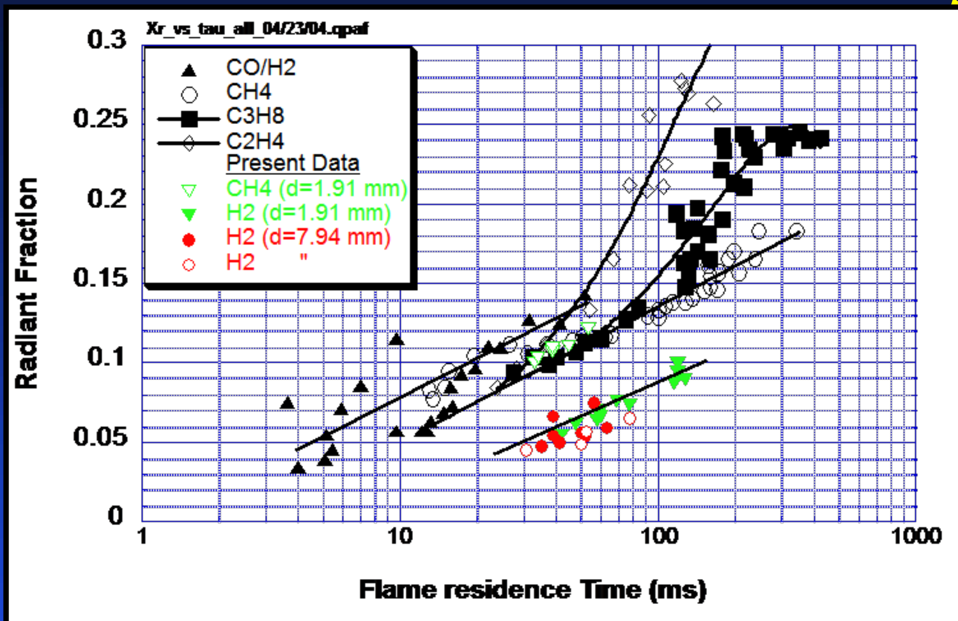
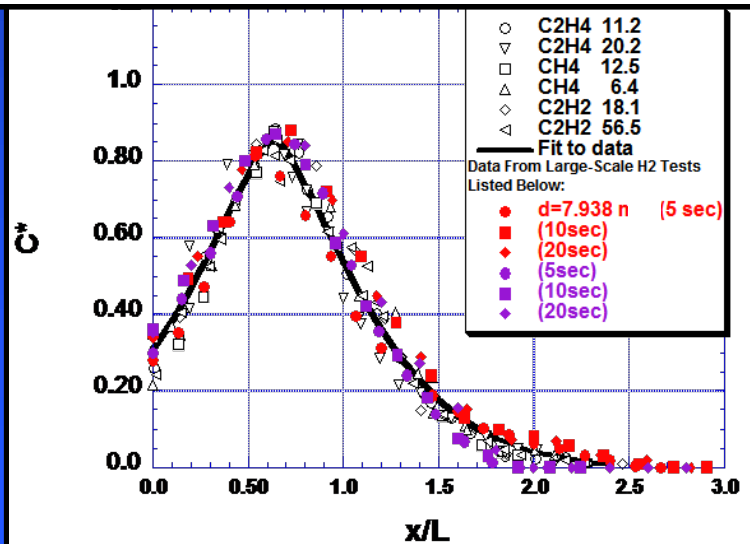
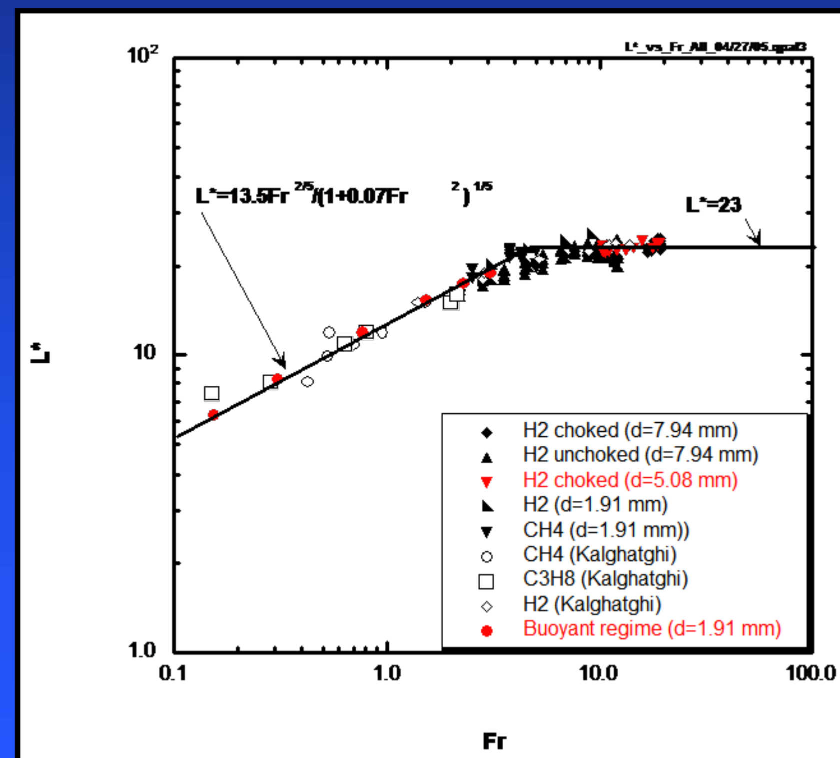
Hydrogen jets and flames are similar to other flammable gases





- Fraction of chemical energy converted to thermal radiation
- Radiation heat flux distribution
- Jet length



