2018 Winter Conference ✶ Chicago, IL

Flammability: A Continuum Vs. Discrete Boundary

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HR Expo Session 4:

Some Low GWP Next Generation Refrigerant will be Flammable: What does it mean to be Flammable?

The work is supported by:

- the U.S. Department of Energy, Building Technologies Office,
  Manager: Antonio Bouza.

- NIST internal funds.

- Describe the fundamentals of refrigerant flammability and basics
- Understand that flammability is a continuum rather than possessing discrete boundaries
- Provide an overview of recent AHRI research on flammable refrigerants
- Describe currently available requirements and best practices on the safe handling, storing and transportation of flammable refrigerants

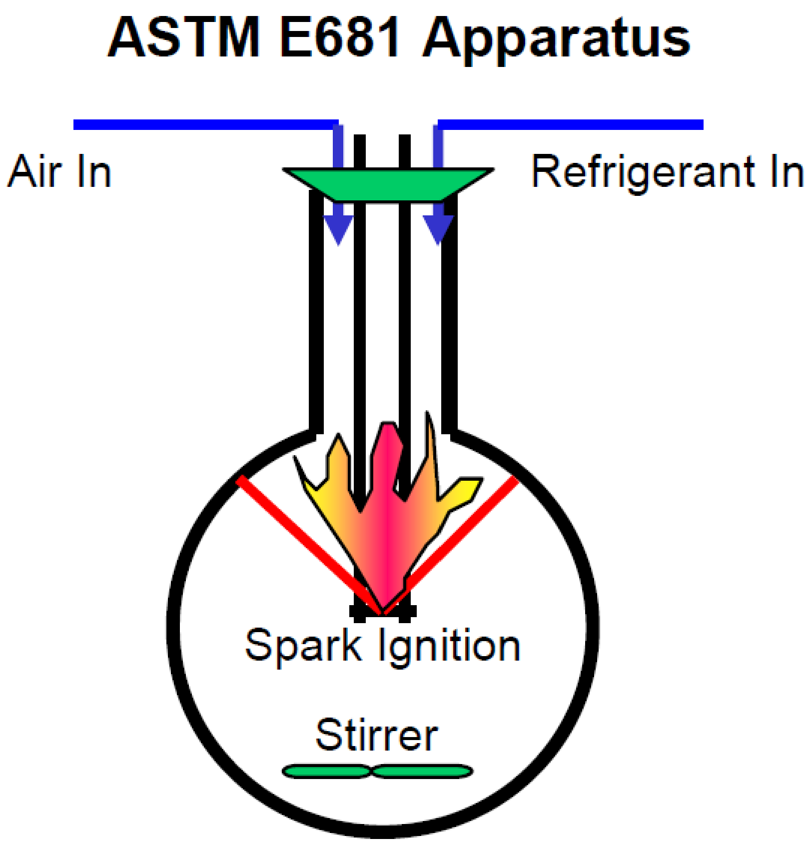
1. Understand that flammability behavior is device/configuration dependent
2. Understand the features that influence the flammability behavior of a fuel-air mixture.

Outline/Agenda

- For marginally flammable compounds, flammability is a continuum, not a discrete boundary.
- Flammability is device dependent.
- What is the criterion for flame stability?

  Characteristic Chemical Time < Characteristic Flow Time
- What affects the characteristic times?
- Examples how flammability varies with environment/test method.
- Burning velocity is a good metric because it captures the continuum nature of reaction and transport rates, and can be used for predictive purposes in a variety of configurations.

