Fire Hazards of Small Hydrogen Leaks

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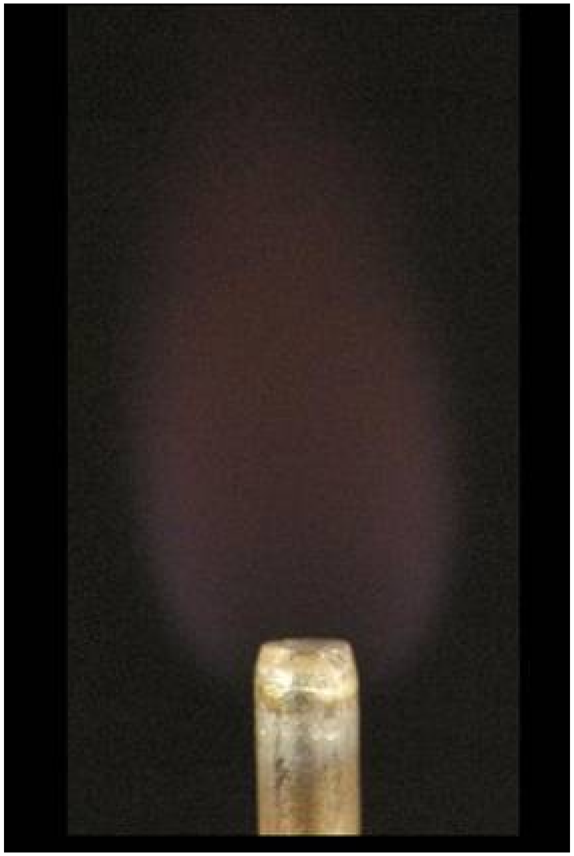

Acknowledgments

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

Unique Fire Hazards of H_2

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

- Smallest ignition energy of any fuel in air (0.028 mJ)
- Lowest autoignition temperature of any fuel ignited by a heated air jet (640 °C)

- Widest flammability limits of any fuel 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)

- Dimmest flames of any fuel in air

Present Fire 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.

Background

- Swain and Swain (1992) modeled and measured H_2, CH_4, and C_3H_8 leak rates.

- 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).

- Khan et al. (2002) considered the effects of heat on carbon fabric composites.

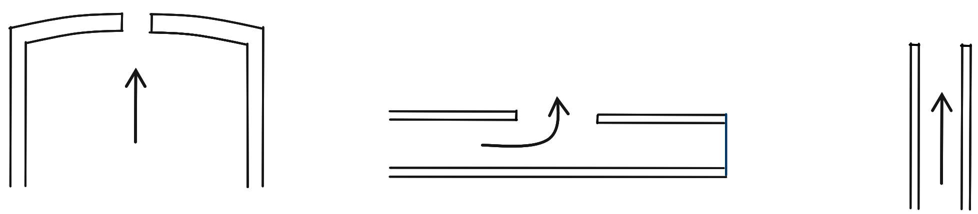
- No codes or standards exist for permissible H_2 leak rates.

Objectives

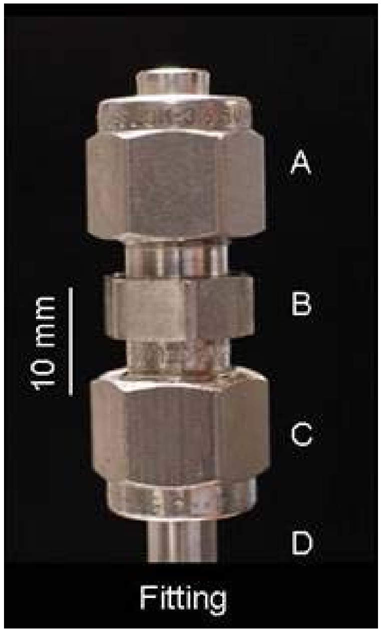
- Measure quenching and blowoff limits for H_2, CH_4 and C_3H_8 on small round burners.
- Measure quenching limits for leaky compression fittings.
- Examine material degradation arising from exposure to H_2 and CH_4 flames.

Experimental

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



Pinhole Burner | Curved-wall Burner | Tube Burner



- Materials degradation
  - Fuels: H_2 and CH_4
  - Materials: aluminum alloy 1100, galvanized steel, stainless steel, SiC
  - Test times: up to 300 hours

Quenching Scaling

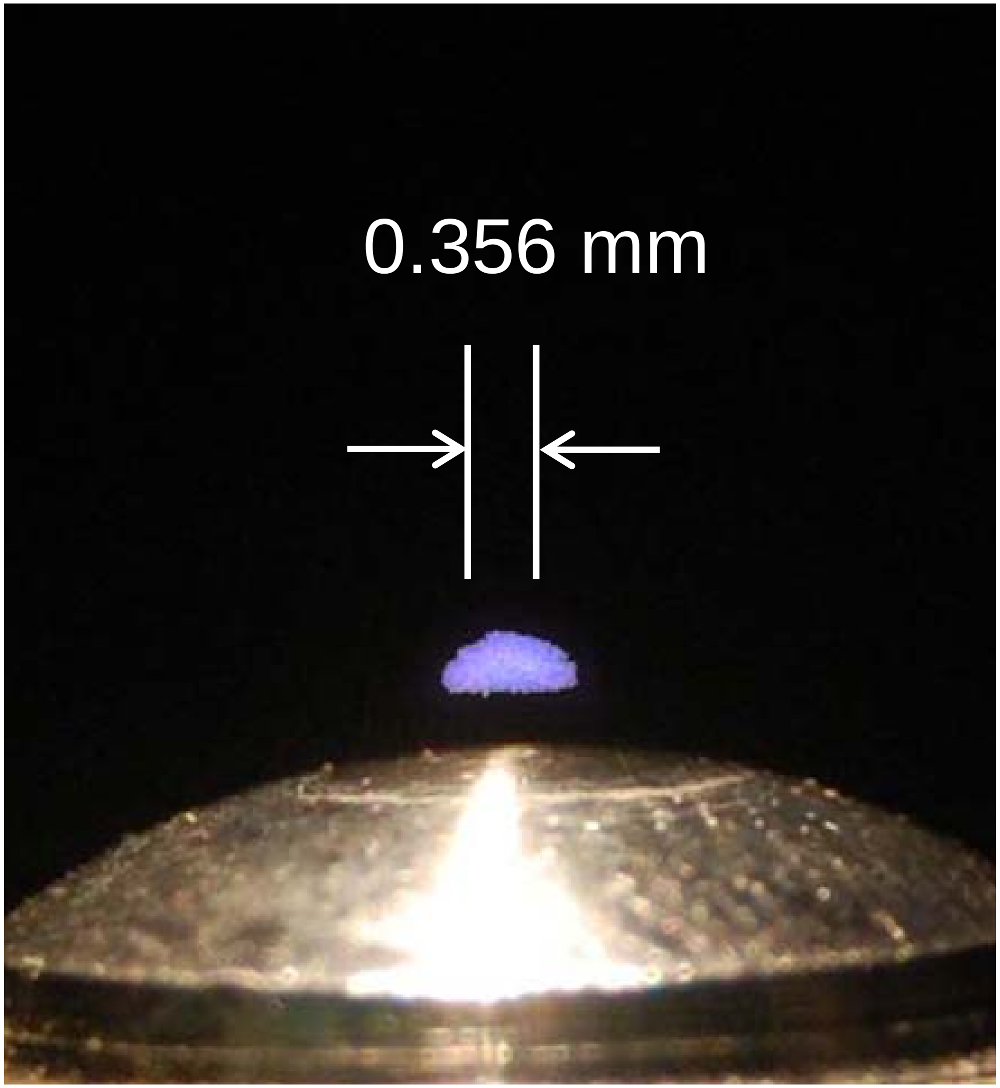
Flame length: $L_f / d = a\, Re = a\, \rho\, u_0\, d / \mu$

