Hydrogen Vehicle Fire Safety

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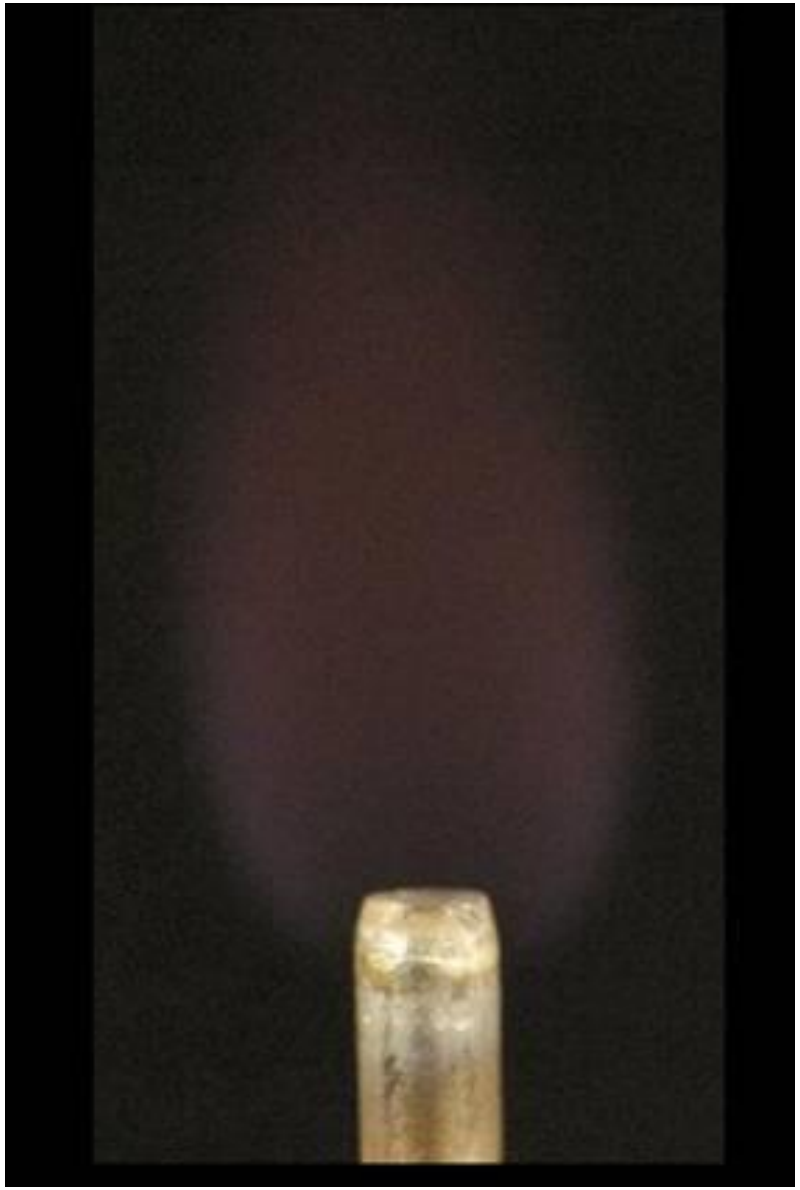
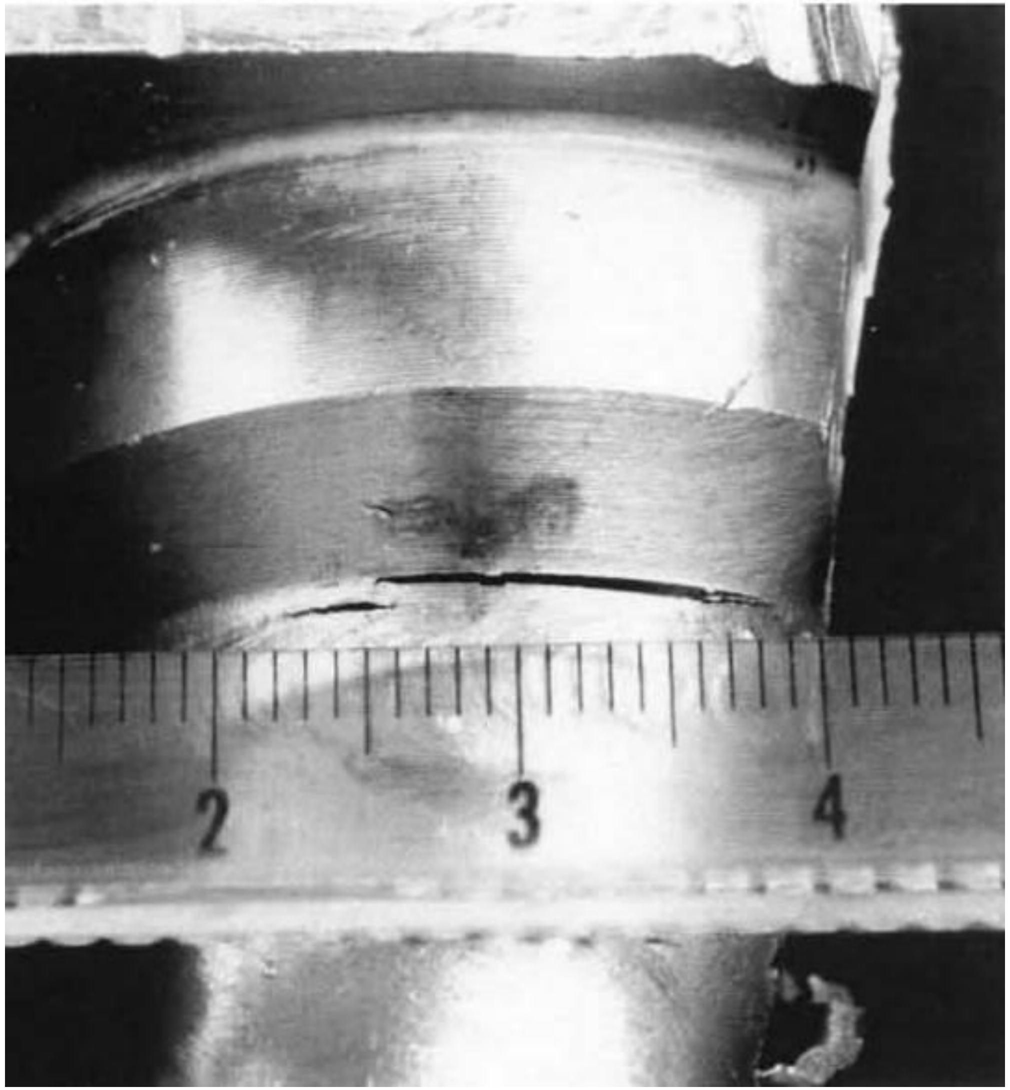
- Students: M.S. Butler, C.W. Moran, N.R. Morton, V.R. Lecoustre.

Most hydrogen flames are barely visible.



H_2 Containment



Barthelme (2006)

Hydrogen Vehicle PRD Test

- Swain (2001) tests comparing hydrogen and gasoline vehicle fires (above).
- https://www.youtube.com/watch?v=OA8dNFiVaF0

CNG Bus Fire Video

Unique Fire Hazards of Hydrogen

- Lightest fuel, thus requiring the highest storage pressure.
- Highest volumetric leak propensity of any fuel.
- Permeation leaks.
- Steel embrittlement.

- Smallest ignition energy of any fuel in air (28 μJ).
- Lowest autoignition temperature of any fuel ignited by a heated air jet (640 °C).

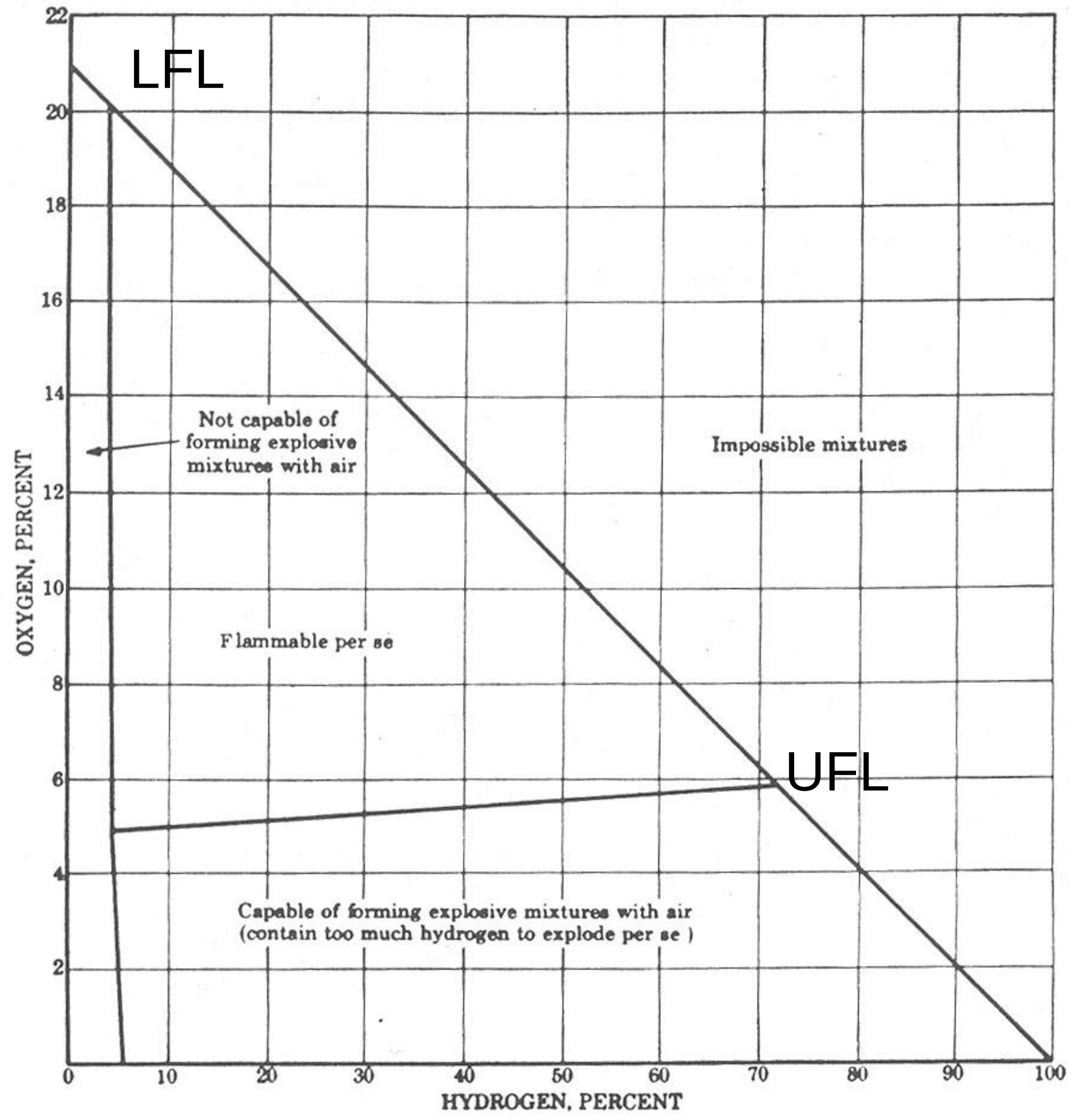
- Wide flammability limits in air (4 – 75% by volume).
- Highest laminar burning velocity of any fuel in air (2.91 m/s).
- Smallest quenching distance of any fuel premixed with air (0.51 mm).
- Highest heat of combustion (120 kJ/g).