ASTM E681

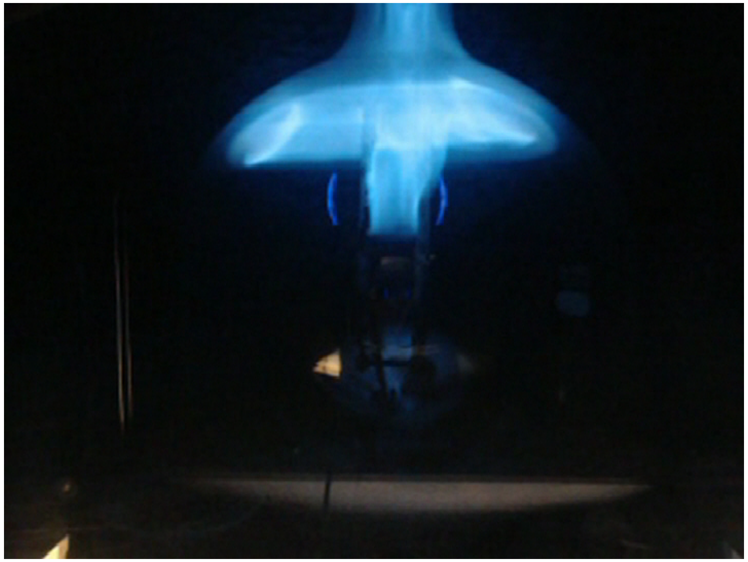


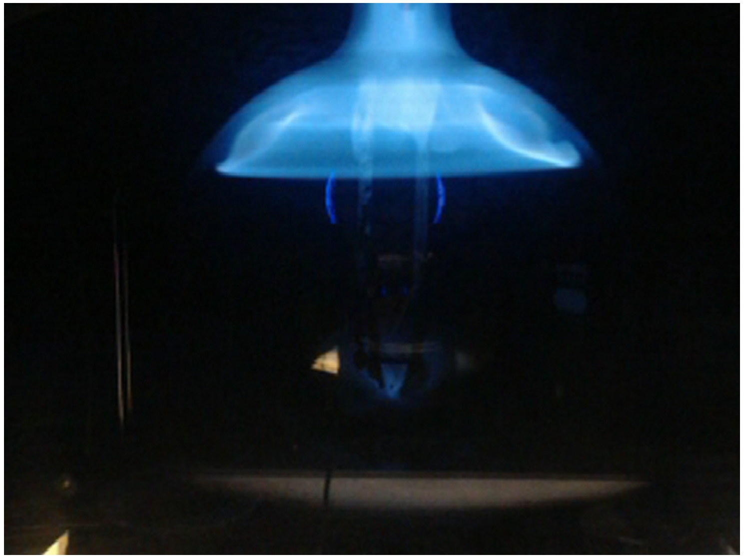
- ASTM E-681 in US
  - 2001 version cited by ASHRAE
    (12 liter flask, spark ignition)
  - Flame must reach the wall and exhibit > 90 degree angle

ASTM E681

Volume percent in air of R32/R134a(35/65wt%):

15 % 16 %

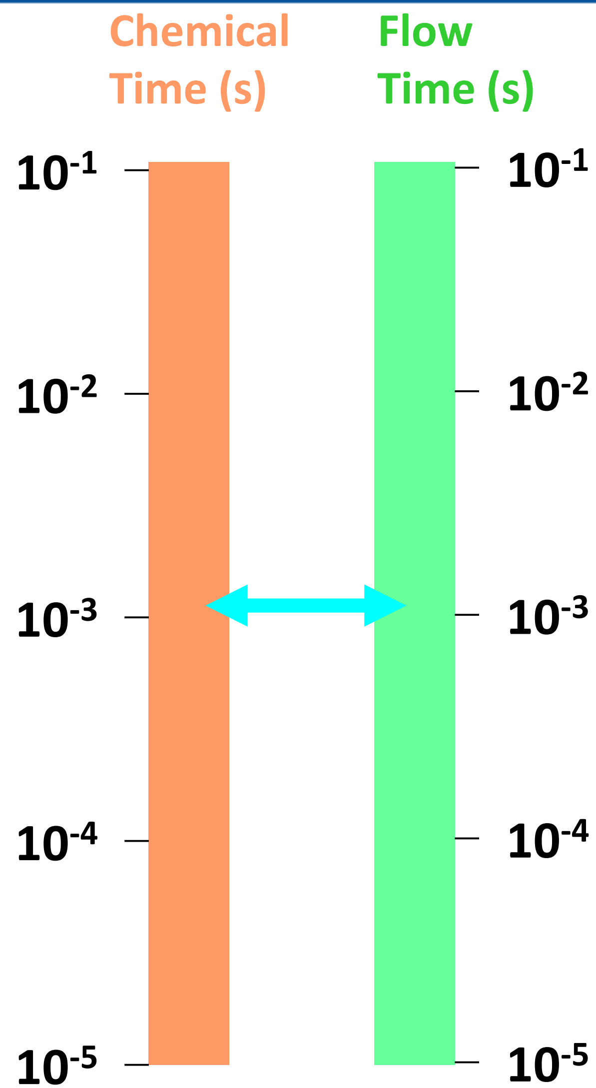




Flame Angle: 85^{o} 95^{o}

Flames go out when: $\tau_{chem} > \tau_{flow}$

$$Da_I = \frac{\tau_{flow}}{\tau_{chem}}$$



The flow-field influences the extinction process:

$$D \equiv \tau_r / \tau_c$$

Chemical Time:

$$\tau_c \equiv \rho / w = \rho\, c_F^{-n} c_O^{-m} A \exp(E / RT).$$

Flow Time:

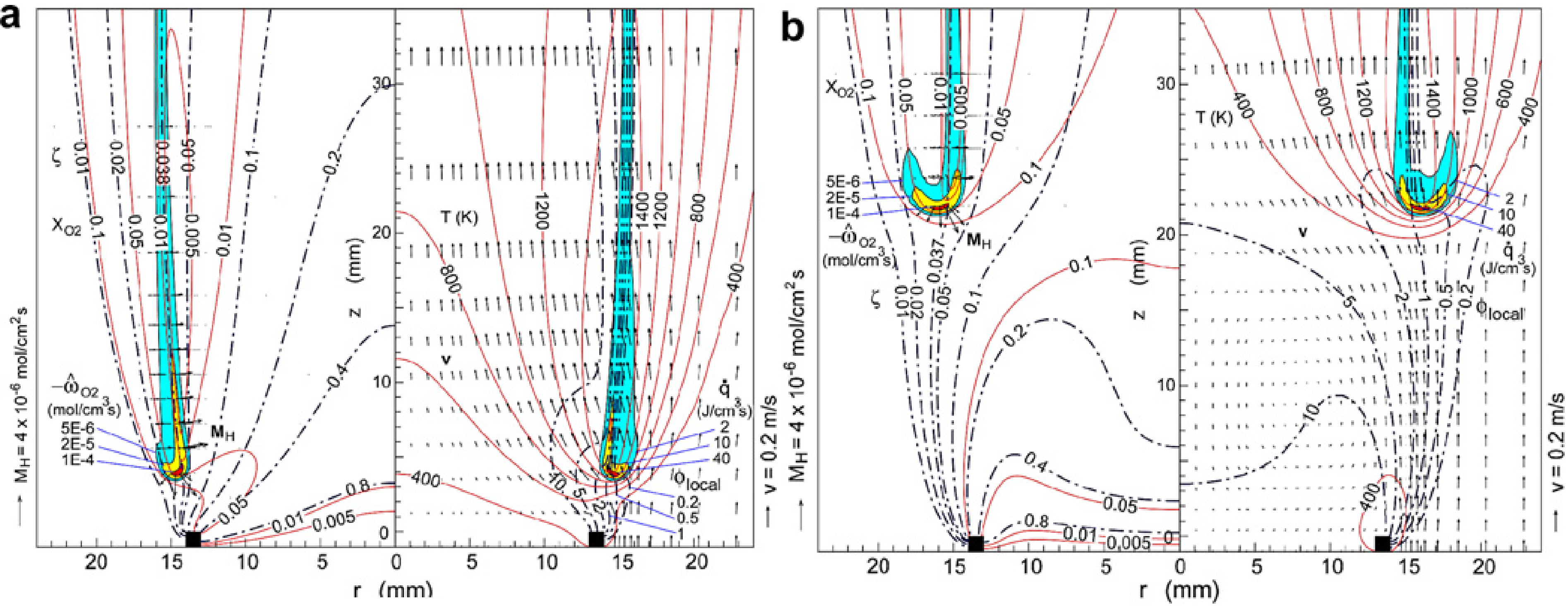
$$\tau_r = \ell / v$$