Length at quenching: $L_f = L_q / 2$

Equating these: $m_{fuel} = \pi\, L_q\, \mu / (\, 8\, a\,)$

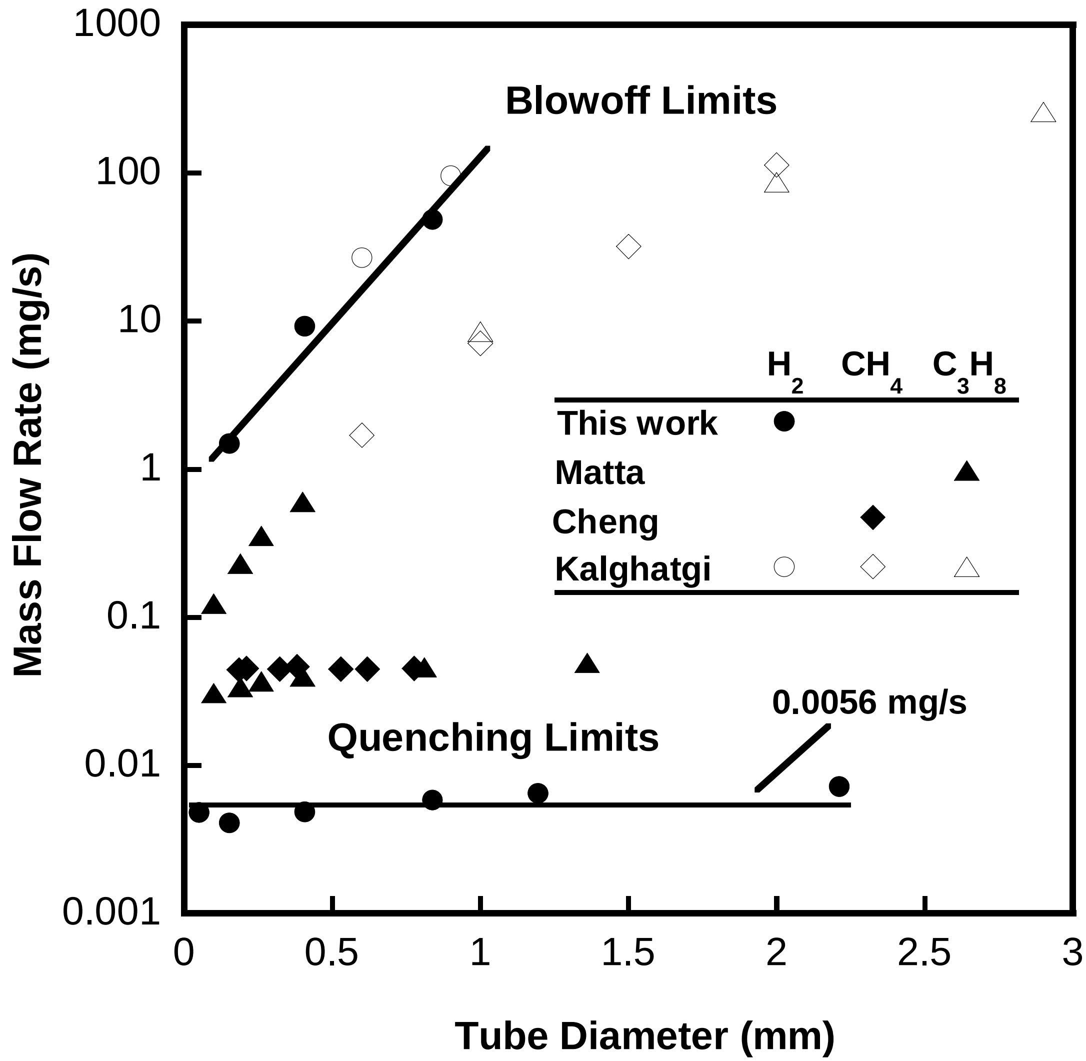
Fuel	a	L_q [mm]	S_L [cm/s]	μ [g/m-s]	m_{fuel} [mg/s] predicted
H_2	0.236	0.51	291	8.76e-3	0.008
CH_4	0.136	2.3	37.3	1.09e-2	0.085
C_3H_8	0.108	1.78	42.9	7.95e-3	0.063

H_2 Pinhole Quenching Limit



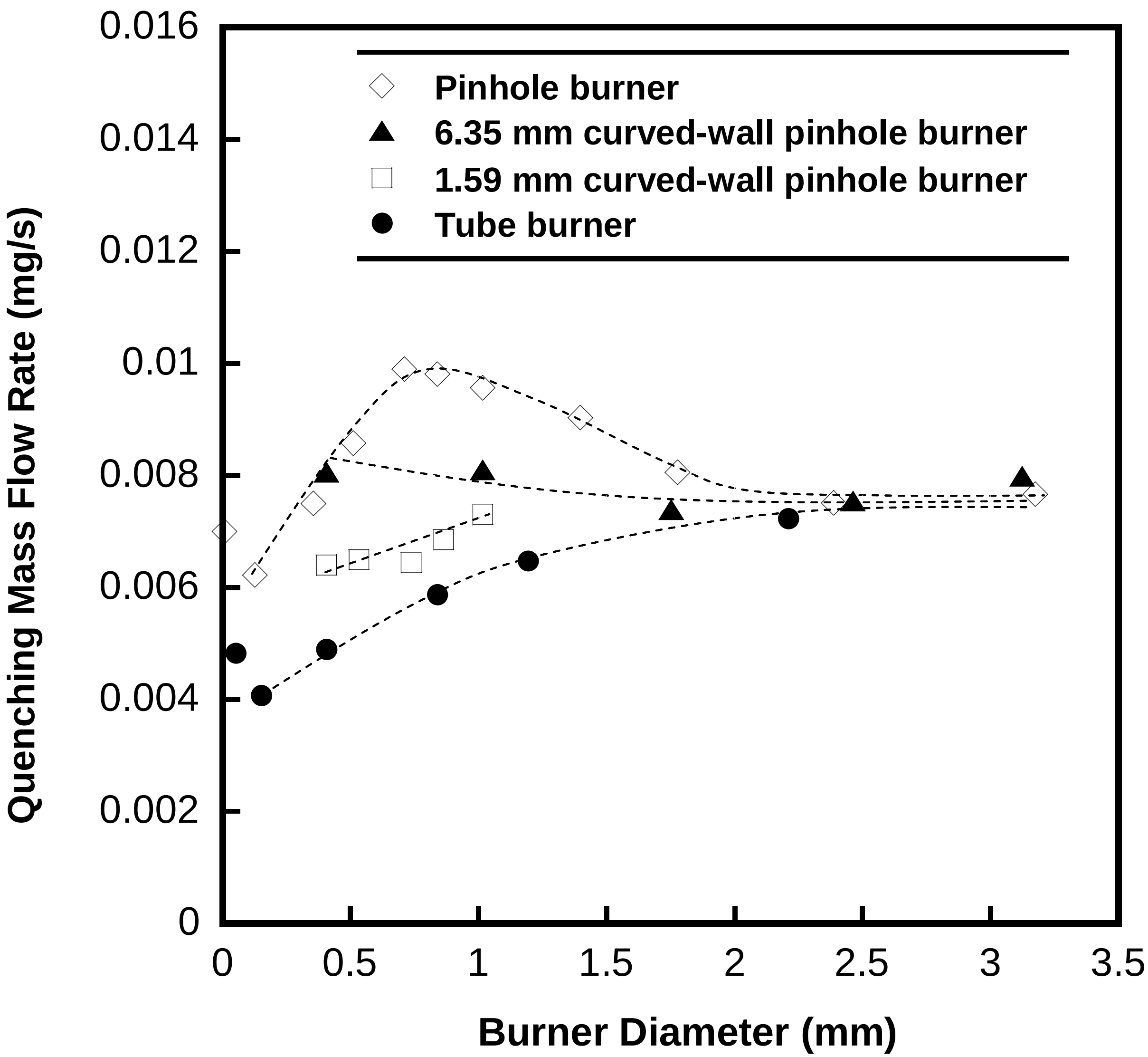
- A H_2 flame at its quenching limit is shown.
- This flame is not visible without aid and required 30 s camera exposures.
- Stand-off height is about 0.25 mm.
- Thermocouples were used to identify flaming conditions.

Tube Burner Limits



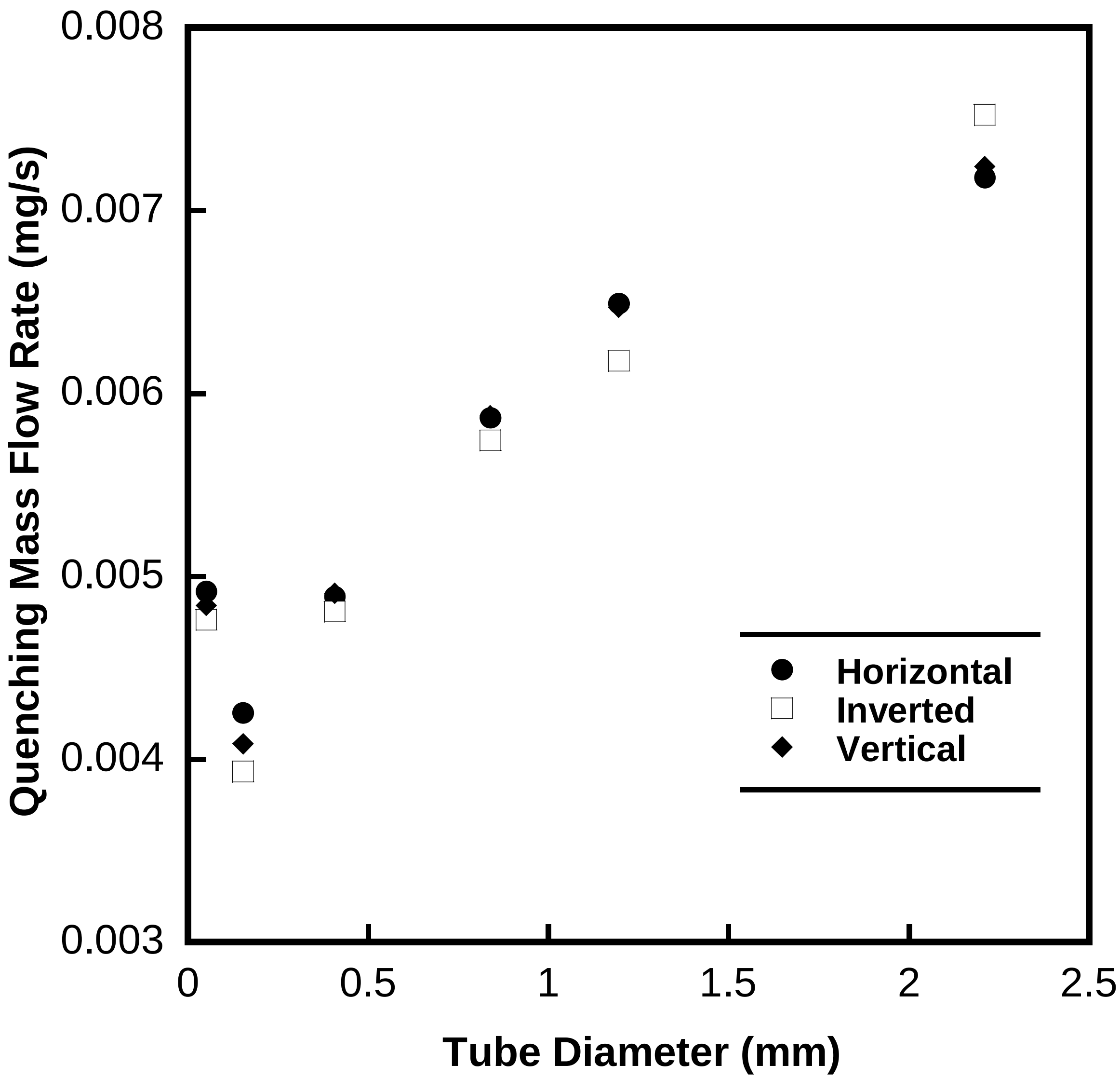
- Quenching limits are nearly independent of *d*.
- H_2 has the lowest quenching limit and the highest blowoff limit.
- CH_4 and C_3H_8 have similar quenching and blowoff limits.