- Dimmest flames of any fuel in air.

Fuel Properties

Fuel	Flash Point, °C	AIT, °C	LFL, %	UFL, %
Gasoline	-40	468	1.4	7.6
Methane	-180	632	3.8	17
Propane	-104	504	2.3	9.5
Hydrogen	-	571	4	75
Ethanol	15	392	3.3	19
Methanol	30	470	6.7	36
Biodeisel	130	240	0.6	5.6

Hydrogen/Air/Nitrogen Flammability Map



Coward and Jones (1952)

Hydrogen Equation of State

- At elevated density, H_2 gas becomes nonideal:

$$p = \rho \; (R_u / MW) \; T \; (1 + \alpha \, p / T)$$

α = non-ideal gas correction factor (1.9155×10^{-6} K/Pa for H_2).

- Applying this equation to H_2 at 1.01 bar and 15 °C yields a density that is increased by a factor of just 1.00067.

- In contrast, at 70 MPa and 15 °C the quantity $(1 + \alpha \, p / T) = 1.47$.

Isentropic Compression and Expansion

- When a H_2 gas container is vented, its T decreases.
- When a H_2 gas container is filled, its T increases.
- These processes are nearly isentropic (i.e., reversible).
- Isentropic processes for ideal gases behave according to:

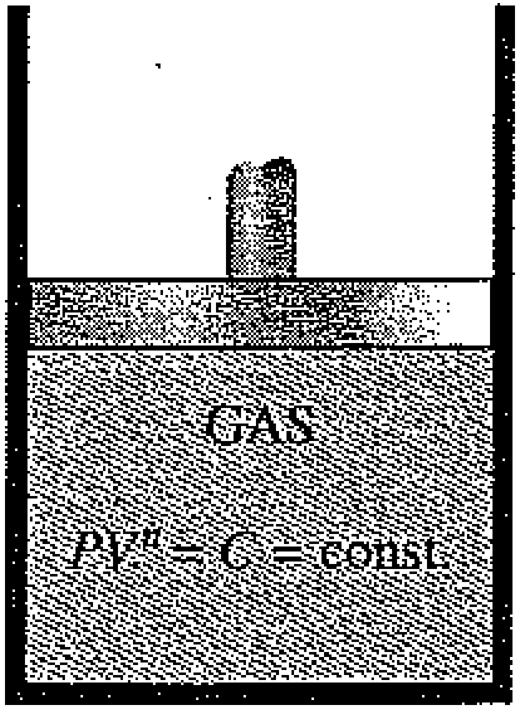
$$p V^{\gamma} = \text{constant}$$

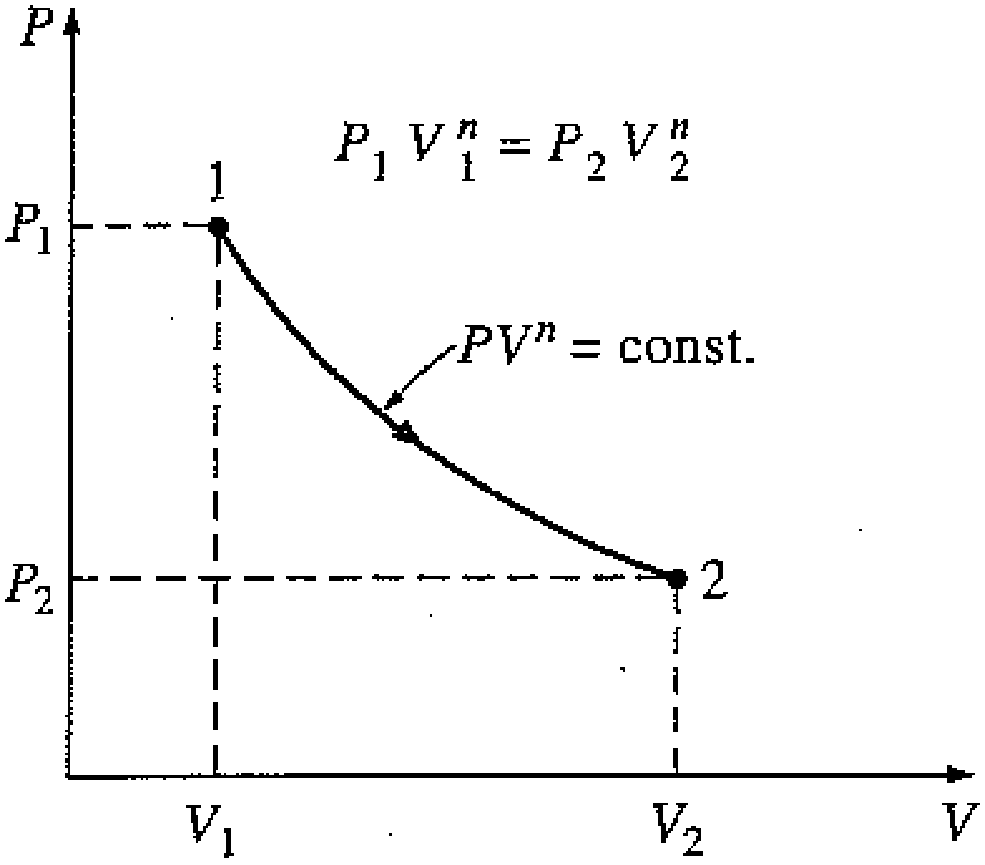
$$T V^{\gamma-1} = \text{constant}$$

$$T^{\gamma} p^{1-\gamma} = \text{constant}$$

Here V is volume and γ is specific heat ratio (1.40 for air and 1.41 for H_2 at standard conditions).

Isentropic Compression and Expansion



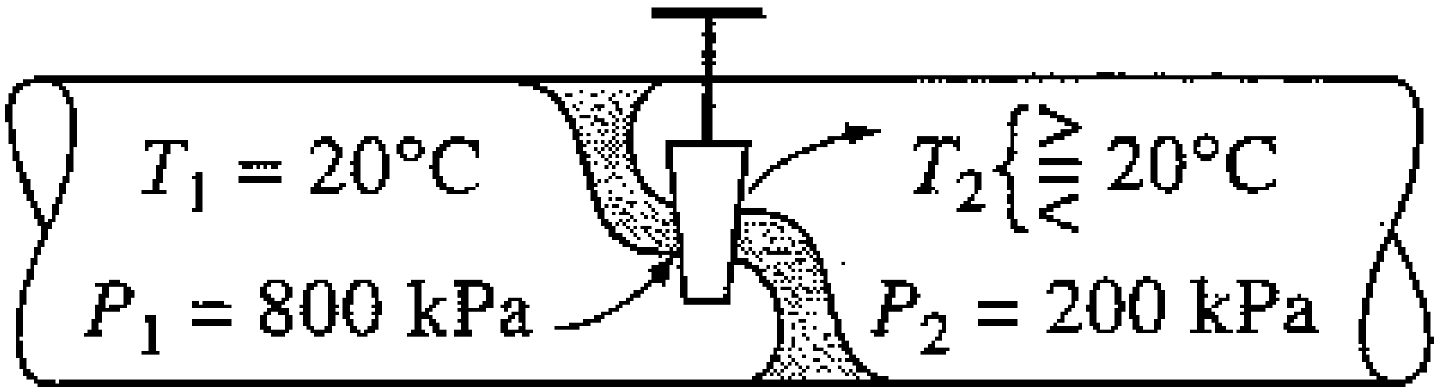


Isentropic Compression and Expansion

- A container initially at 25 °C and 70 MPa that is rapidly vented to 1 bar will have a final T of 45 K.
- Normal driving will not vent this quickly, but an accident could.
- A container initially at 25 °C and 2 MPa that undergoes isentropic compression to 70 MPa will have a final T of 565 °C. This is avoided because:
  - The fill gas is much cooler than 565 °C.
  - Filling is slow enough that heat is lost to the container.

Isenthalpic Throttling

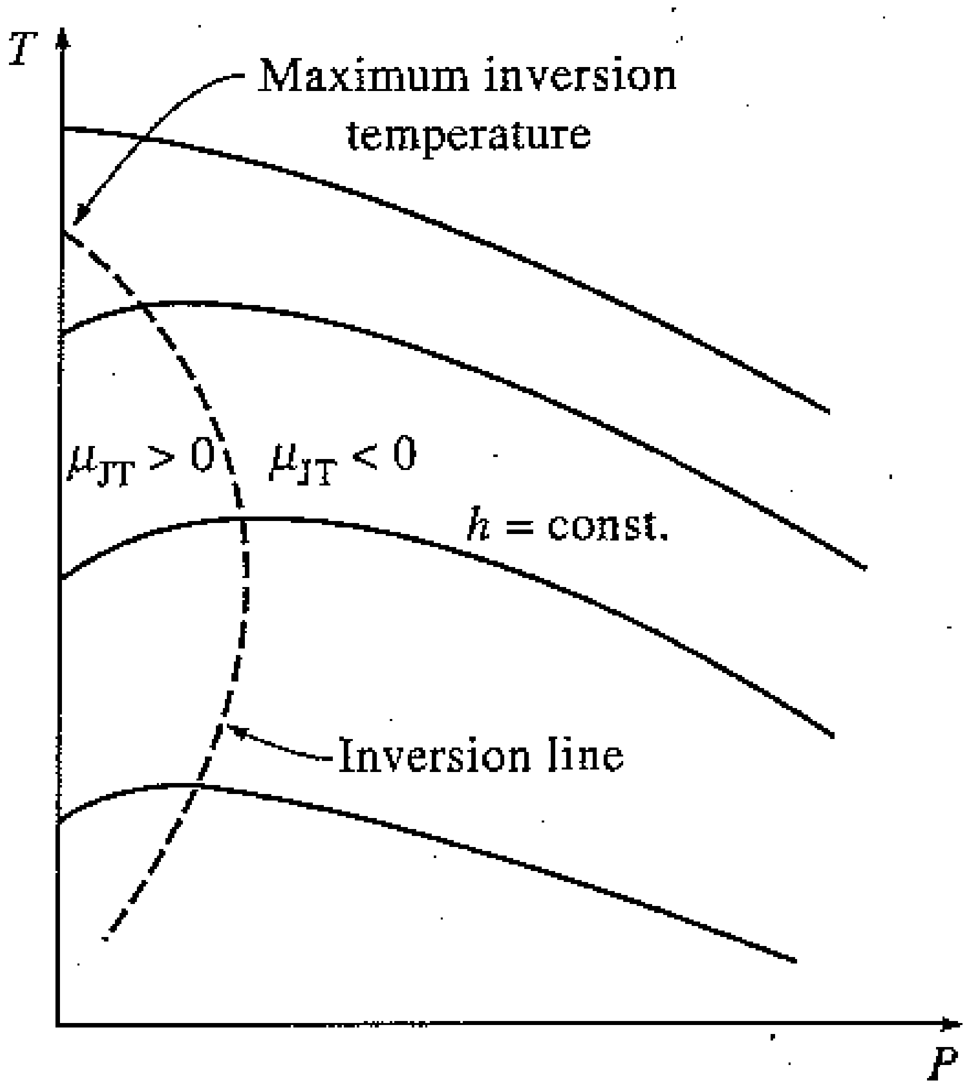
- Throttling is when gas flows through a restriction with no shaft work or increase of kinetic energy.
- Examples include flows through a porous plug, a capillary tube, or other long restriction.
- If there is no heat transfer, enthalpy is conserved.