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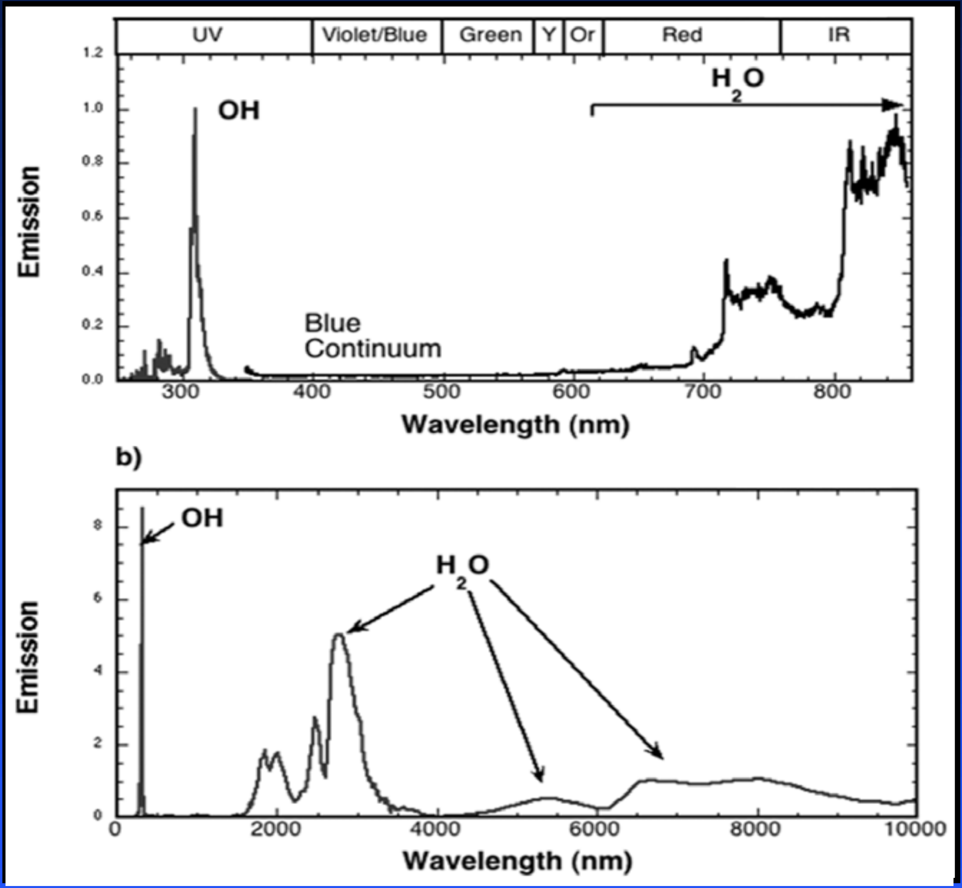
H_2 Flame Radiation



- Orange emission due to excited H_2O vapor
- Blue continuum due to emission from OH + H => H_2O + hν
- UV emission due to OH*
- IR emission due to H_2O vibration-rotation bands

H_2O emission in IR accounts for 99.6% of flame radiation

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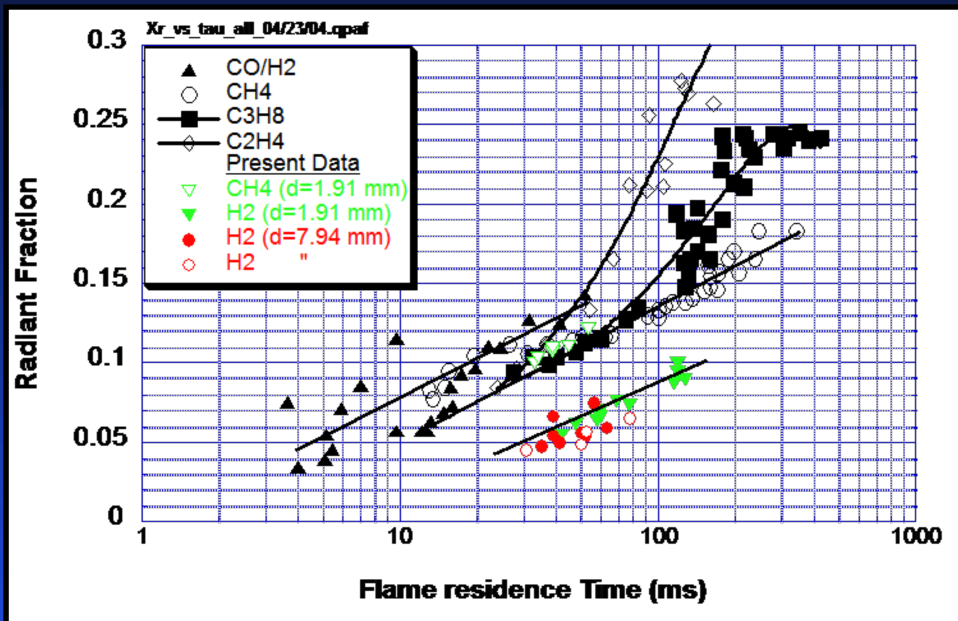