H_2 Quenching Limits



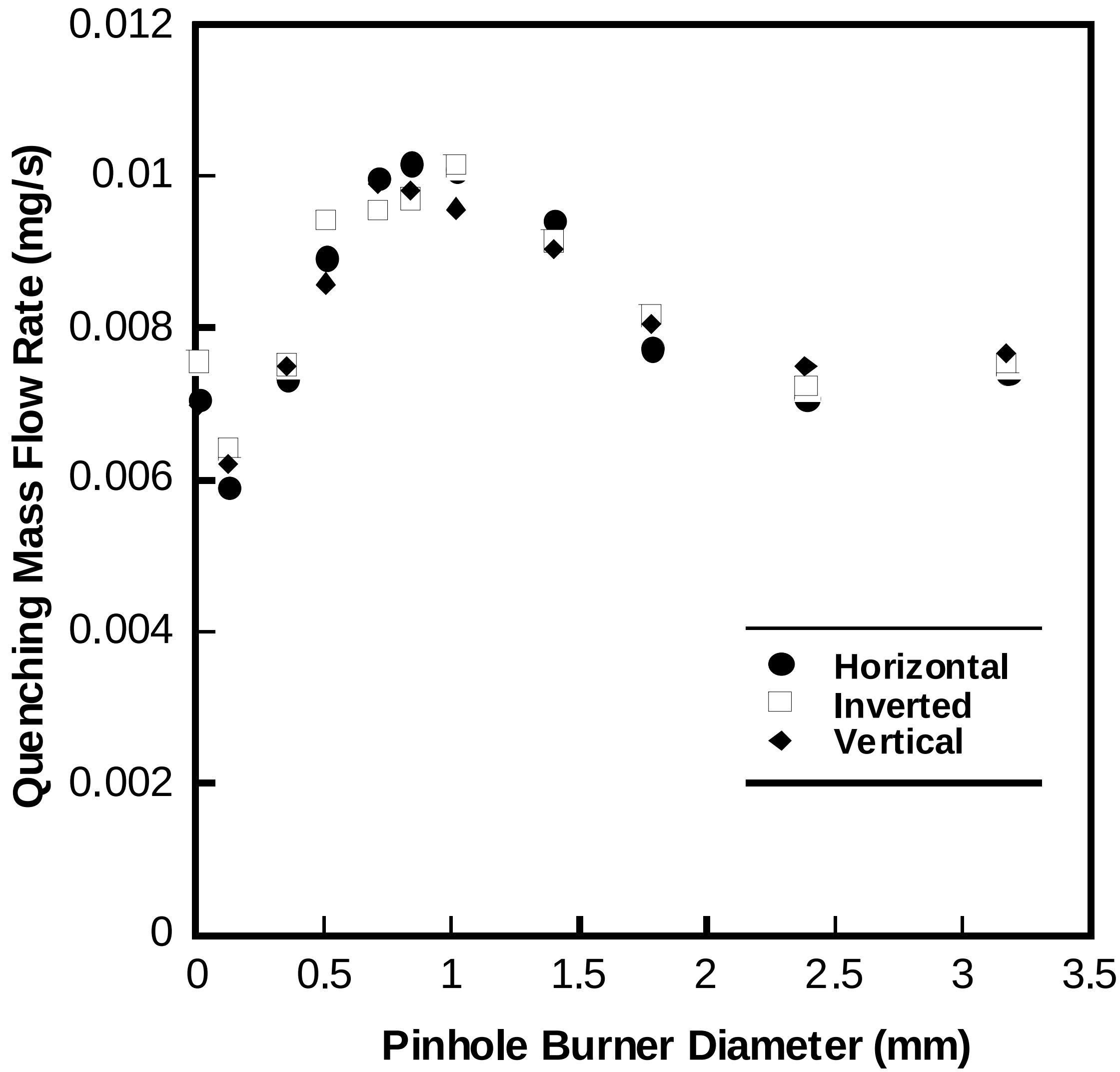
- Three burner types are shown.
- For large *d* the limits converge.
- Heat losses are greatest for pinholes, least for tube burners.
- Limits increase at the smallest *d*.
- This plot helped identify the world's weakest flame (0.25 W).

Tube Burner Orientation Effects



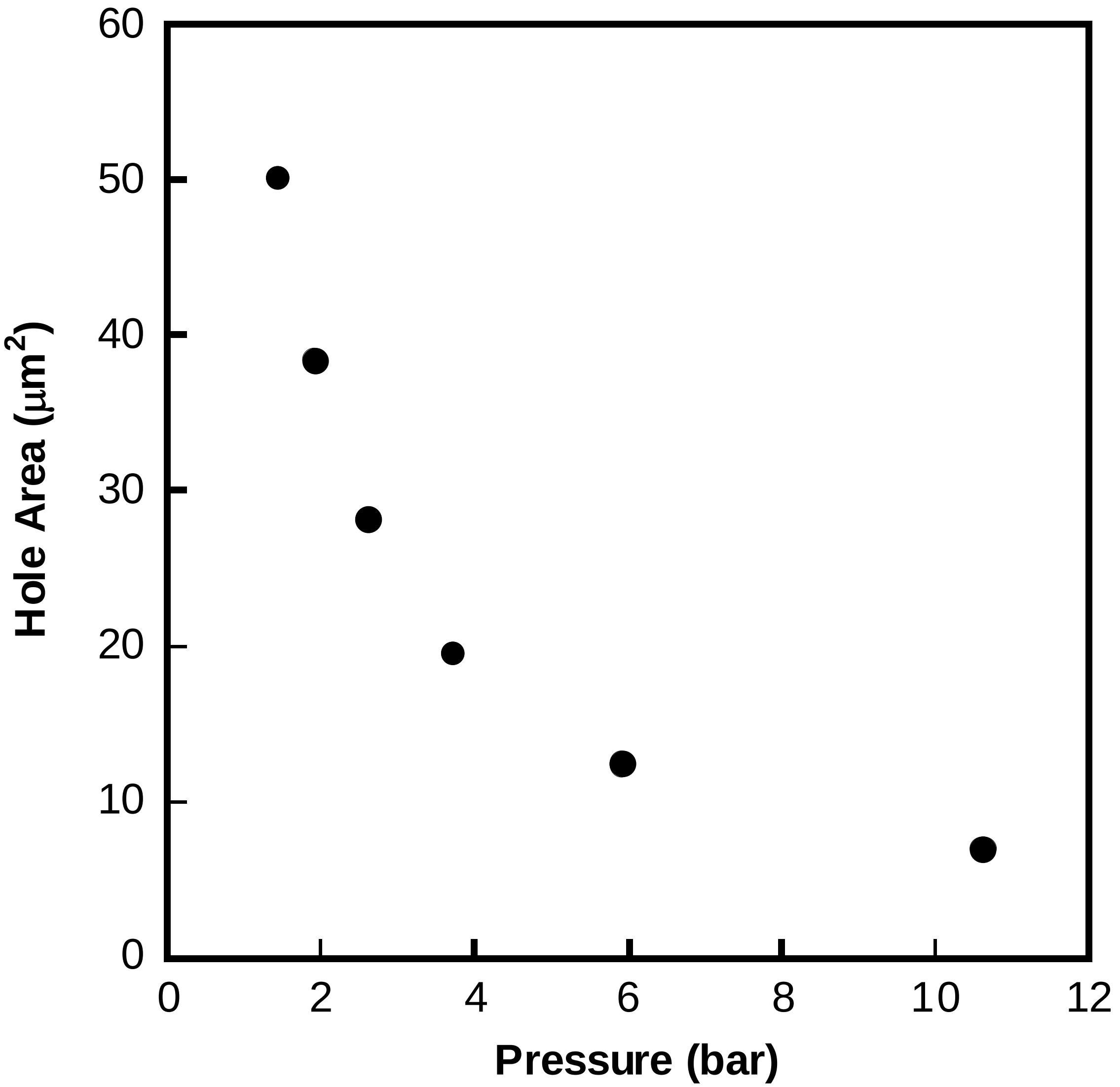
- H_2 quenching limits generally decrease for small burners owing to heat losses.
- Inverted limits are lowest, attributed to fuel preheating and flame anchoring.