Joule-Thompson Coefficient

- The T change of a throttling process is given by:

  $\mu_{JT} = (\partial T / \partial p)_h$ = Joule-Thompson coefficient.
- $\mu_{JT} = 0$ for ideal gases.
- H_2 is has a negative μ_{JT} when above –68 °C.
- For vehicle container conditions, μ_{JT} is about –0.5 K/MPa.
- H_2 throttling from 70 MPa to 2 MPa will increase its T by 34 °C.



SAE J2579

Hydrogen Detectors

- The traditional way to detect H_2 flames is with a straw broom.
- H_2 gas detectors can detect down to 15 ppm (molecular sieve).
- These require gas sampling and will not alert if flames consume the H_2.
- H_2 flame detectors can detect a H_2 flame of 50 mm from 30 m (UV/IR).
- Thermal imaging firefighting cameras are effective.

H2Scan Corp.
Hy-Alerta Model 500
$3750

Det-Tronics (UTC)
Model X3302

Hydrogen Vehicle Labeling

SAE J2578

Hydrogen Firefighting

- Listen for leaking gas.
- Look for white clouds near liquid hydrogen spills.
- Watch for heat shimmering.
- Use outstretched brooms, hydrogen detectors, and thermal imaging cameras.
- Prevent ignition sources (sparks, heat).

- In U.S. there are 30,000 fire departments and 1M firefighters, 75% of whom are volunteers.

Hydrogen Firefighting

- Stop the flow of hydrogen if possible.
- Otherwise, allow the flames to consume the entire gas supply when this can be done safely.
- Protect nearby objects and fuels.
- Extinguishing flames without stopping leaks can result in explosive mixtures.
- Use water or a dry powder extinguisher.

CNG Vehicle PRD Case Studies

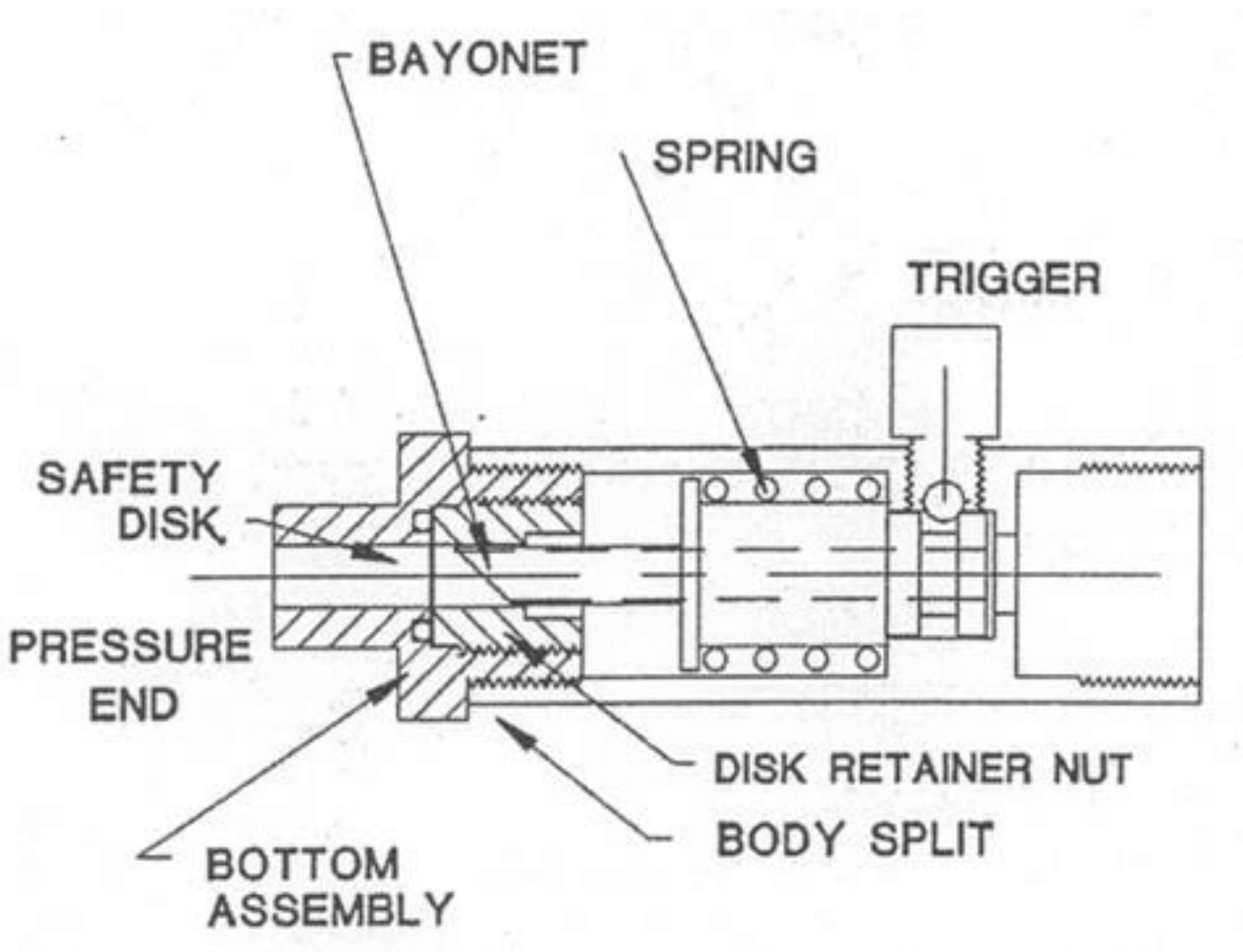
- CNG bus fires often involve safe venting by the PRDs.
- A CNG Ford Crown Victoria in a fire experienced a container rupture in 2003.
- A CNG Honda Civic ruptured in 2007 (below).

Seattle FD (2007).

Pressure Relief Devices

- CNG and Hydrogen vehicle containers require PRDs, primarily to protect against impinging fires.
- PRDs can be activated by pressure, temperature, or a combination.
- Most hydrogen, CNG, and propane containers are protected by temperature-activated PRDs.
- Modern composite tanks are good thermal insulators that weaken at high temperatures.
- Fuel pressure may not increase significantly during an impinging fire. A container may not be filled with fuel at the time of the fire.

Mirada Bayonet PRD



Rolander et al. (2003)

Microflame Scenario

- A small leak develops in a H_2 system, e.g., a H_2 vehicle.
- The leak could arise from H_2 embrittlement, H_2 permeation, impact, equipment failure, or improper repair.
- The leak ignites from static discharge or heat.
- The leak burns undetected for a long period, damaging the containment system and providing an ignition source for a subsequent large release.

Microflame Background

- Micro diffusion flames have been observed for microcombustor applications.
- Quenching and blowoff of CH_4 and C_3H_8 flames were measured and modeled by Matta et al. (2002) and Cheng et al. (2006).
- Schefer et al. (2006) analyzed H_2 leak rates for choked flow, subsonic laminar flow, and turbulent flow.

Microflame Objectives

- Measure quenching and blowoff limits for H_2, CH_4 and C_3H_8 on small round burners.

- Measure quenching limits for leaky compression fittings.

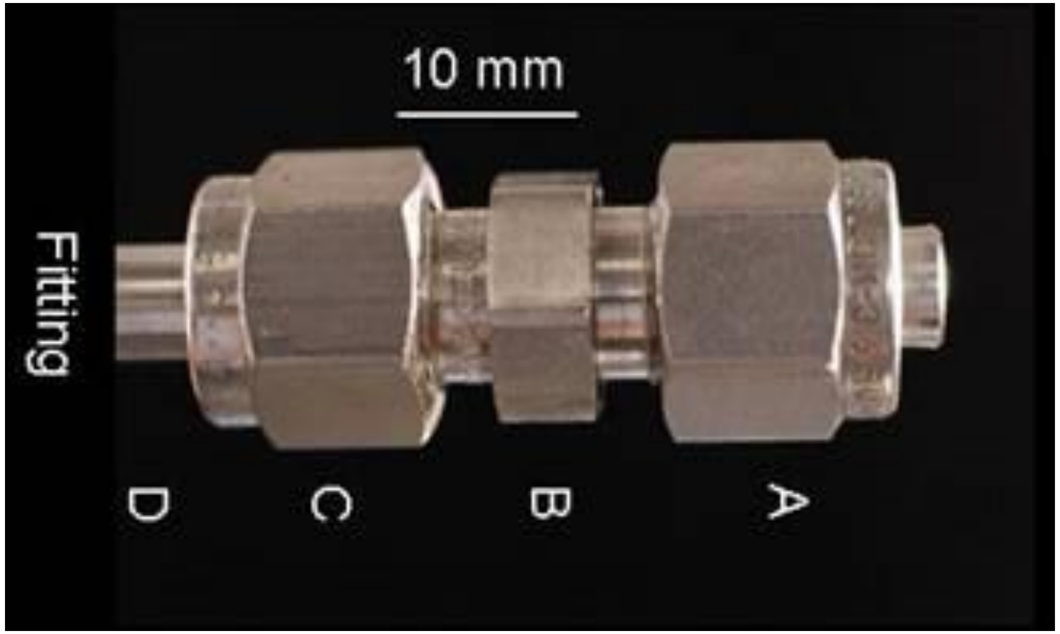
- Examine material degradation arising from exposure to H_2 and CH_4 flames.