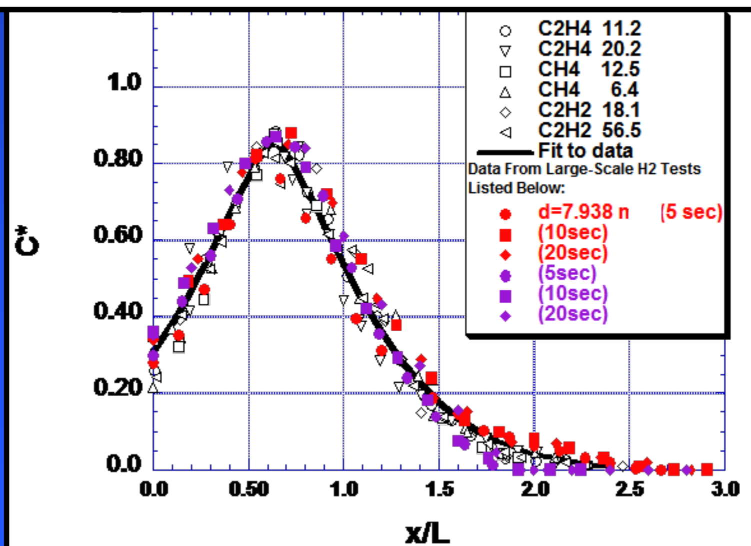

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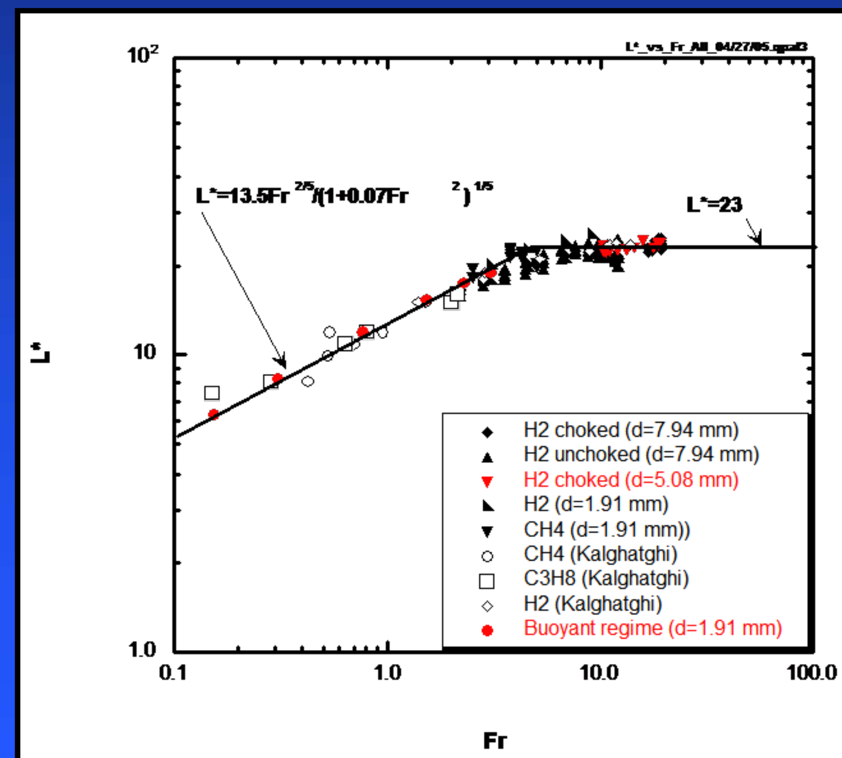
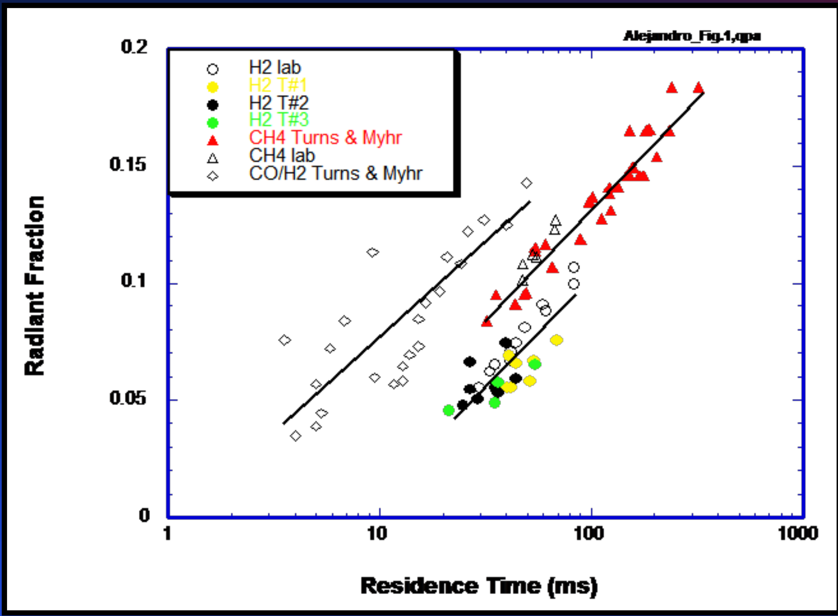
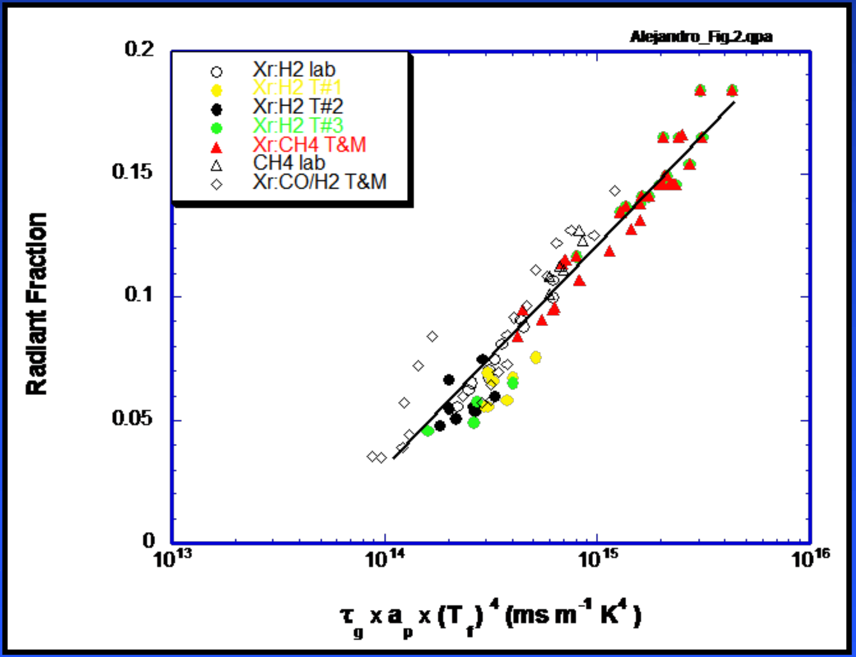


Thermal Radiation from Hydrogen Flames



- Radiation heat flux data collapses on singe line when plotted against product τ_G x a_p x T_f^4 .
- a_p (absorption coefficient) is factor with most significant impact on data normalization
- ***Plank mean absorption coefficient for different gases must be considered***

- Previous radiation data for *nonsooting* CO/H_2 and CH_4 flames correlate well with flame residence time.
- Sandia's H_2 flame data is a factor of two lower than the hydrocarbon flame data.