Pinhole Burner Orientation Effects



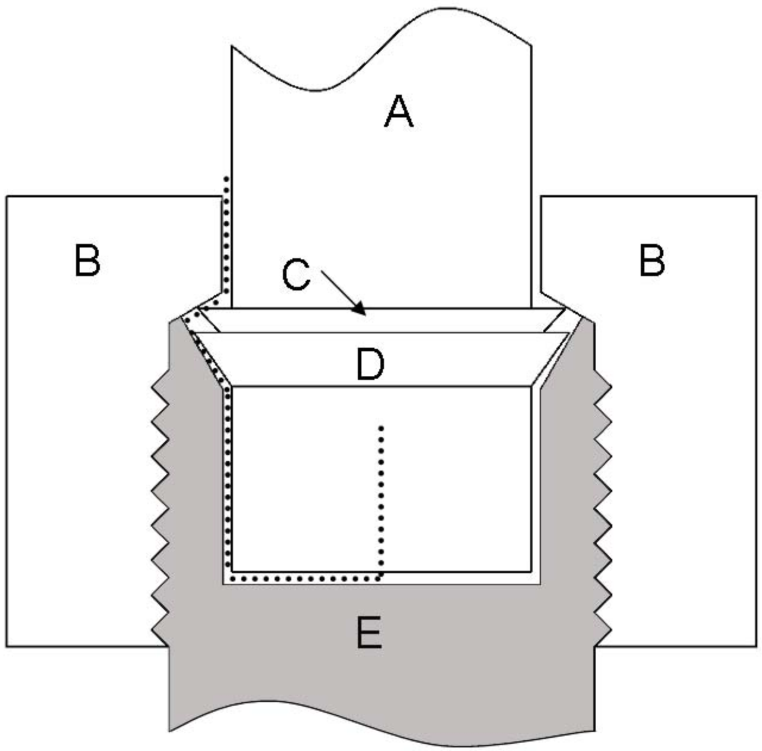
- No significant effect of orientation is seen.
- Choked flow is likely at the smallest diameter.

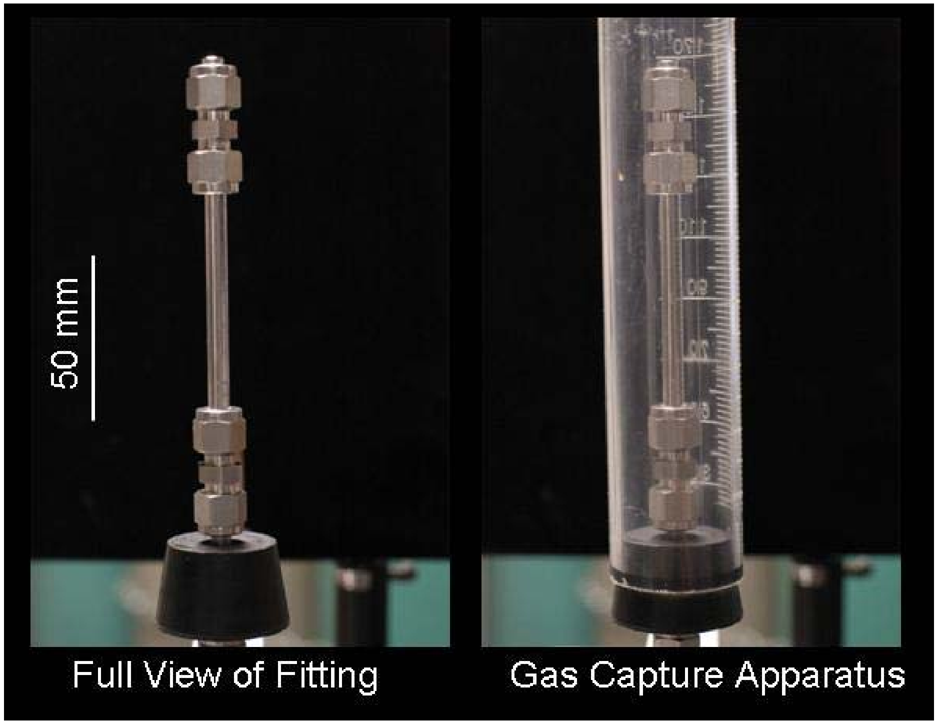
Upstream Pressure Effects



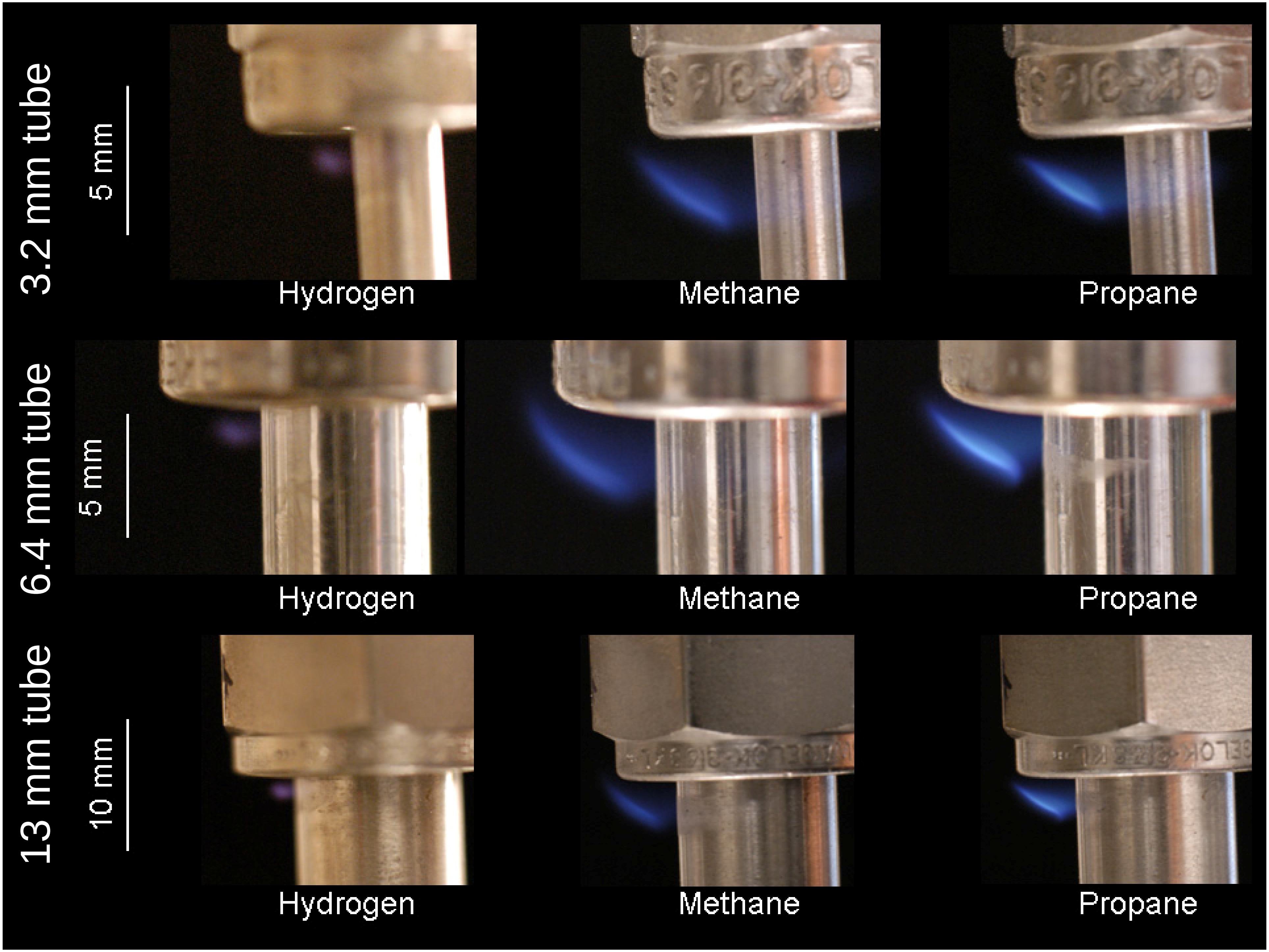
- Upstream pressure required for 8 μg/s H_2 isentropic choked flow is shown.
- Viscous effects are neglected here.
- This predicts that very small pinholes can support flames in high pressure H_2 systems.