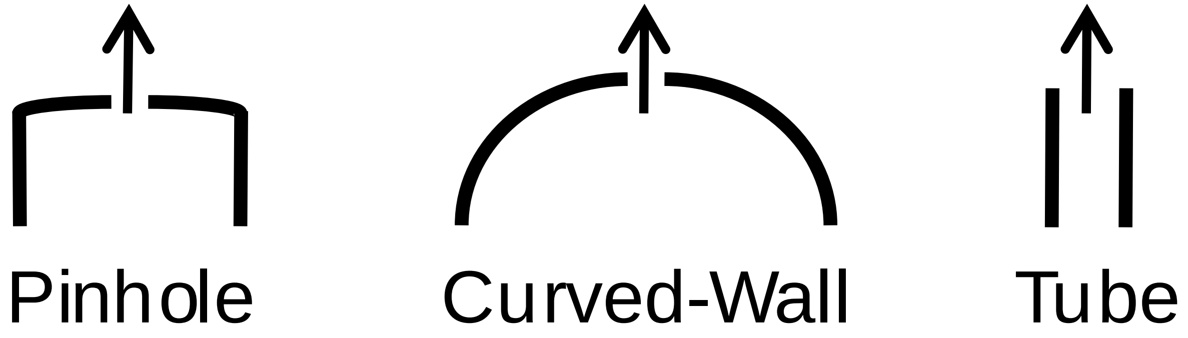
Experimental

- Quenching and blowoff limits
  - Fuels: H_2, CH_4, and C_3H_8
  - Diameters: 8 μm – 3.2 mm
  - Leaky compression fittings

Hole diameters in mm

Pinhole	Curved wall	Curved wall	Tube
0.008	0.41	0.41	0.051
0.13	0.53	1.75	0.152
0.36	0.74	2.46	0.406
0.53	0.86	3.12	0.838
0.71	1.02		1.194
0.84			2.21
1.01			
1.40			
1.78			
2.39			
3.18			



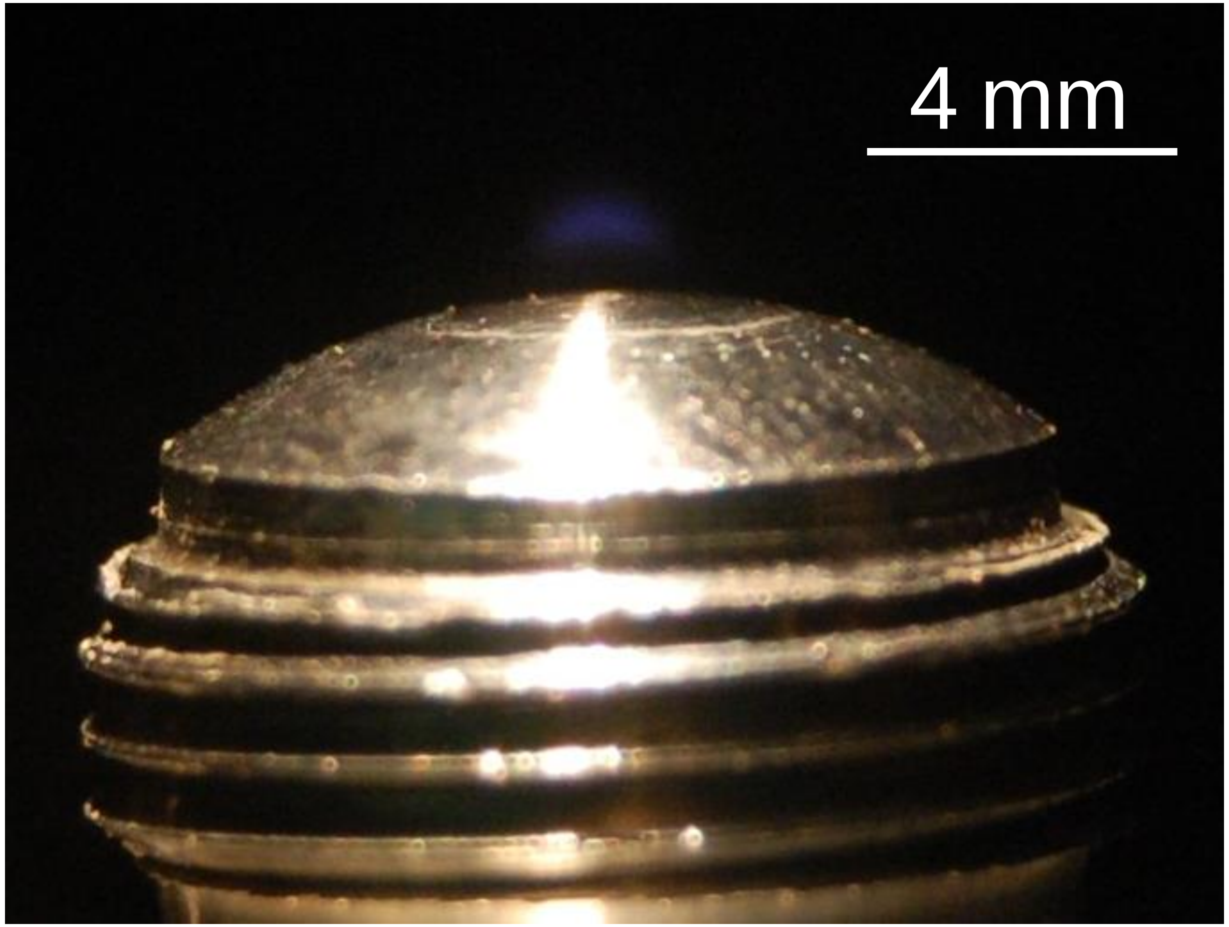


Quenching Scaling

Laminar flame length: $L_f / d = a \,\mathrm{Re} = 4\, m_{fuel}\, a / (\pi\ \mu\, d)$
Length at quenching: $L_f = L_q / 2$
Equating these: $m_{fuel} = \pi\, L_q\, \mu / (8\, a)$

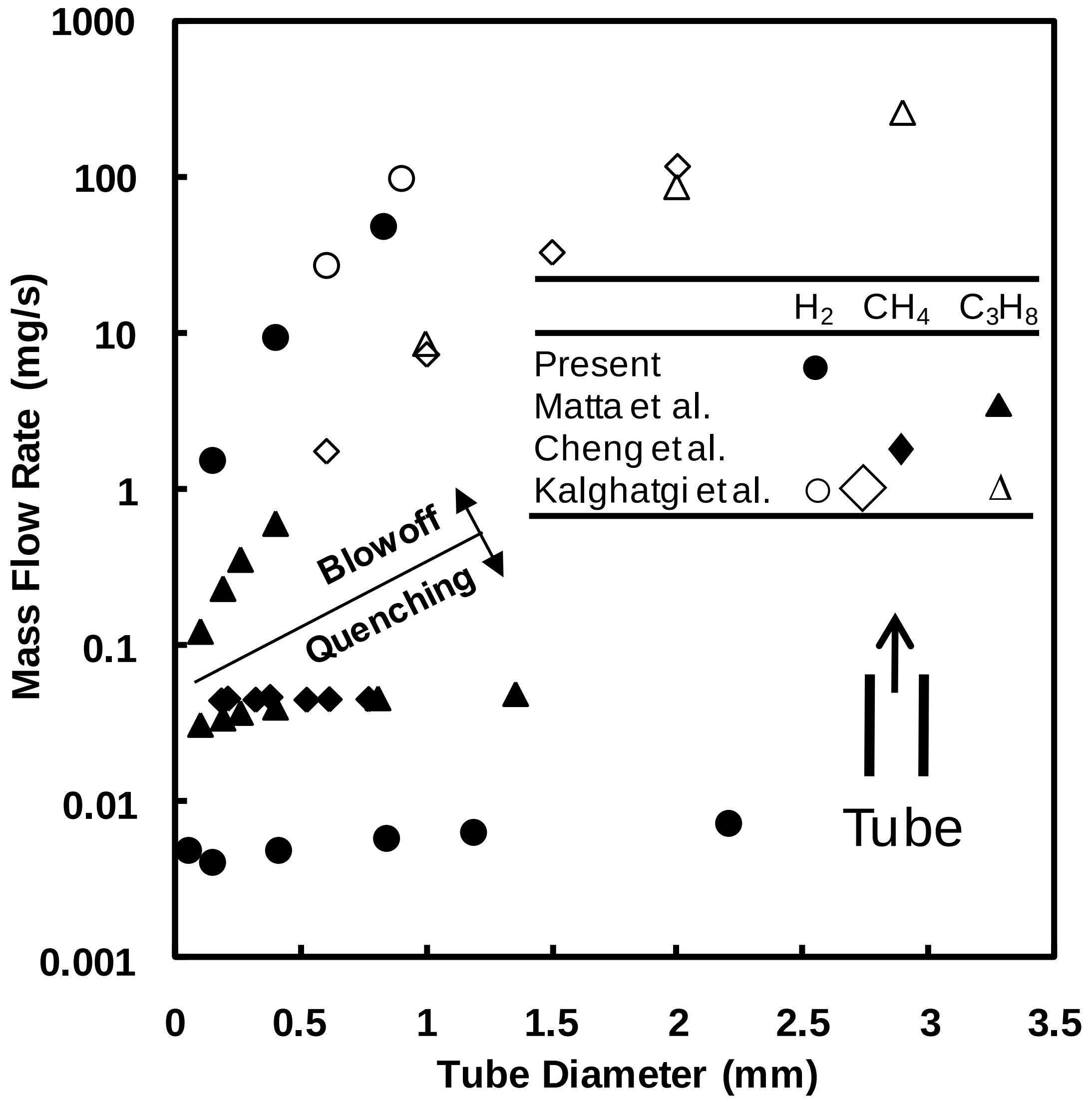
Fuel	a	L_q (mm)	S_L (cm/s)	μ (g/m-s)	m_{fuel} (μg/s)
H_2	0.236	0.51	291	8.76E-3	8
CH_4	0.136	2.3	37.3	1.09E-2	85
C_3H_8	0.108	1.78	42.9	7.95E-3	63

H_2 Pinhole Quenching Limit



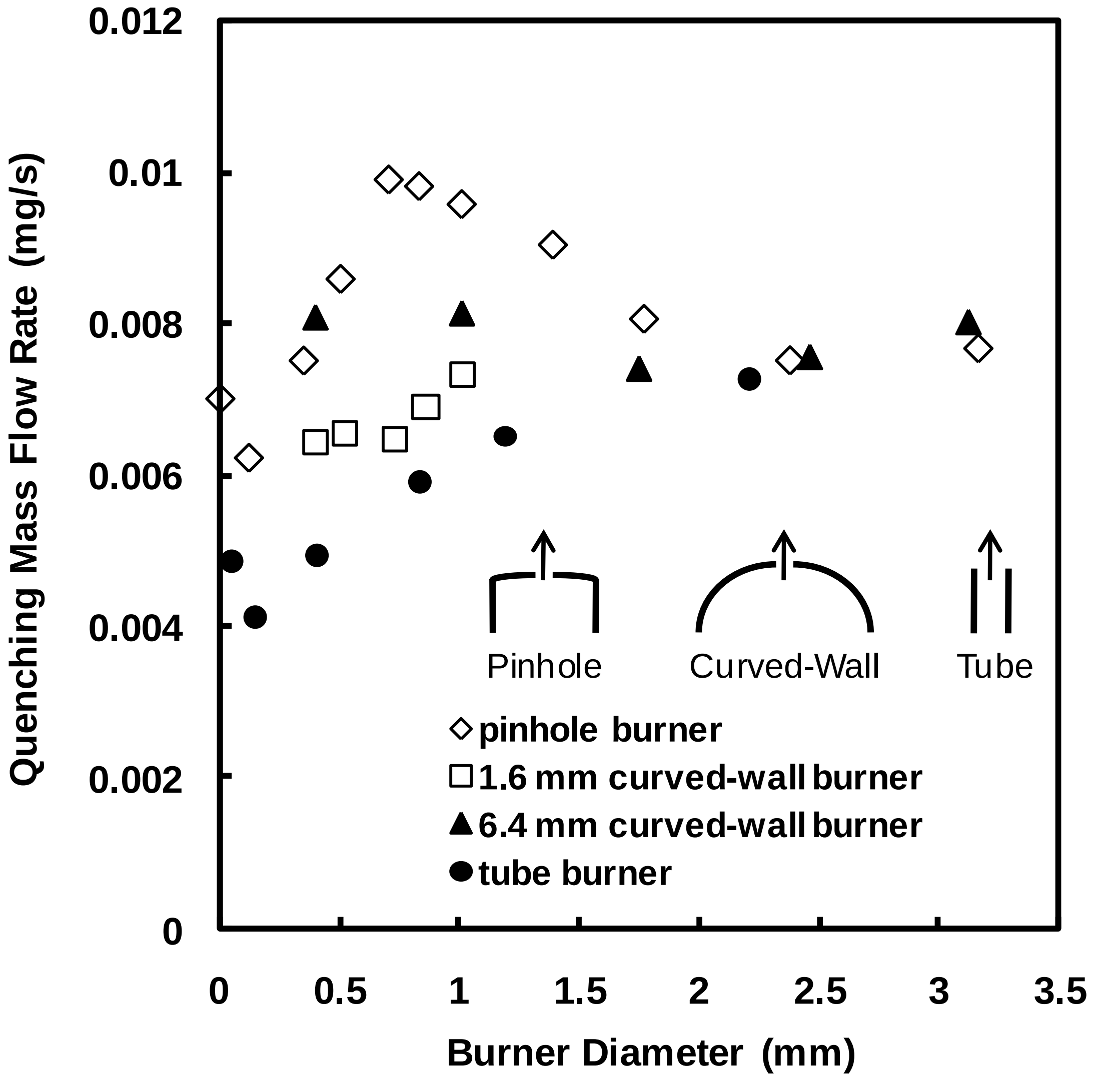
- A H_2 flame at its quenching limit is shown.
- This flame is not visible to the eye and required a 30 s camera exposure.
- Stand-off height is 0.25 mm.
- Thermocouples identified flaming.