- Extinguishment of Methane-Air Co-Flow Diffusion Flames

Methane in 84.1%Air + 15.9%CO_2

d =2.8 cm, U_{CH4}= 0.92 cm/s, U_{ox}= 6.7 cm/s

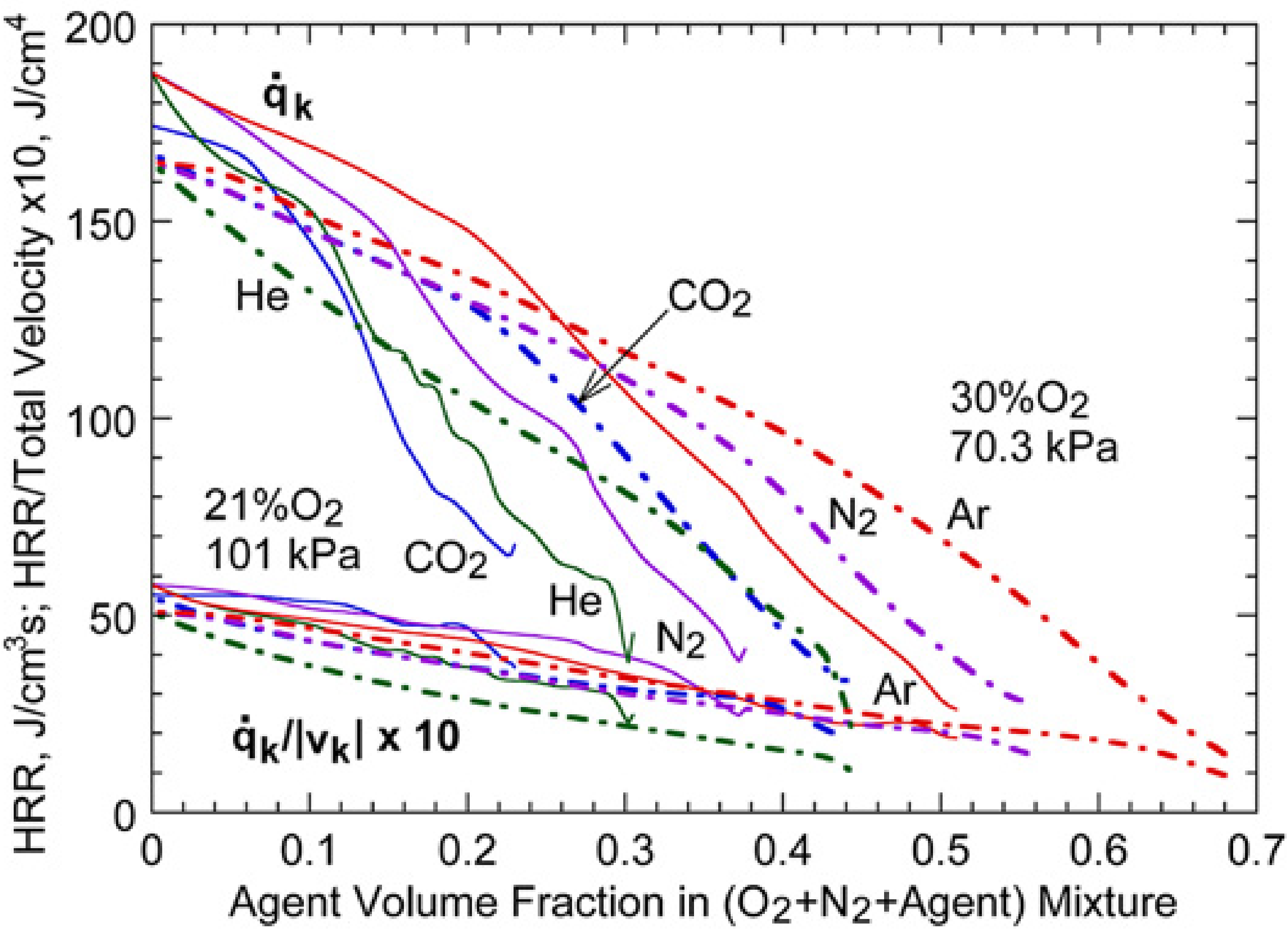
Flame structure at stabilization point.