Leaky Fittings Tests

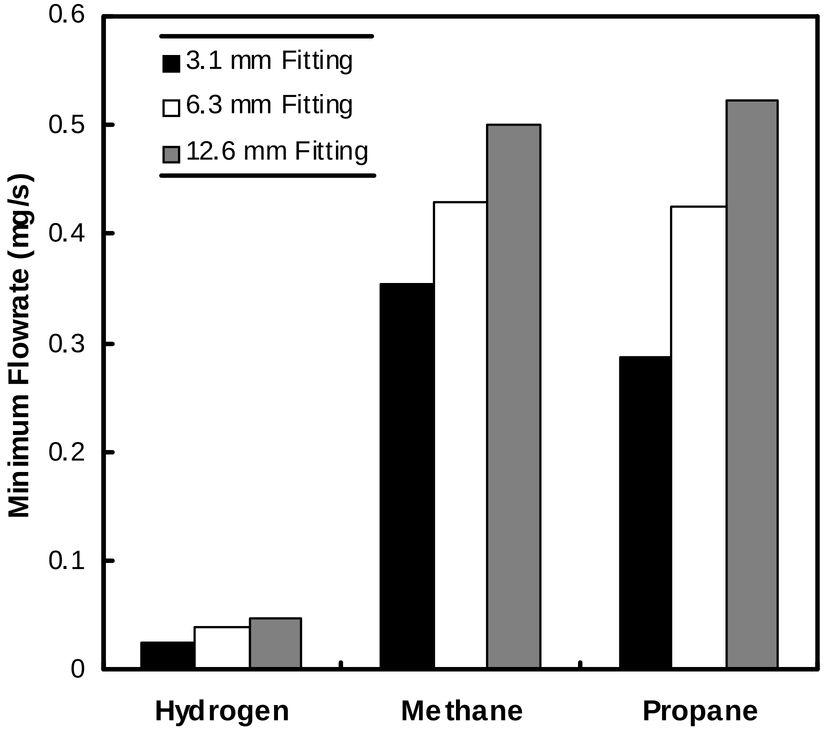




- Leak path shown obtained with loose fittings.
- Flow rates were measured downstream of the leaks.

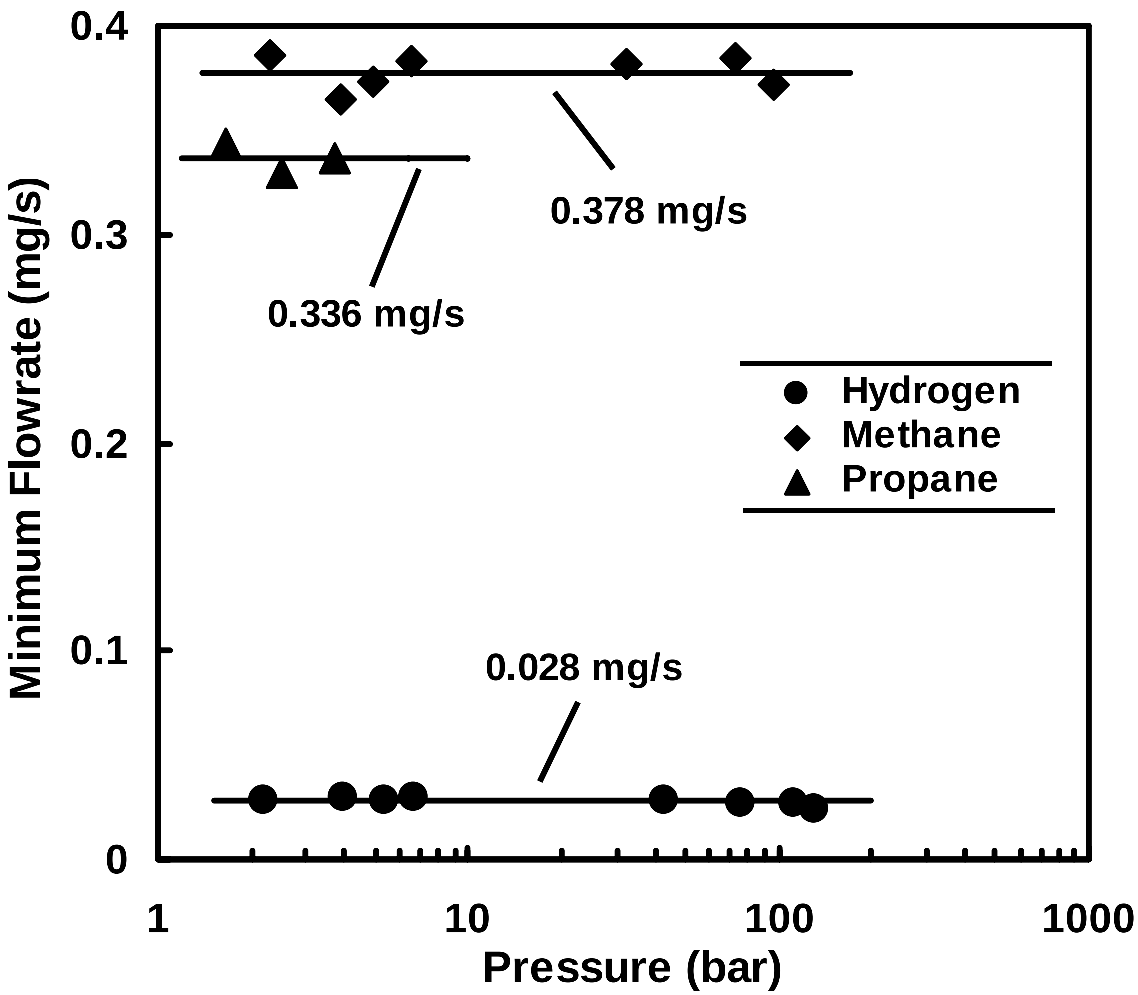

3.2 mm tube
5 mm
Hydrogen
Methane
Propane
6.4 mm tube
5 mm
Hydrogen
Methane
Propane
13 mm tube
10 mm
Hydrogen
Methane
Propane

Leaky Fittings



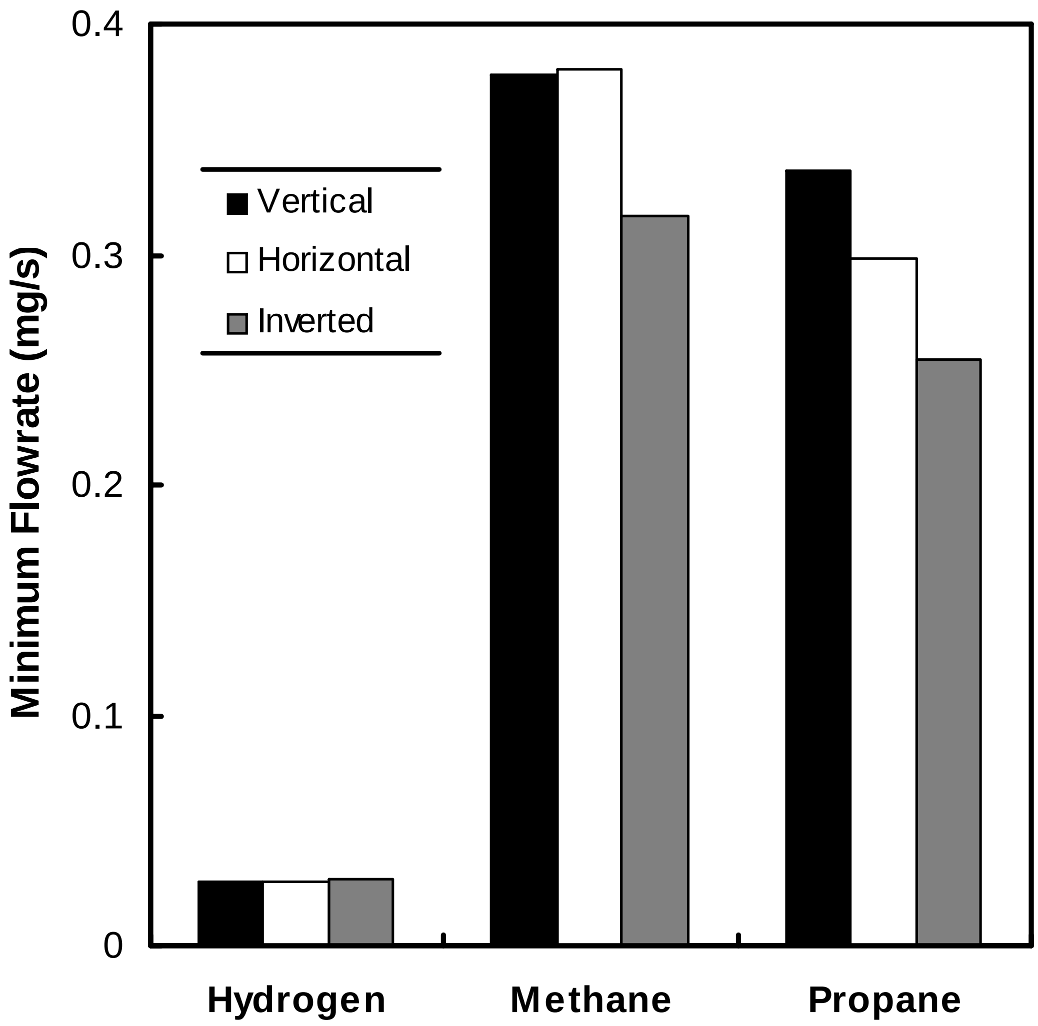
- Previous slide shows flaming leak quenching limits for compression fittings (vertical orientation).
- H_2 flame is smallest here, attributed to quenching distance.
- H_2 mass flow rate is an order of magnitude lower than CH_4 or C_3H_8.
- Leaks large enough to burn produce bubbles when soap water is applied.