Tube Burner Quenching and Blowoff Limits



- Quenching limits are nearly independent of *d*.
- H_2 has the lowest quenching limit and the highest blowoff limit.
- CH_4 and C_3H_8 have similar quenching and blowoff limits.

Pinhole Burner H_2 Quenching Limits



- Three burner types are shown.
- For large *d* the limits converge.
- Heat losses are highest for pinholes, lowest for tube burners.
- Limits increase at the smallest *d*.

SAE J2579 Leak Limits

Localized leaks must not be capable of supporting a flame.

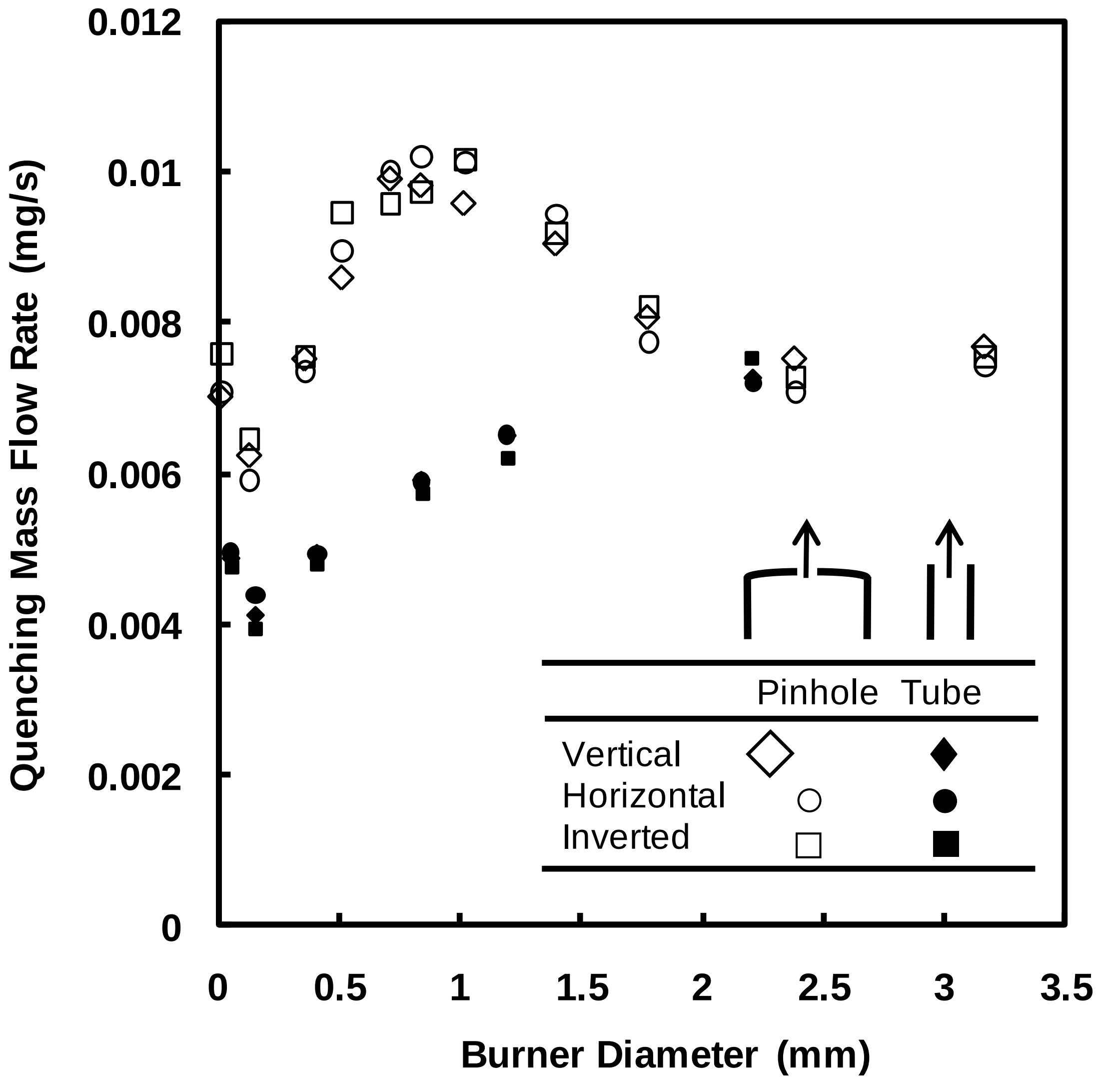
The maximum localized leak rate is 5 µg/s (i.e., 3.6 sccm).

This equates to about 33 bubbles/s under water.

Total system leakage is limited to 150 sccm.

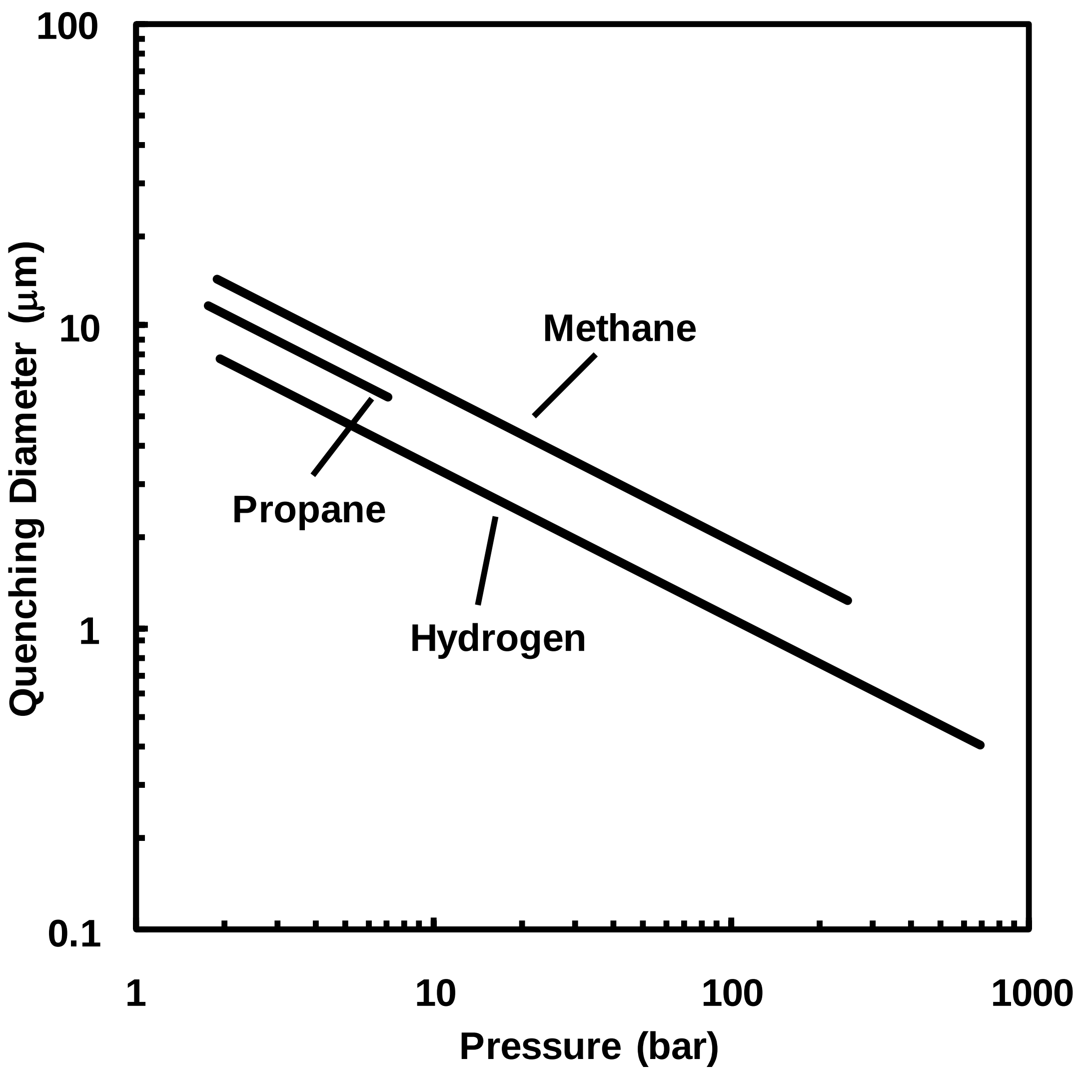
SAE J2579, Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

Orientation Effects



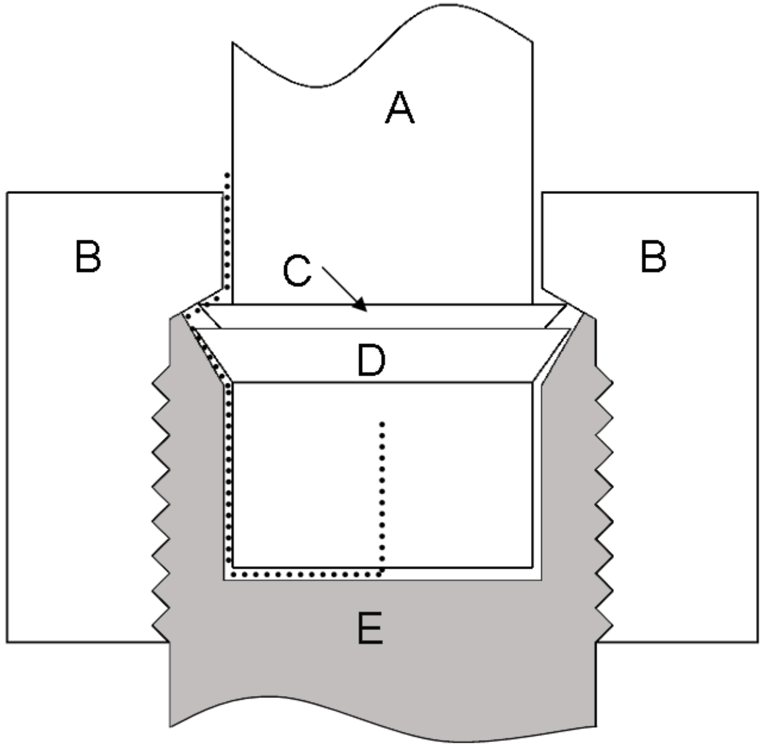
- H_2 quenching limits generally increase with burner diameter owing to heat losses.
- Inverted limits are lowest, attributed to fuel preheating and flame anchoring.
- This plot helped identify the world's weakest flame.