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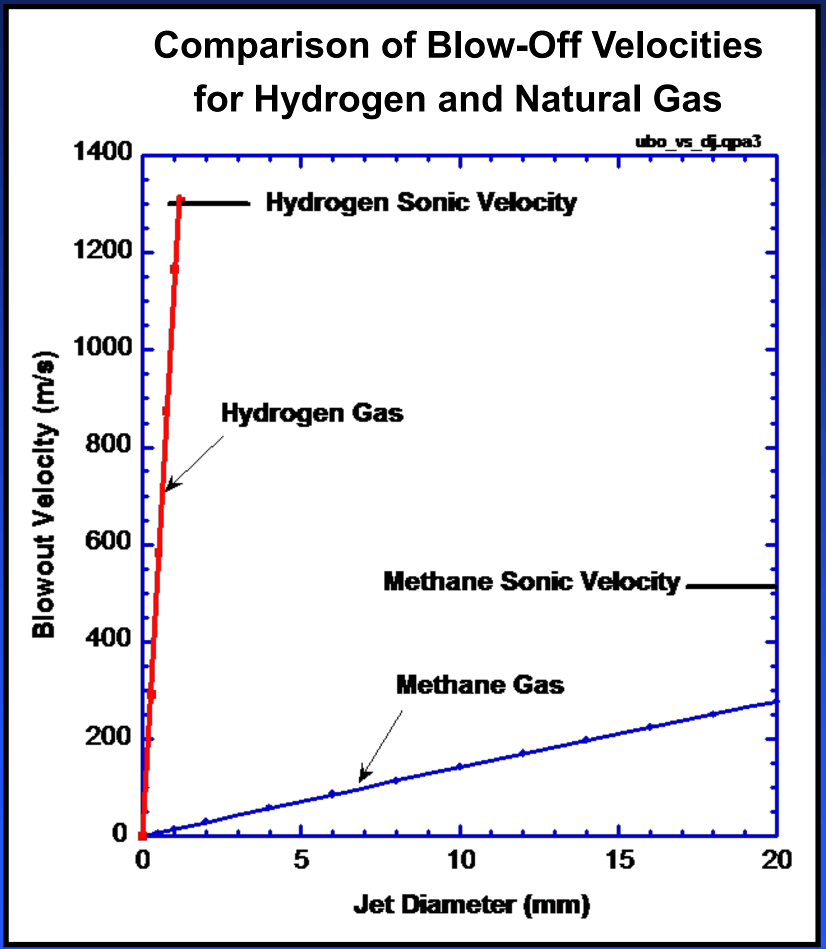
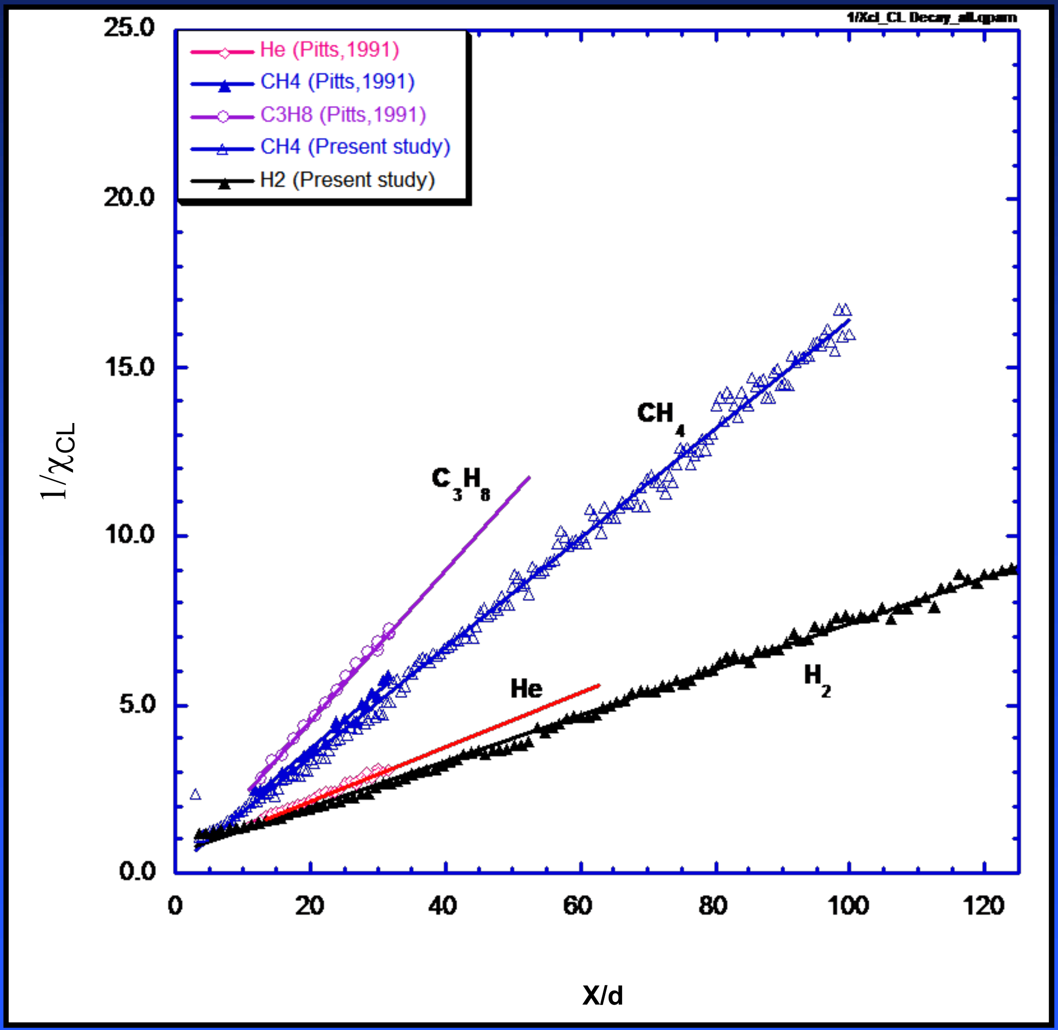
Comparisons of NG and H_2 Behaviors



- Assume 3.175 mm (1/8 inch) dia. hole
- Unignited jet lower flammability limits
  - LFL H_2 - 4% mole fraction
  - LFL NG - 5% mole fraction
- Flame blow-off velocities for H_2 are much greater than NG
- Flow through 1/8" diameter hole is choked
  - V_{sonic} = 450 m/sec for NG (300K)
  - V_{sonic} = 1320 m/sec for H2 (300K)
- Hole exit (sonic) velocity for NG is greater than NG blow-off velocity
  - No NG jet flame for 1/8" hole
- Hole exit (sonic) velocity for H_2 is much less than blow-off velocity for H_2
  - H_2 jet flame present for 1/8" hole

Small Unignited Releases: Momentum-Dominated Regime

Data for round turbulent jets



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- The mole fraction centerline decay rate increases with increasing molecular weight.

The decay rate for H_2 is significantly slower than for methane and propane.

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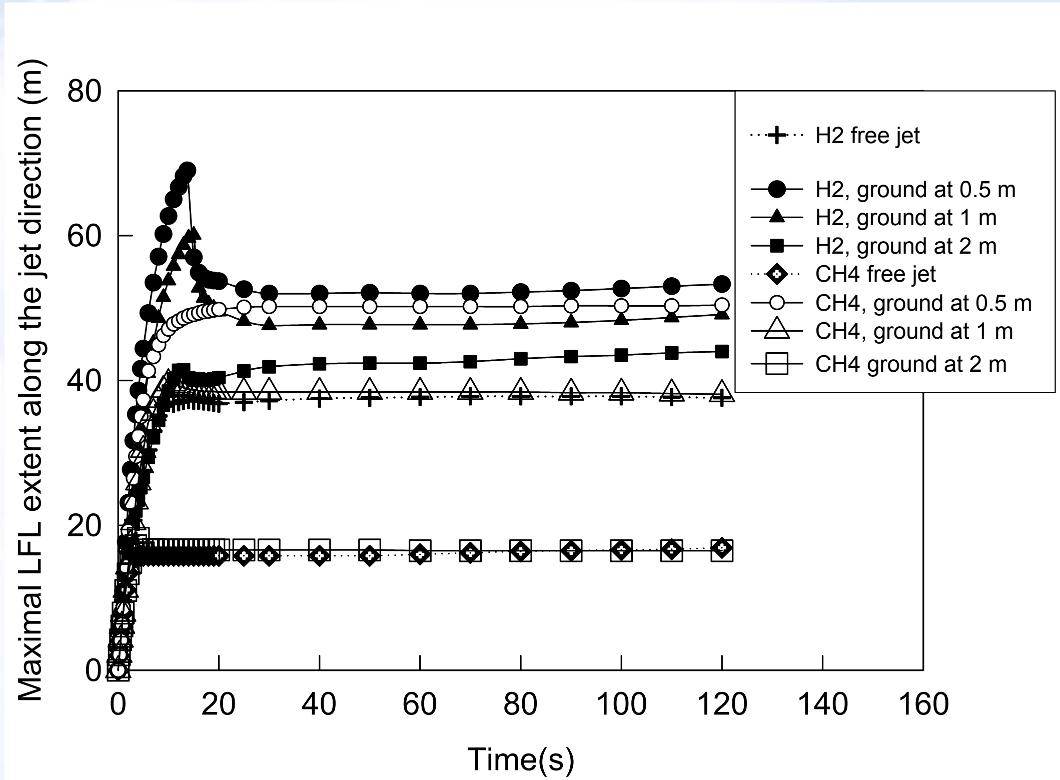
Unignited jet concentration decay distances for NG and H_2.