Effects of Upstream Pressure



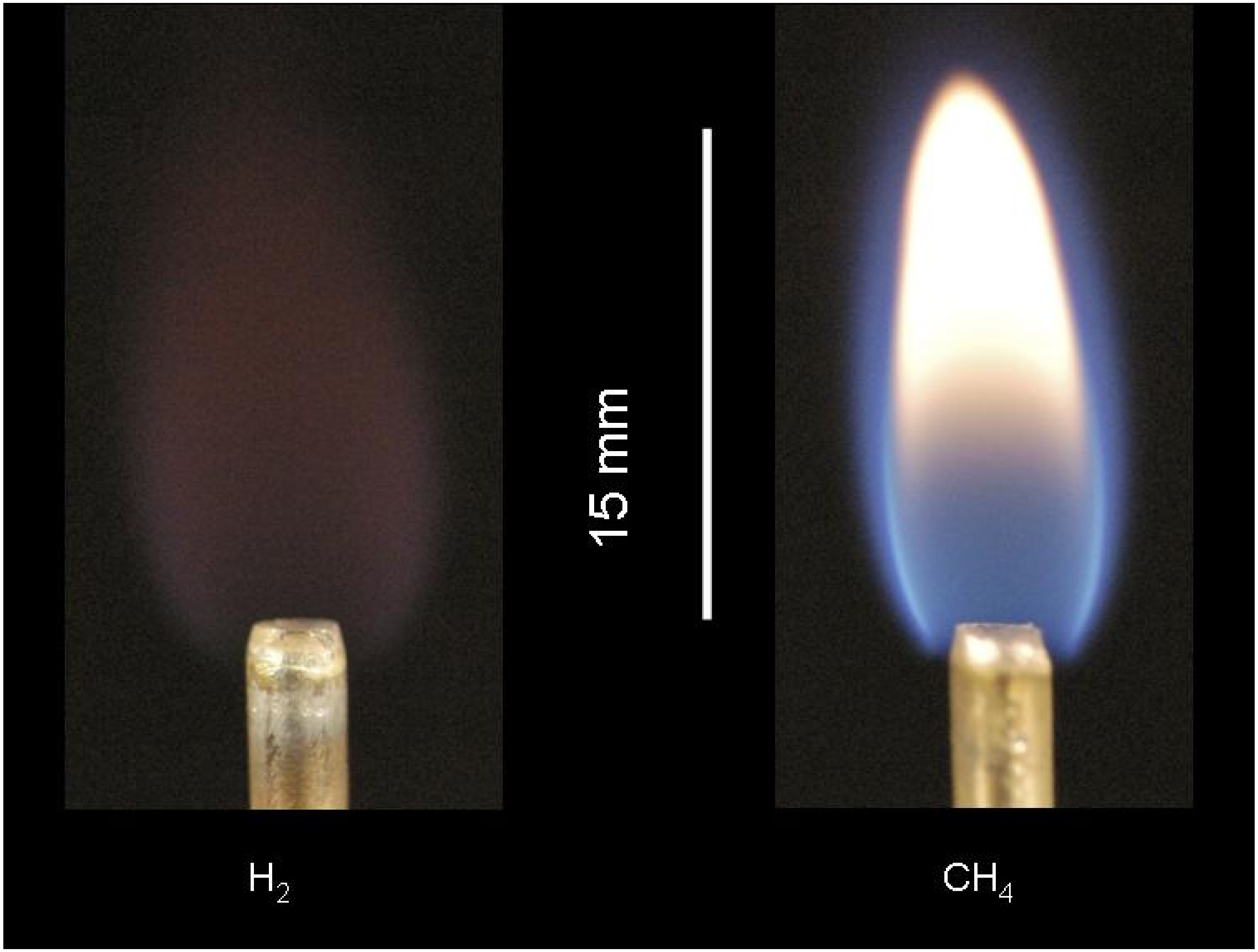
- Quenching limits for a 6 mm compression fitting are shown.
- H_2 limits are the lowest.
- Limits are independent of pressure.
- Results should guide future codes and standards.

Orientation Effects

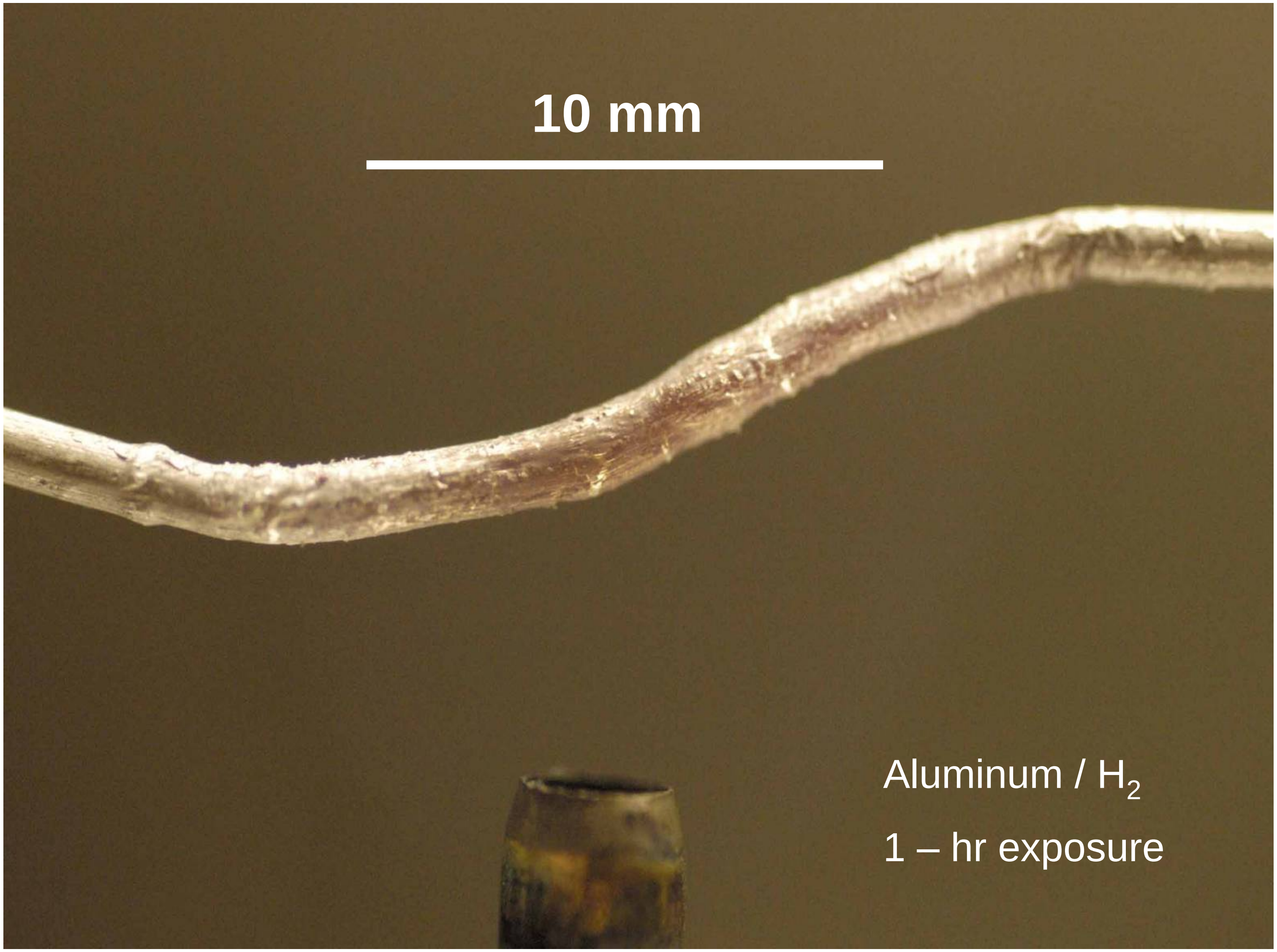


- Quenching limits for 6 mm compression fittings are shown.
- Orientation has a weak effect.
- Inverted orientation has the lowest heat loss rates.