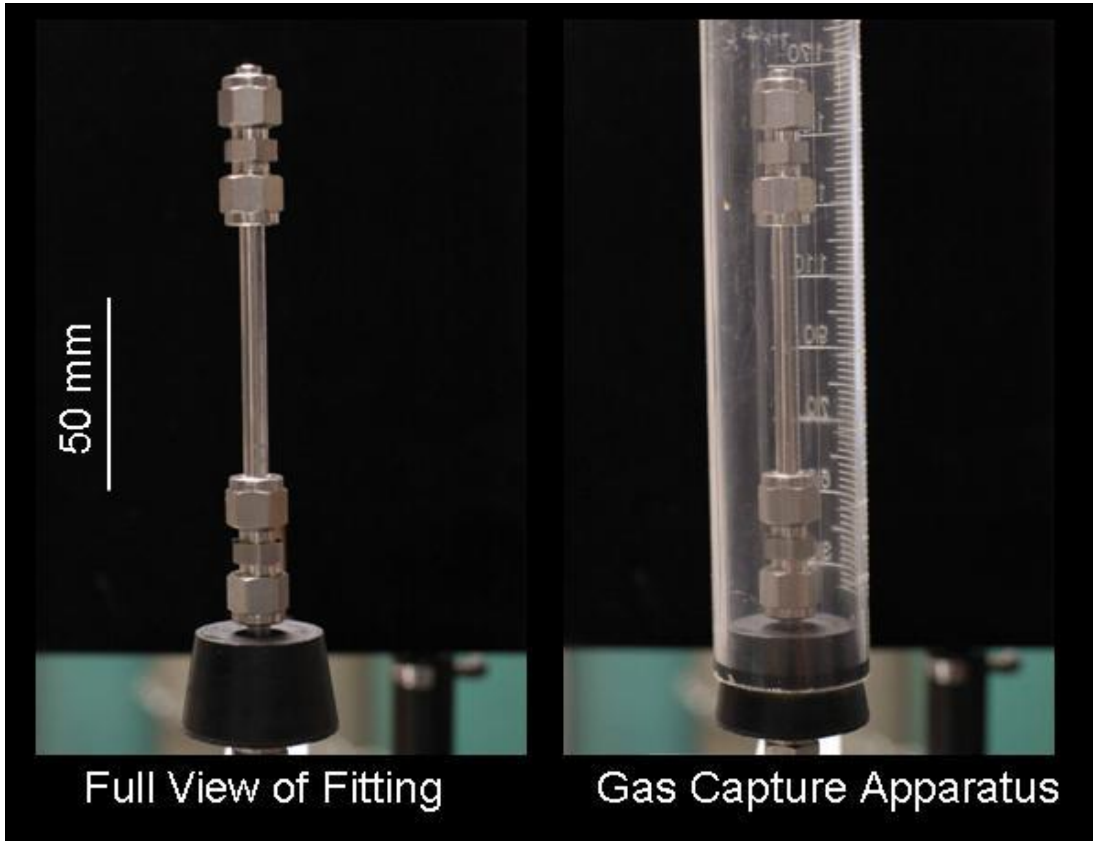
Minimum Hole Size for Flaming



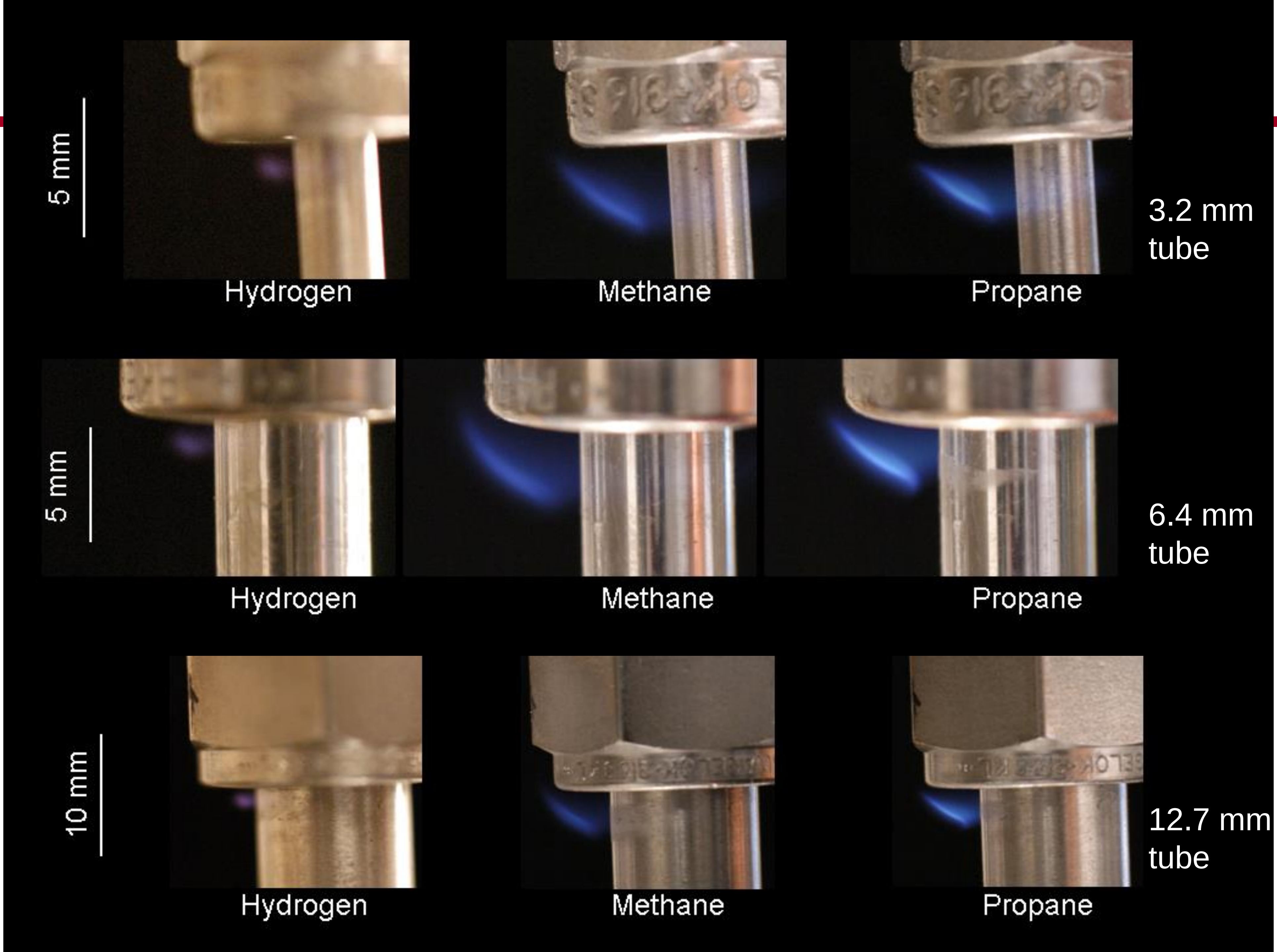
- Upstream pressure required for 5.6 μg/s H_2 isentropic choked flow is shown.
- For H_2 at 70 MPa, any hole larger than 0.4 μm will support a stable flame.

Leaky Fittings Tests

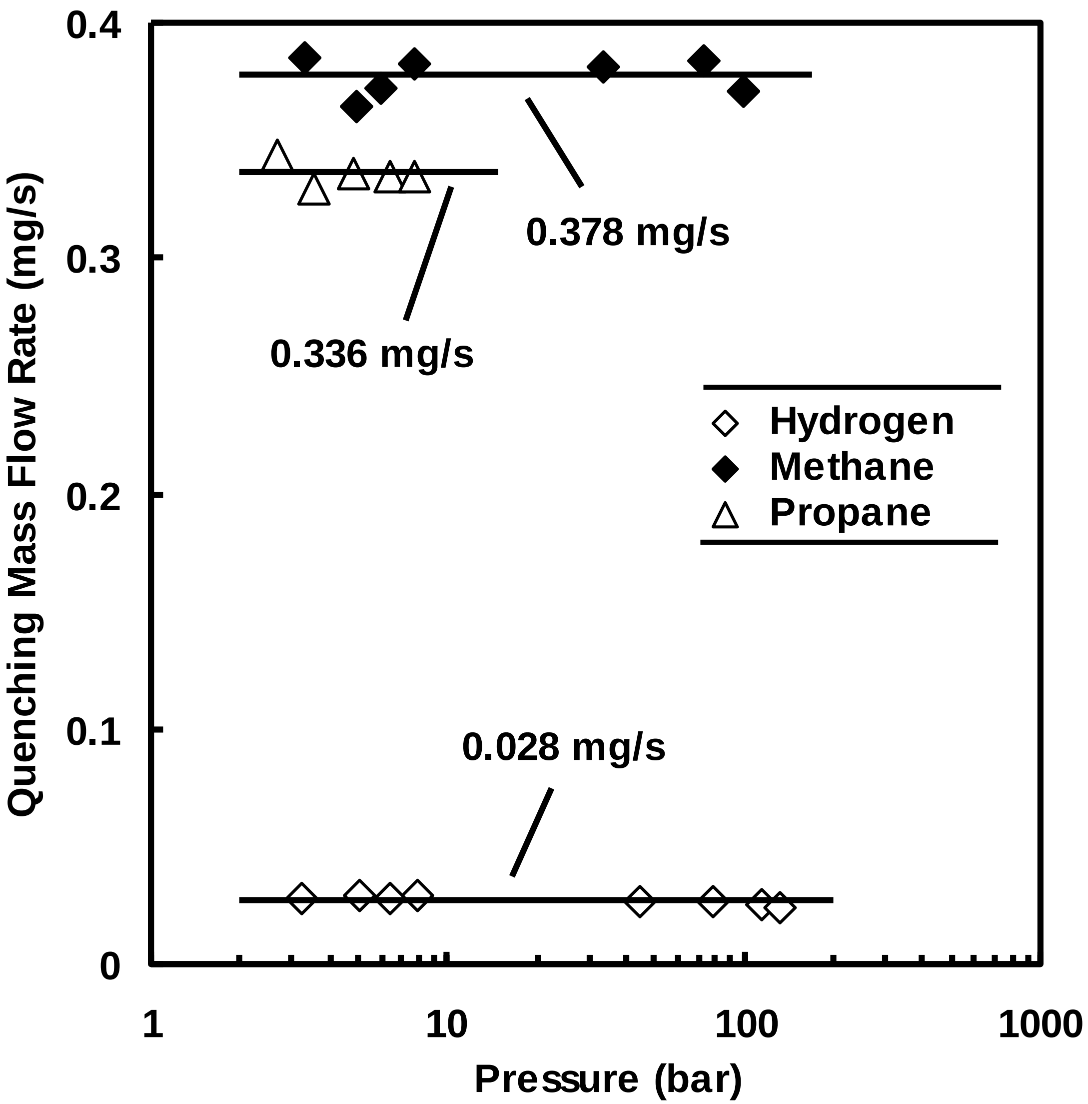




- Leak path for loose fittings.
- Flow rates were measured downstream of the leaks.