Distance on Jet Centerline to Lower Flammability Limit
for Natural Gas and Hydrogen

Tank Pressure	Hole Diameter	Distance to 5% Mole Fraction Natural Gas	Distance to 4% Mole Fraction. Hydrogen
18.25 bar (250 psig)	3.175 mm (1/8 inch)	1.19 m (3.90 ft)	4.24 m (13.91 ft)
	1.587 mm (1/16 inch)	0.59 m (1.93 ft)	2.12 m (6.95 ft)
207.8 bar (3000 psig)	3.175 mm (1/8 inch)	3.92 m (12.86 ft)	13.54 m (44.42 ft)
	1.587 mm (1/16 inch)	1.96 m (6.43 ft)	6.77 m (22.21 ft)

Distance to the lower flammability limit for hydrogen is about 3 times longer than for natural gas

Maximum LFL Extents vs Time – Horizontal H2 and CH_4 Jets along Horizontal Surface

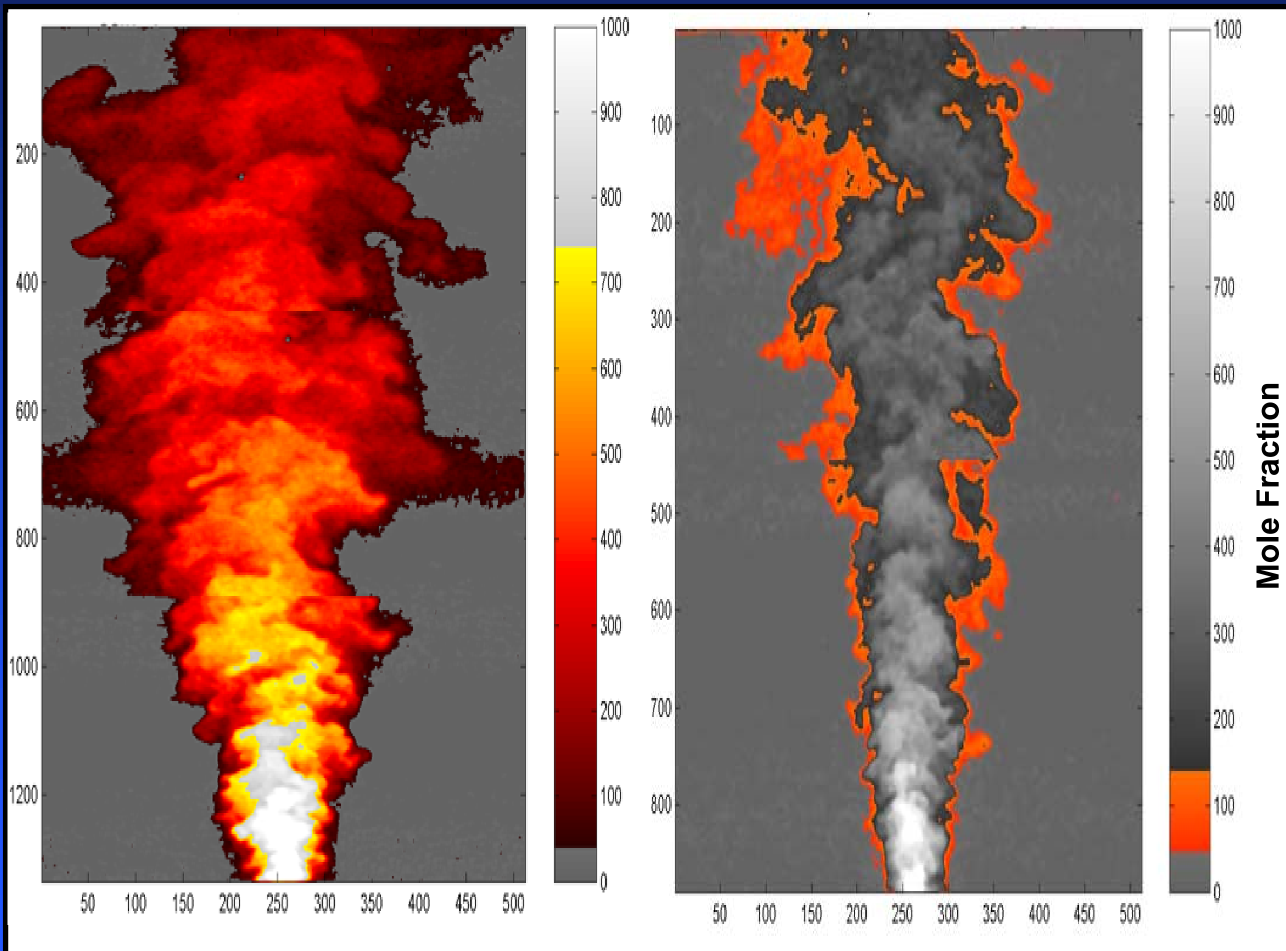


- Features: strong transient overextent of the hydrogen cloud (larger than at steady state), not observed in case of methane
- Much stronger effect of surface on methane jets vs hydrogen jets:
  - ✓ While methane free jet max LFL extent is almost 3 times shorter than that of hydrogen, at 0.5 m above ground the max LFL extents for both gases become almost equal

Courtesy of P. Bénard and A.V. Tchouvelev

Small Unignited Releases: Ignitable Gas Envelope

H_2 Jet at Re=2,384; Fr = 268 CH_4 Jet at Re=6,813; Fr = 478



- H_2 flammability limits: LFL 4.0%; RFR 75%
- CH_4 flammability limits: LFL 5.2%; RFR 15%