CH_4 – air flame

CH_4 – air flame with added N_2

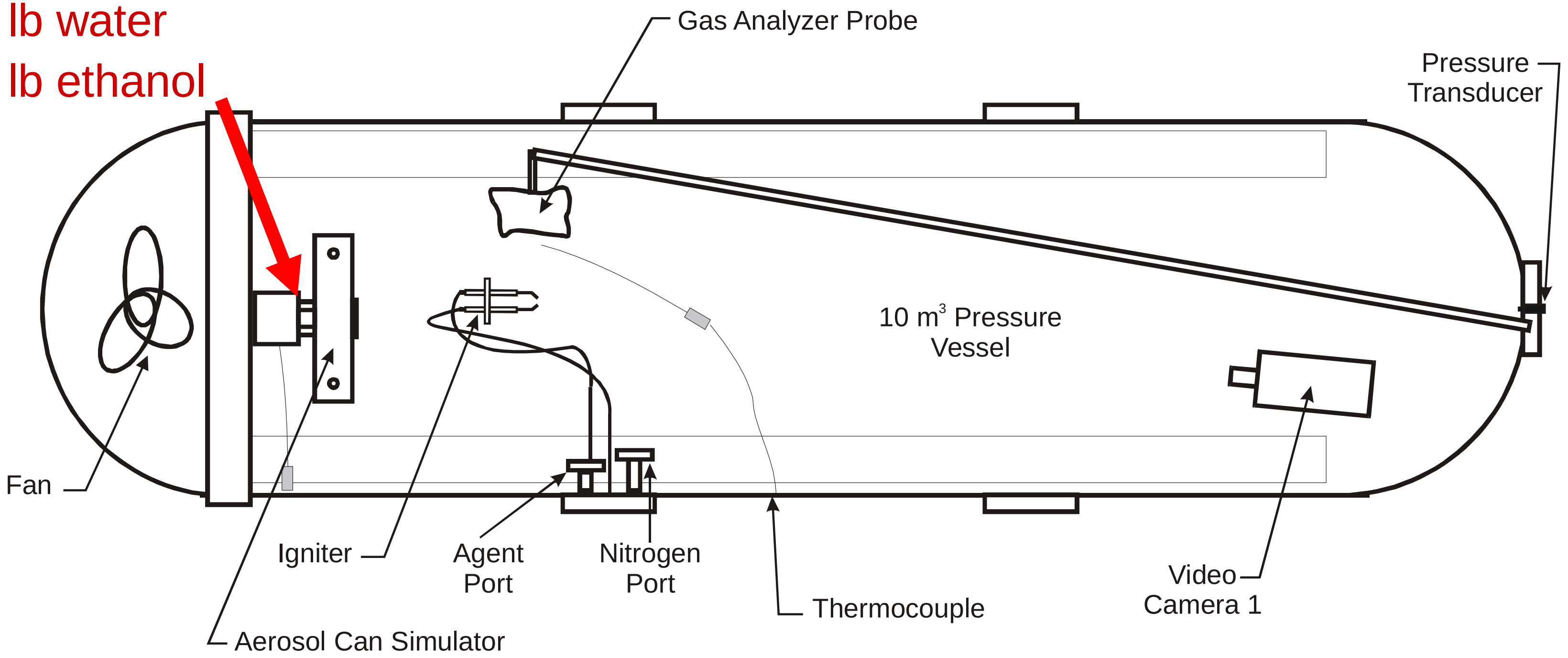
With inhibitor addition, heat release decreases significantly, but Da is relatively constant.