5 mm
Hydrogen
Methane
Propane
3.2 mm tube
5 mm
Hydrogen
Methane
Propane
6.4 mm tube
10 mm
Hydrogen
Methane
Propane
12.7 mm tube

Upstream Pressure Effects

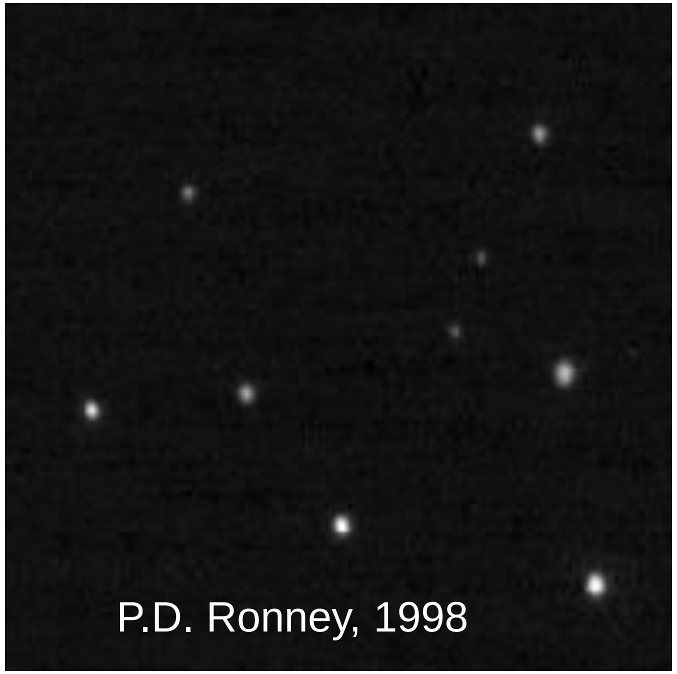


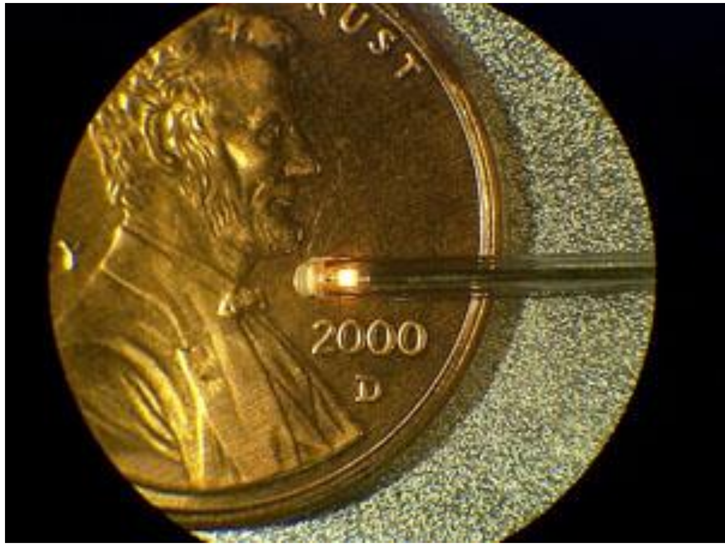
- Quenching limits for a 6 mm compression fitting are shown.
- Limits are independent of pressure.
- Limits are about 10X those of tube burners.
- H_2 limits are the lowest.

World's Weakest Flames

- Ronney et al. (1998) observed $H_2/O_2/CO_2$ SOFBALL flames with HRR as low as 0.5 - 1 W.

- Microcombustors can benefit from high turndown ratios and weak flames that remove the need for ignitors.

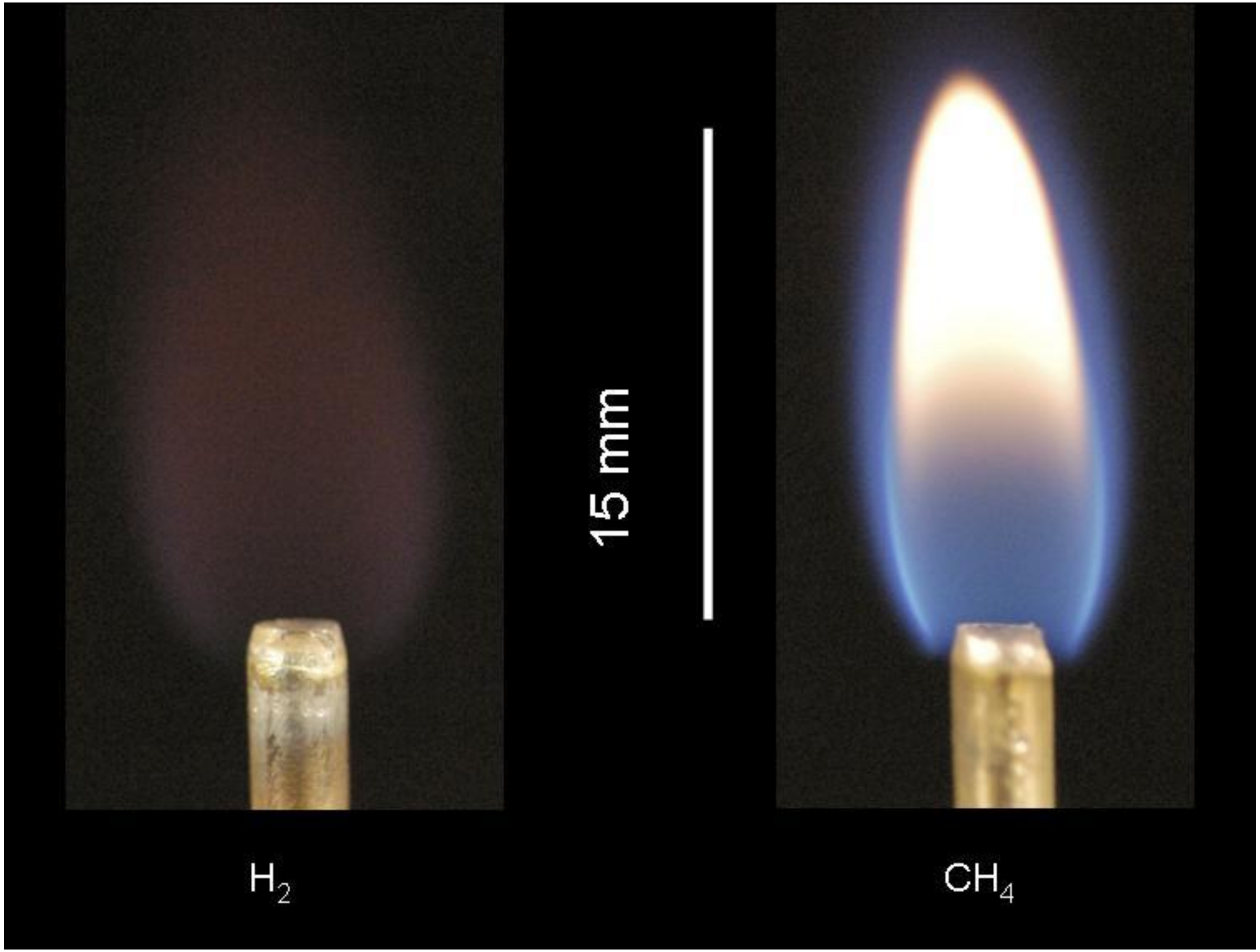




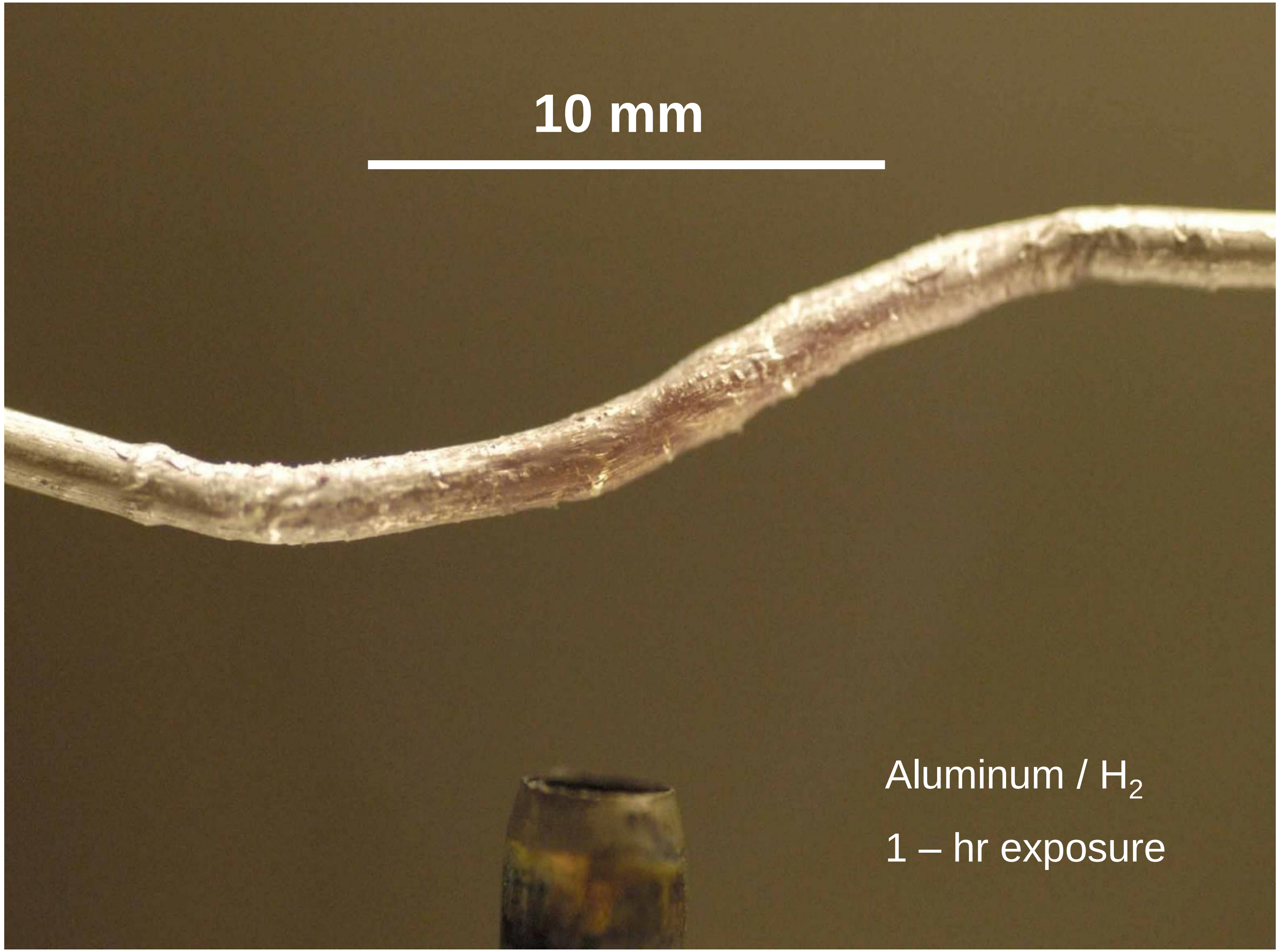
Weakest Flames

- At left is H_2 flowing downward into air (3.9 μg/s, 0.46 W).
- At right is H_2 flowing downward into O_2 (2.1 μg/s, 0.25 W).
- The tube inside and outside diameters are 0.15 and 0.30 mm.
- The exposure time was 30 s.