Radial profiles in H_2 jet, d = 1.91 mm, Re = 2384

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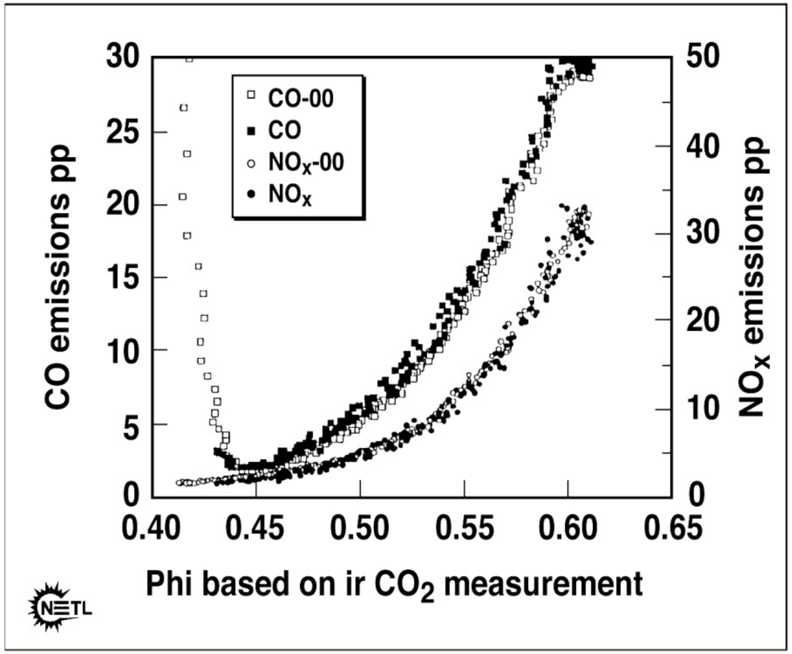
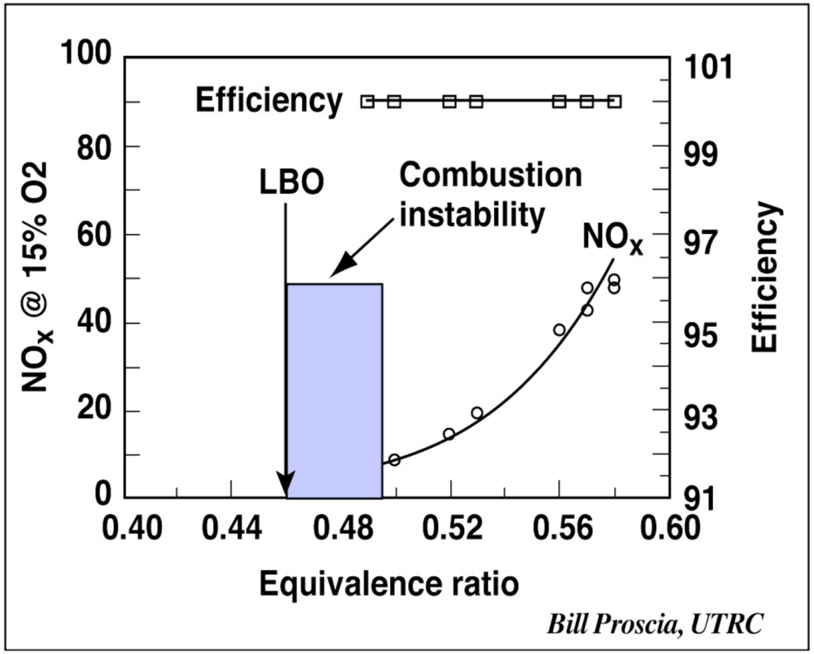
Lean Premixed Combustion for NOx Control



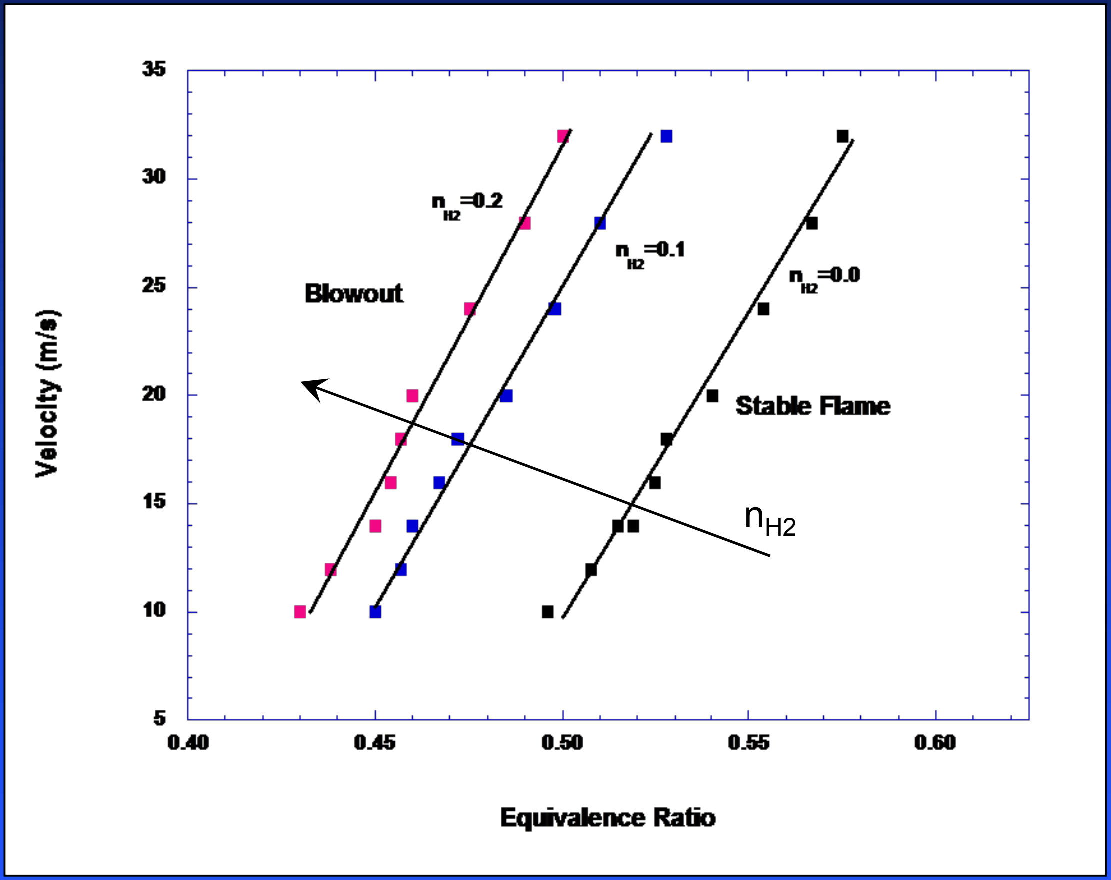


At ultra lean conditions a tradeoff exists between NOx and CO emissions

Ultimately, lean operation is limited by the onset of flame instability and blowout