Problem: want to eliminate Halon 1301 from use in aircraft cargo bays

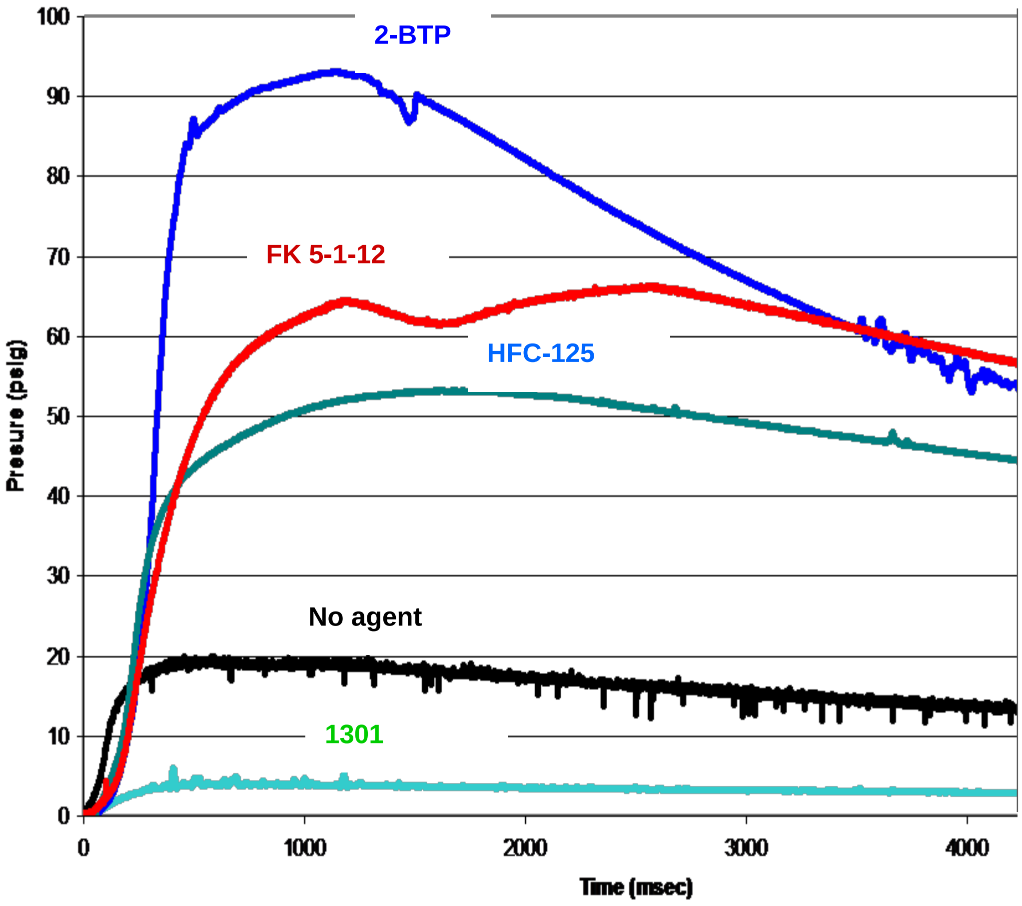
2. But in one FAA-mandated qualification test, the possible replacements make things worse.

0.2 lb propane