Materials Degradation

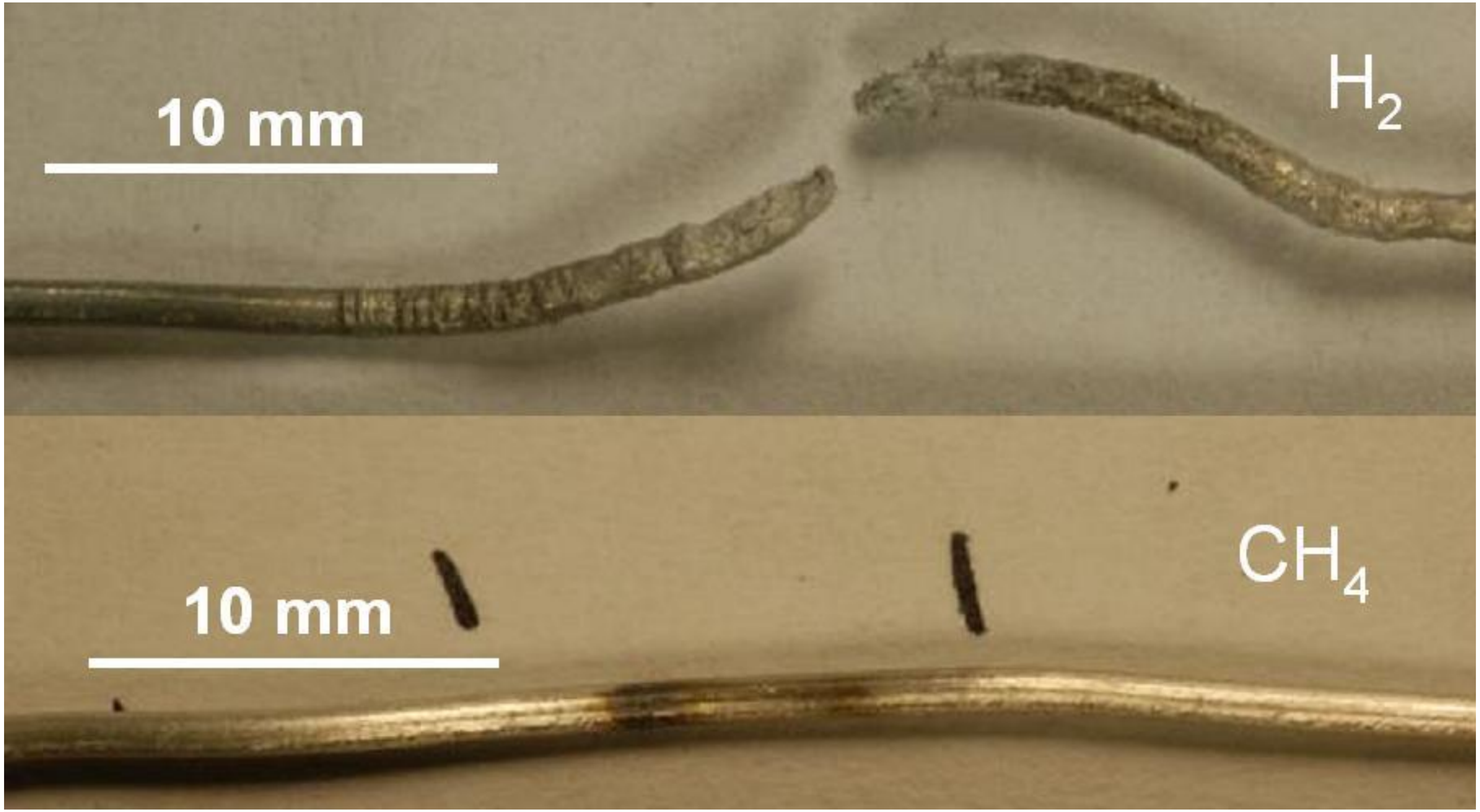


Al Degradation



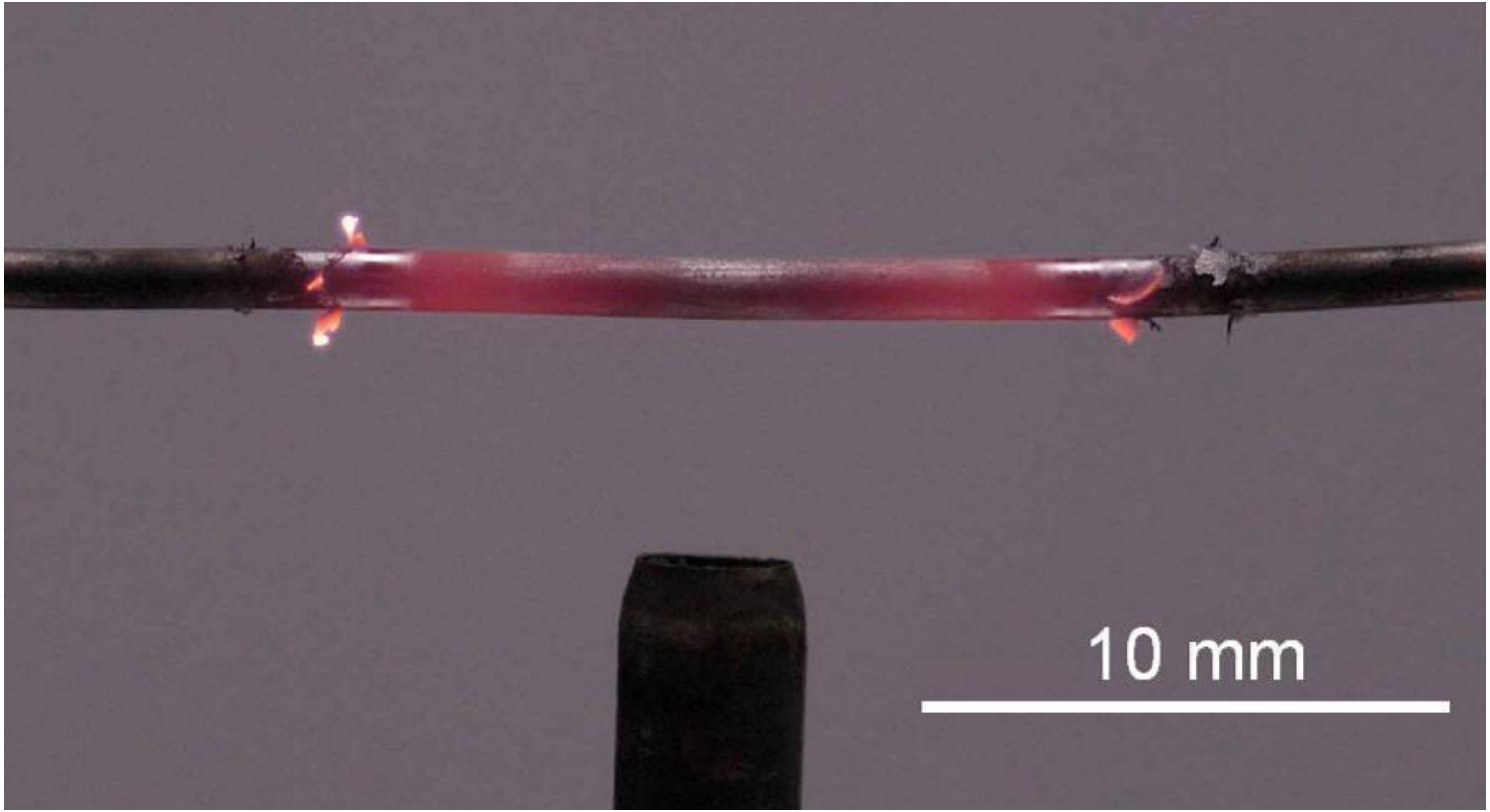
Al Degradation

- Aluminum failed in H_2 flame at 8 hours.



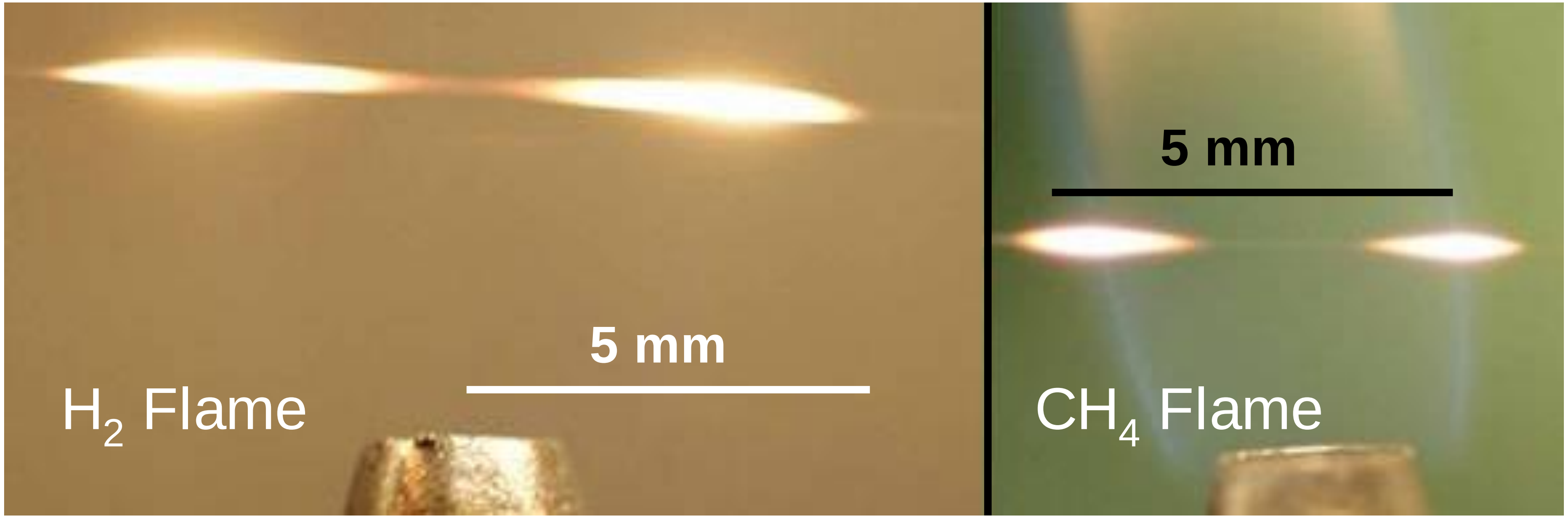
304 SS Degradation

- Corrosion after prolonged H_2 flame exposure.



SiC Degradation

- SiC filaments failed at 12 minutes in the H_2 flame, and at 356 minutes in the CH_4 flame.



Possible Mitigation Strategies

- Intumescent paints

- Steel wool or ceramic blankets

- Flame detectors:
  - Cable heat detectors
  - UV and IR detectors

Summary

- In the US there are 3,500 fire deaths annually, 10% of these in vehicles.

- We understand and accept the risk of gasoline and diesel vehicles with 4 mm thick HDPE containers.

- Hydrogen vehicles present different fire hazards. More research is needed for these to be understood.