H_2 addition extends lean flammability limit and reduces CO emissions

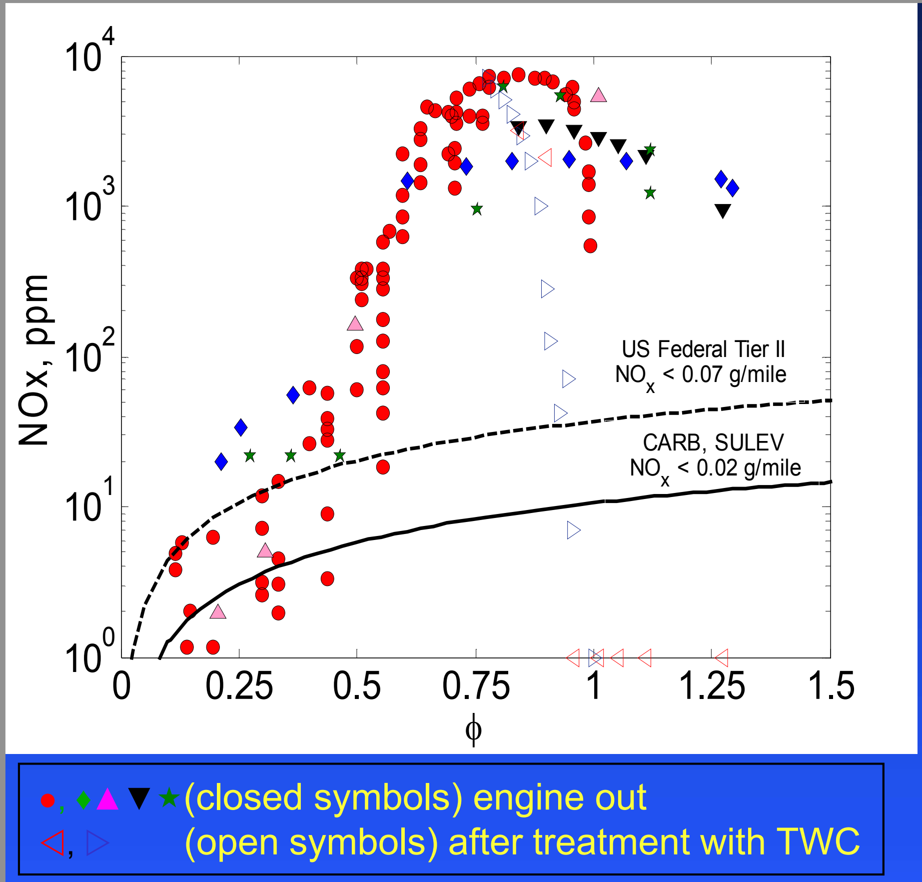
Effect of Hydrogen -Enrichment on Flame Stability



- Data points indicate minimum equivalence ratio at which a stable flame can be maintained
- Hydrogen addition significantly extends lean flame stability
- Expected NO_x levels less than 3 ppm can be achieved with 20 % hydrogen addition

Present Day H_2ICEs: Emissions

- NO_x is the only non-trivial engine-out emission pollutant
  - Engine out Dial-a-NO_x value ~ 5-6 ppm
  - With after-treatment NO_x values can be near zero ***
    - Measured tailpipe NO_x emissions equal to ambient levels of about 50 ppb
- HC, CO all near zero engine-out emissions **
  - Trace amounts from lubricating oil
    - CO – O(1) ppm, HC – O(5) ppm for a reduction of a factor of 1000, 250 respectively compared to gasoline



*BMW presentation @ 2006 National Hydrogen Association Meeting March, 2006
**SAE Papers #'s 2002-01-0240 thru 0243 and 2003-01-0631; Ford Research

***James Heffel, University of California, Riverside, College of Engineering – Center for Environmental Research and Technology (CE-CERT); Personal Communication; Under the technical guidance and contract to Sandia National Laboratories, funding from the Hydrogen Program Office; OPT

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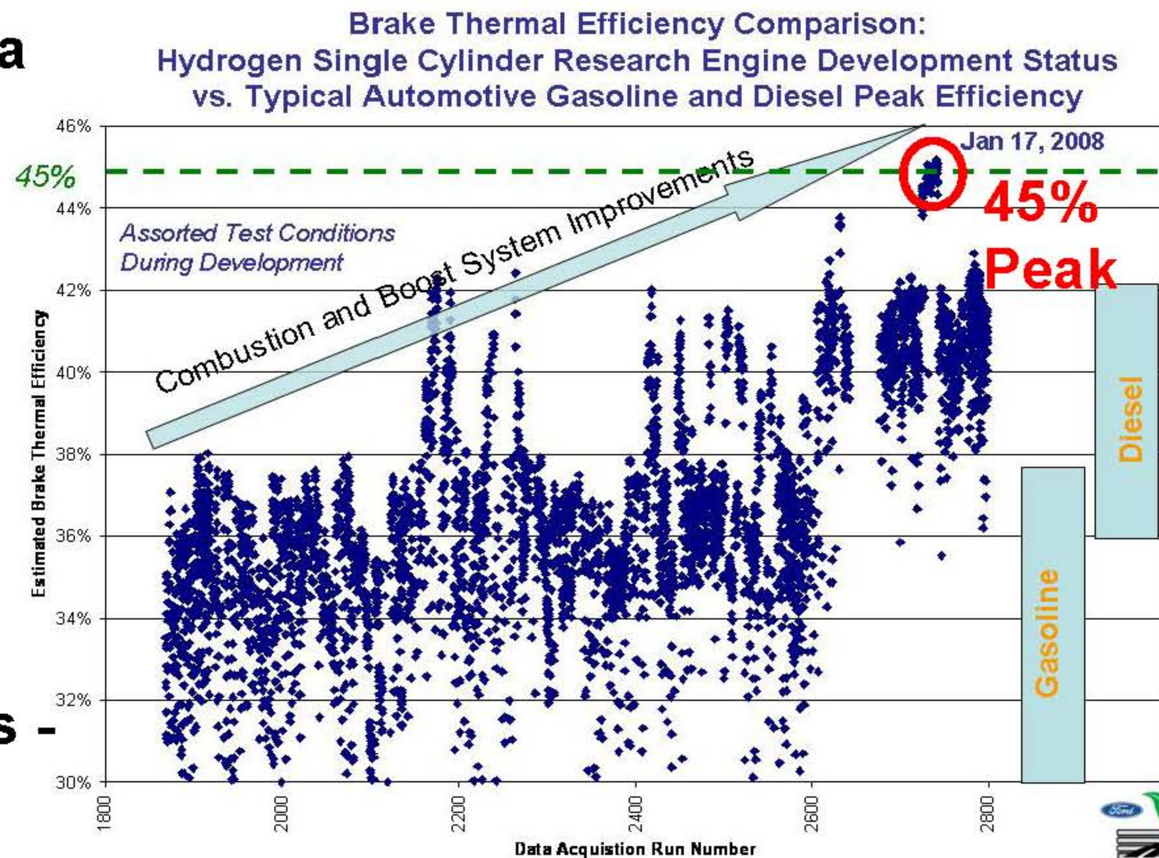
Brake Thermal Efficiency Trend – Projected to Multi-cylinder Engine

- •3+ years of data
- •Different injection rates
- •Mostly 1500-4500 RPM
- •Naturally aspirated & boosted.
- •Discrete clouds - different boost condition.