Materials Degradation

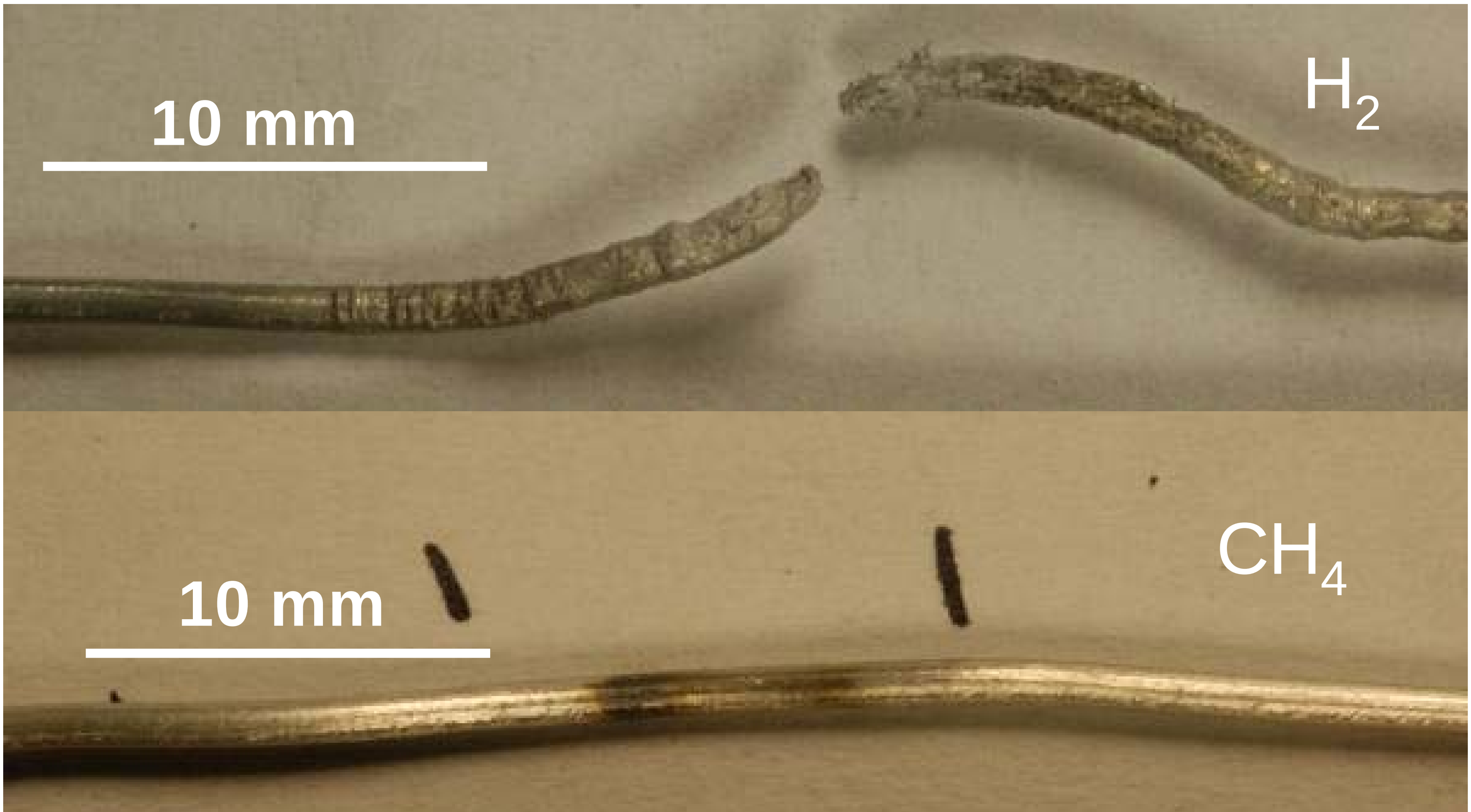


Al Degradation



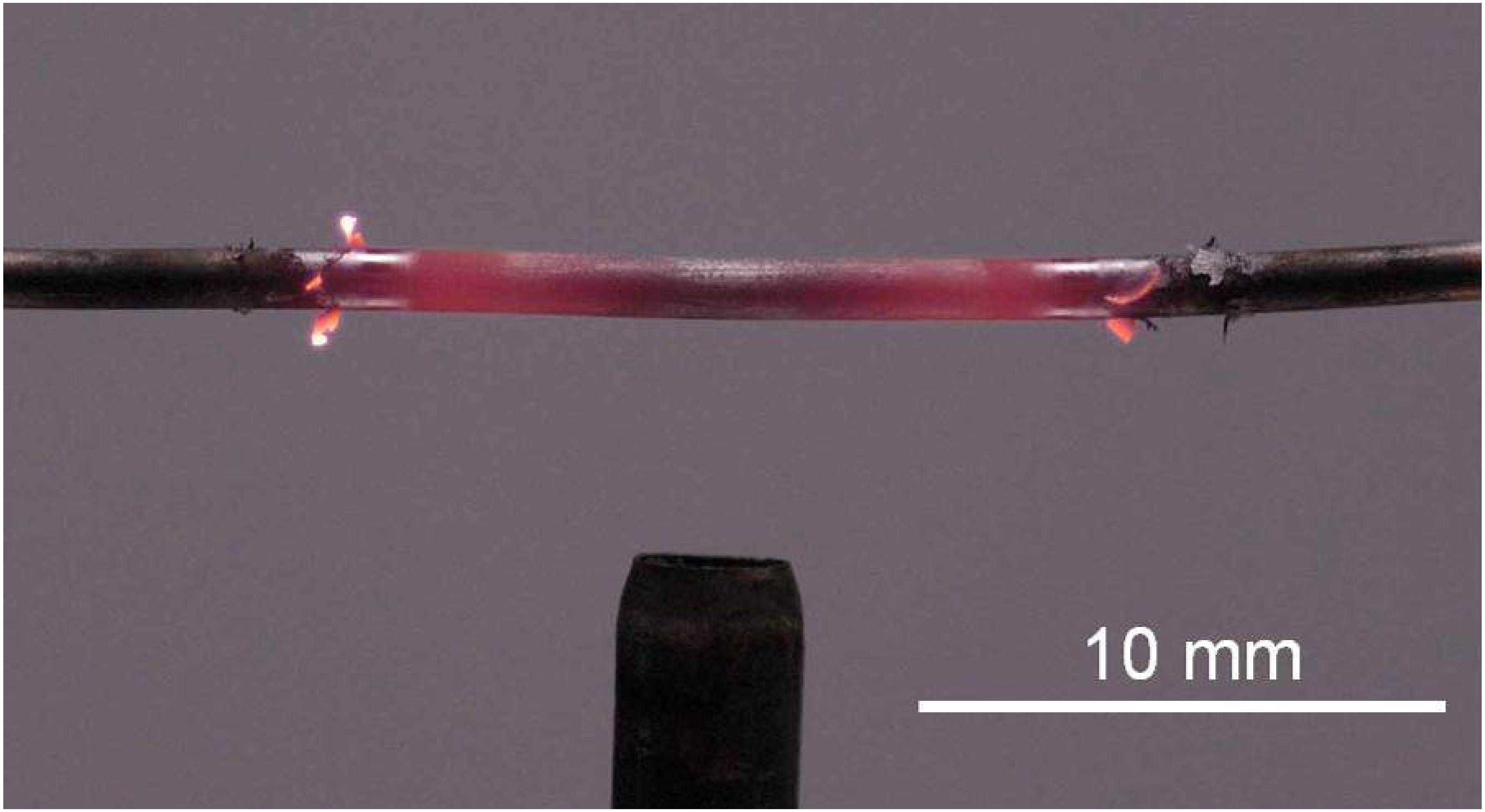
Al Degradation

- Aluminum failed in H_2 flame at 8 hours.



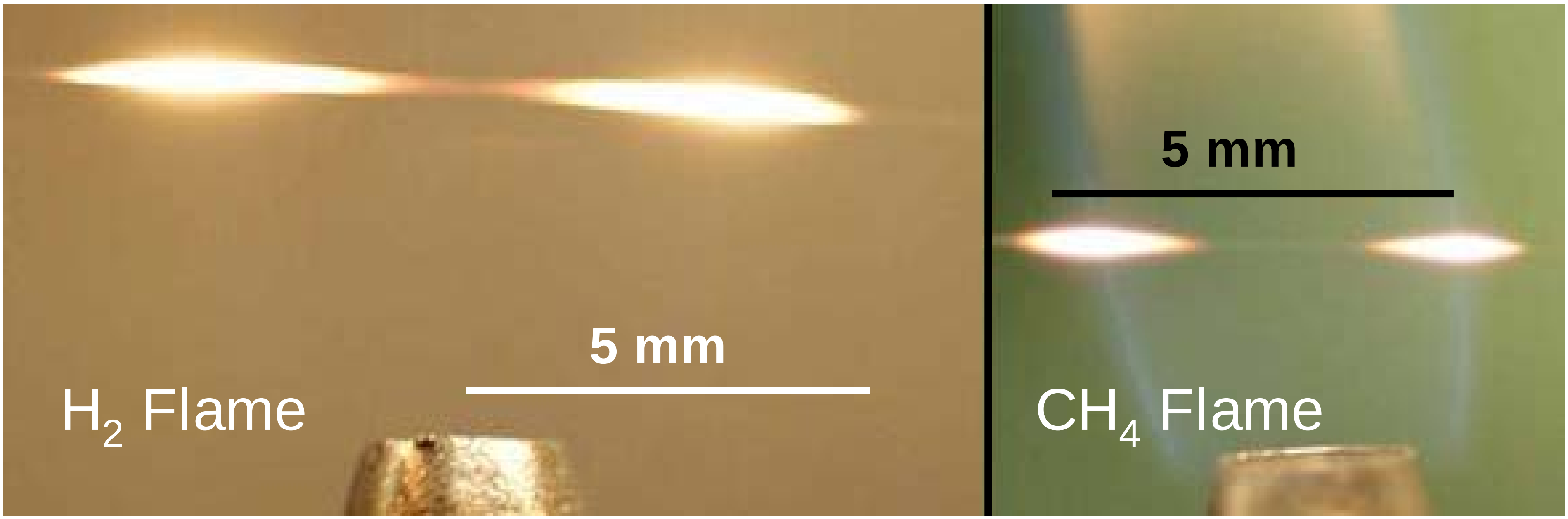
304 SS Degradation

- Corrosion after prolonged H_2 flame exposure.