0.2 lb water
0.6 lb ethanol



FAA Aerosol Can Simulator

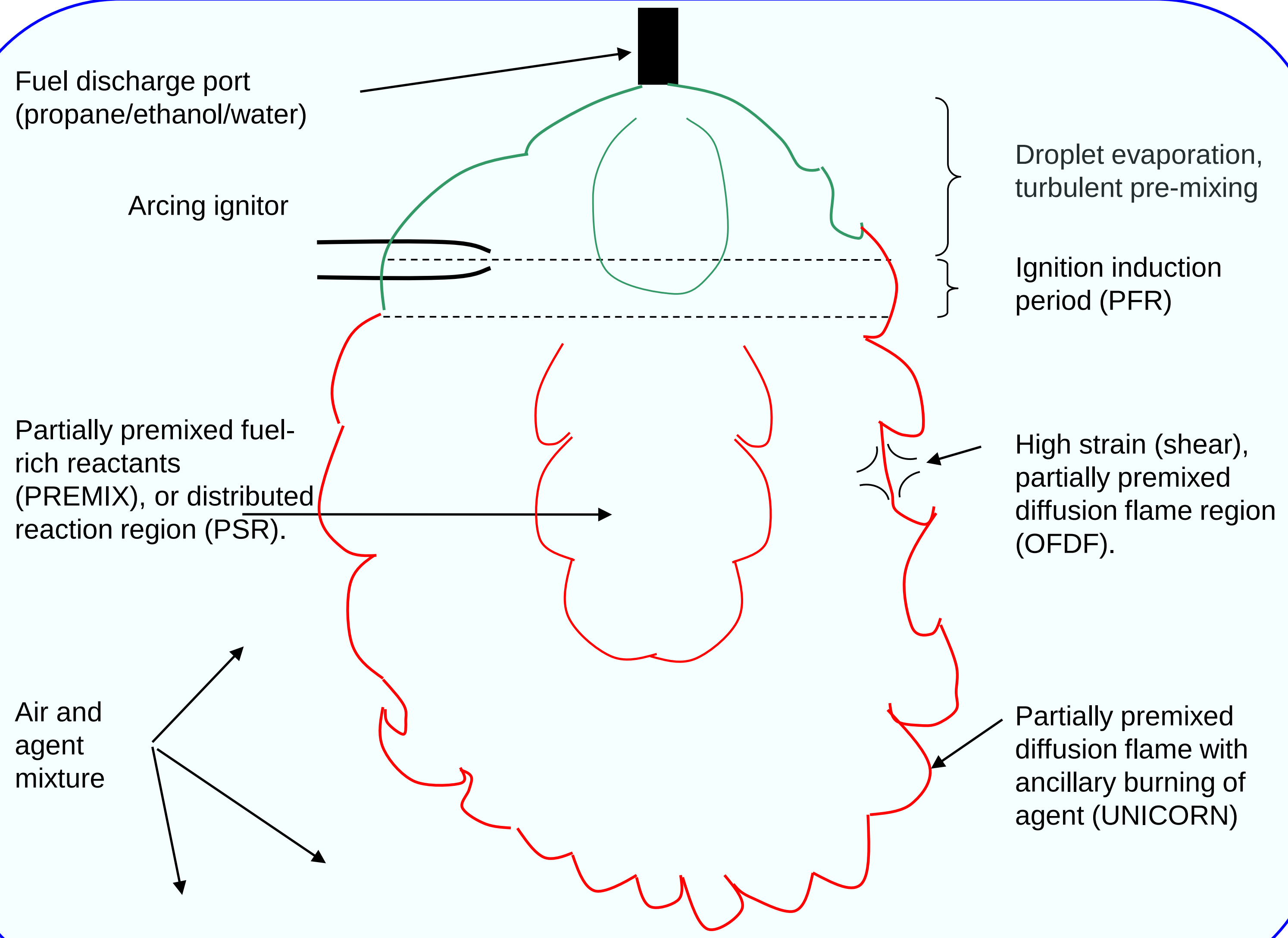
Fire Suppressants Added to FAA Aerosol Can Test Increased the Heat Release and Overpressure in aircraft cargo bays