2008-01-2379

Alan Welch, David Mumford, Sandeep Munshi, Westport Innovations Inc., James Holbery, Pacific Northwest National Laboratory, Brad Boyer, Matthew Younkins, Howard Jung, Ford Motor Co. "Challenges in Developing Hydrogen Direct Injection Technology for Internal Combustion Engines", SAE 2009-01-2379

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Proposed Mechanisms for Spontaneous Ignition

- 81 ignitions of H_2 releases have been reported (MHIDAS database). In 11 cases the ignition source was identified (flame, electric, hot surface). *In the remaining 70 no ignition source could be identified*.
- Proposed causes include the following:
  - Joule-Thomson
  - *Static charge buildup in the flow*
  - *Shock heating that leads to ignition of H_2/air mixtures*
  - *Catalytic reaction with materials present in the flow (iron oxide)*
  - *Friction heating of particulates / hot surface ignition*

Area of current research

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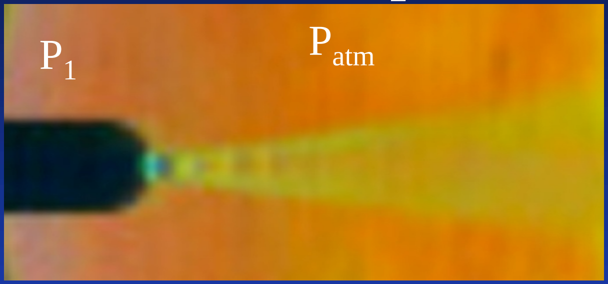
  - Catalytic reaction with materials present in the flow (iron oxide)
  - Friction heating of particulates / hot surface ignition

Joule-Thomson Effect

High-pressure H_2 Jet



- The direction and magnitude of temperature change is determined by the Joule-Thomson coefficient which is a function of upstream pressure (P_1).

$$\mu_{JT} = (\delta T / \delta P)_H = (\Delta T / \Delta P)_H$$

- Above the inversion temperature, the expanding gas temperature increases.
- The inversion temperature of H_2 is between 28 and 200 K (depending on pressure); at ambient temperature the expanding H_2 increases in temperature.
- For initial compressed gas pressure of 14 MPa, the estimated temperature rise is approximately ~6 K.
- At pressures up to 250 MPa, the maximum estimated coefficient is 0.53 K/MPa. Thus, at future H_2 storage pressures of 100 MPa, the maximum temperature rise would be 53 K.[1] If the initial temperature was 300K (room temperature) the exit gas temp would be 353K

[1] Astbury and Hawksworth, "Spontaneous ignition of hydrogen leaks: postulated mechanisms", International Conference on Hydrogen Safety, Pisa, Italy (2005).

Given the H_2 auto-ignition temperature of 858 K, Joule-Thomson heating is insufficient to cause ignition

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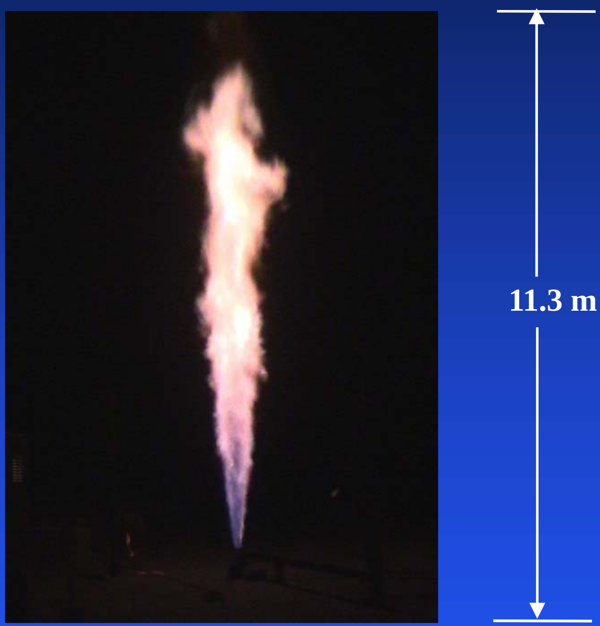
Publication list



Nighttime photograph of ~40 MPa large-scale H2 jet-flame test (d_j = 5.08mm, L_{vis} = 10.6 m) from Sandia/SRI tests.

(1) Houf and Schefer, “Predicting Radiative Heat Fluxes and Flammability Envelopes from Unintended Releases of Hydrogen,” accepted for publication Int. Jour. of Hydrogen Energy, Feb. 2006.

(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,” submitted to Int. Jour. of Hydrogen Energy, 2006.

(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 R. W., “Combustion Basics,” in National Fire Protection Association (NFPA) Guide to Gas Safety, 2004.

(9) P. Bénard (2007), Chapter 3 – Hydrogen Release and Dispersion - Release of hydrogen - section a.1, , Biennial Report on Hydrogen Safety, HySafe.

(10) B. Angers, A. Hourri, P. Bénard, P. Tessier and J. Perrin (2005), “Simulations of Hydrogen Releases from a Storage Tank: Dispersion and Consequences of Ignition”. International Conference on Safety 2005, Sept 8-10, 2005, Pisa, Italy.

(11) A.V. Tchouvelev, P. Bénard, V. Agranat and Z. Cheng (2005), “Determination of Clearance Distances for Venting of Hydrogen Storage”. International Conference on Safety 2005, Sept 8-10, 2005, Pisa, Italy (NRCAN, AUTO 21).

(12) Tchouvelev A., P. Bénard, D. R. Hay, V. Mustafa, A. Hourri, Z. Cheng, Matthew P. Large, Quantitative Risk Comparison of Hydrogen and CNG Refuelling Options, Final Technical Report to Natural Resources Canada for the Codes and Standards Workshop of the CTFCA, August 2006 (194 pages).

(13) Bénard, P., Tchouvelev, A., Hourri, A., Chen, Z., Angers, B. High Pressure Hydrogen Jets in a Presence of a Surface. Proceedings of International Conference on Hydrogen Safety, San Sebastian, Spain, September 2007.

(14) Tchouvelev, A.V., Howard, G.W. and Agranat, V.M. Comparison of Standards Requirements with CFD Simulations for Determining of Sizes of Hazardous Locations in Hydrogen Energy Station. Proceedings of the 15th World Hydrogen Energy Conference, Yokohama, June 2004.

Some people just do not get it!

- **H_2**
  - **is not toxic,**
  - **it is environmentally benign**
  - **we just borrow it -- ($2H_20 + E \rightarrow 2H_2 + O_2$; then $2H_2+O_2 \rightarrow 2H_2O + E$)**
- **H_2 is a fuel and as such has stored chemical energy**
  - **It has hazards associated with it**
    - **It is no more dangerous than the other fuels that store chemical energy**
    - **IT IS JUST different; -- *WE UNDERSTAND THE SCIENCE***

Following NFPA 52 / 2 - Hydrogen Installations are no more dangerous than current refueling stations.

Presentation End