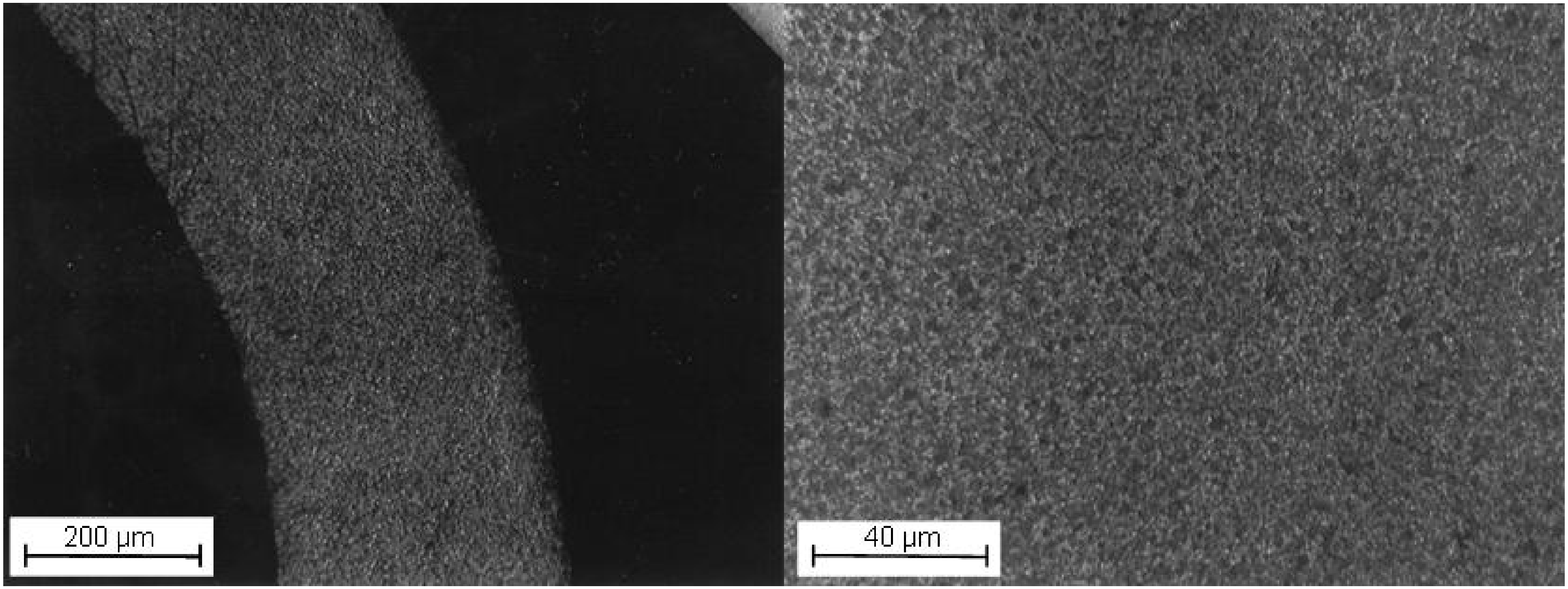


SiC Degradation

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

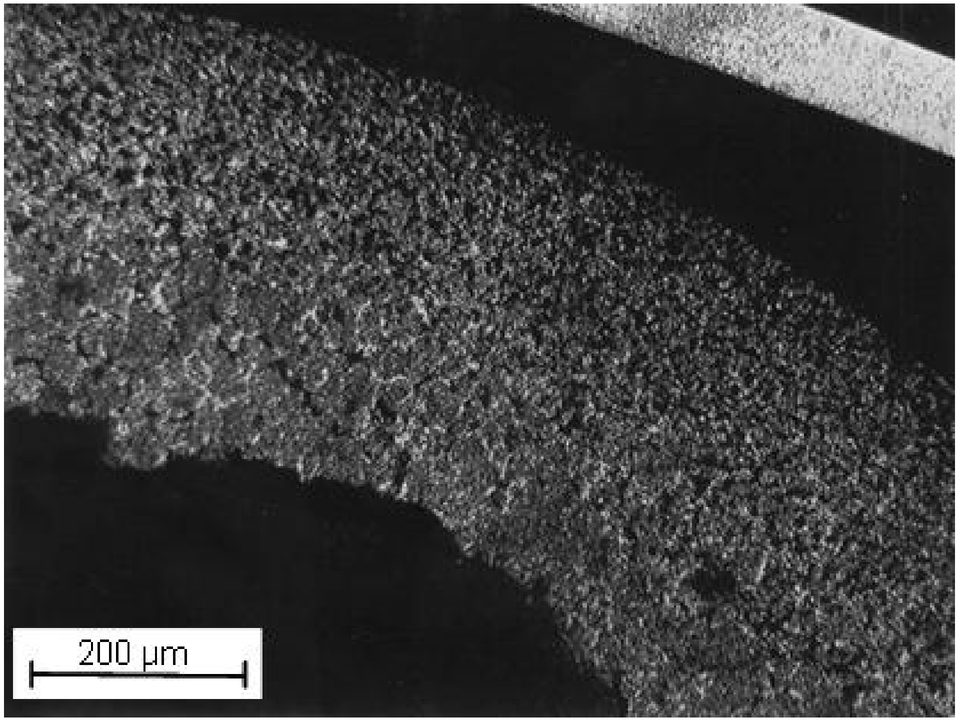


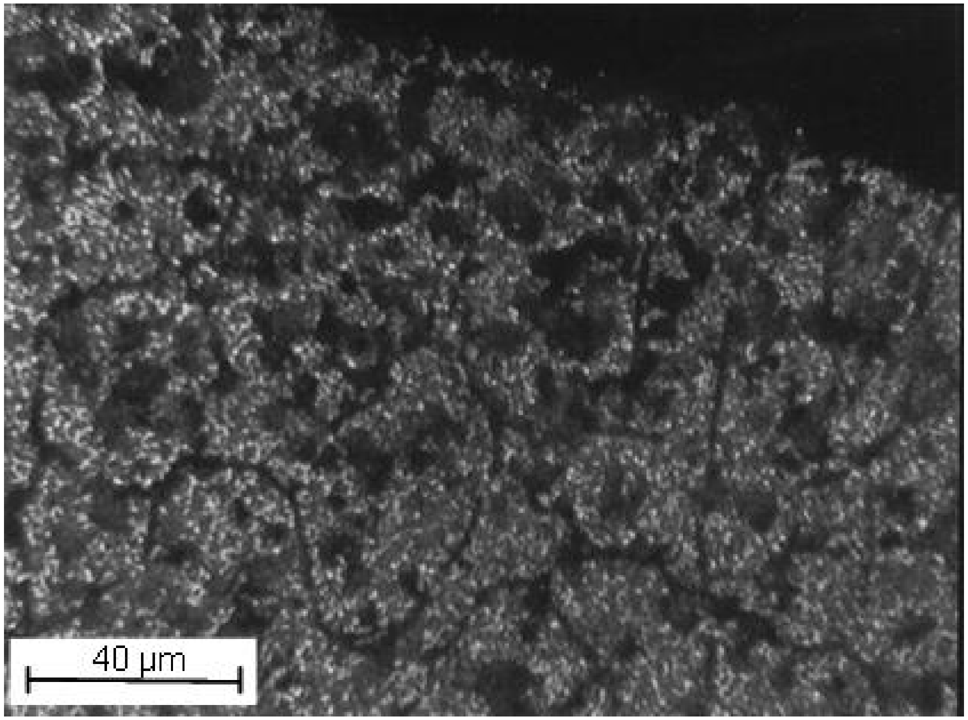
Al Degradation Microscopy



- Control specimen is shown.

Al Degradation Microscopy





- Images following exposure to H_2 flame.

Possible Mitigation Strategies

- Apply intumescent paints.

- Apply steel wool or ceramic blankets.

- Consider novel flame detectors:
  - Cable heat detectors
  - UV and IR detectors

Conclusions

- Stable H_2 flames were observed on round burners and leaky compression fittings at flow rates down to 4 and 28 μg/s, respectively.
- Fuel mass flow rate at quenching is largely independent of burner diameter.
- H_2 has a lower mass flow rate at quenching and a higher mass flow rate at blowoff than either CH_4 or C_3H_8.
- H_2 flames caused much faster corrosion than CH_4 flames to aluminum and SiC fibers.