FAA Aerosol Can Simulator

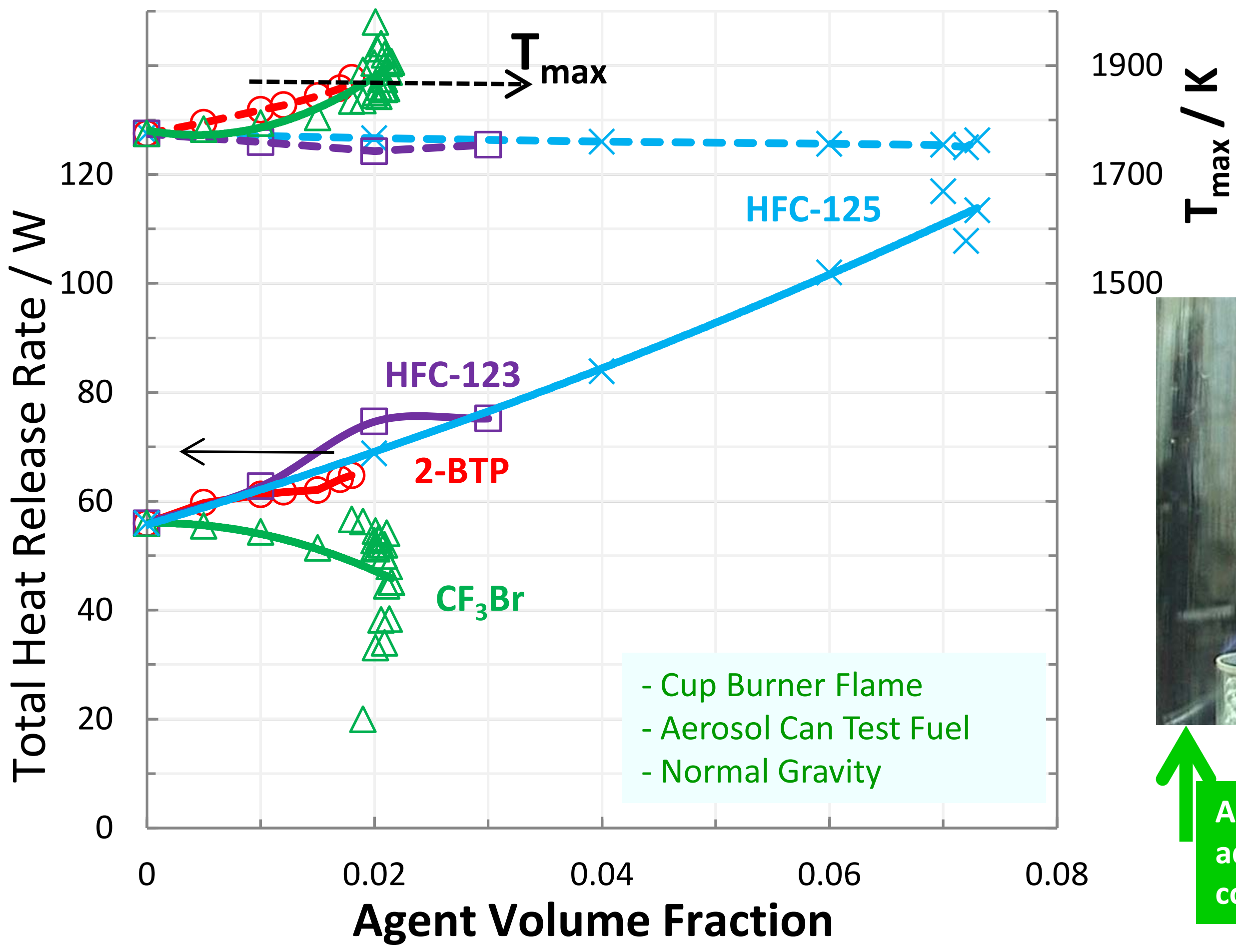
Approach

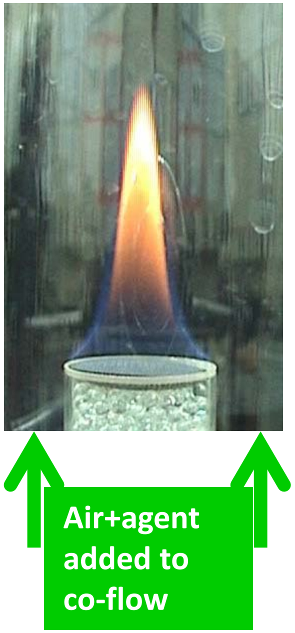
Physics in FAA test is too complicated to examine with detailed kinetics, so <u>simplify</u>.



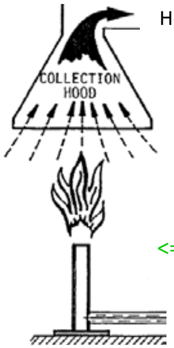
Co-Flow Diffusion Flames with Added Fire Suppressant in the Air (e.g. R125)

In the vicinity of other flames, even fire suppressants can become flammable.





Added HFCs to Propane-air Flame Increases Heat Release

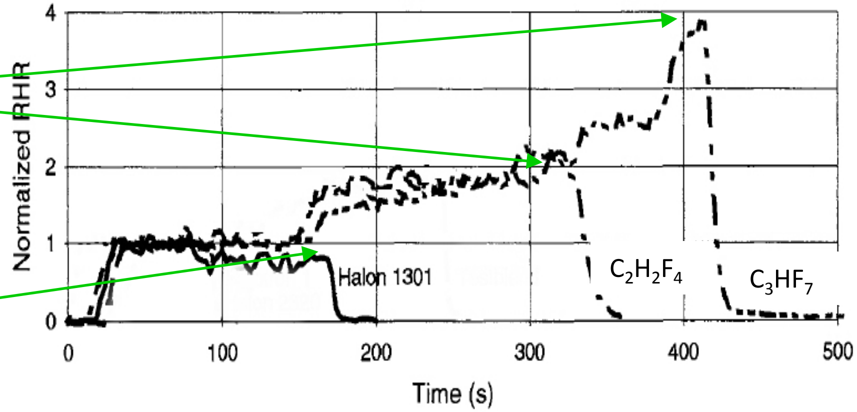


Heat Release Rate Measurement

<= air and agent input (Increase agent concentration in air linearly in time.)

<= propane

From: Holmstedt et al. 1994



⇒ Total heat release increases (≈2 to 4 times) for $C_2H_2F_4$ (HFC-134a)
or C_3HF_7, (HFC-227ea)
at concentrations just below extinction,

=> but decreases for halon 1301.

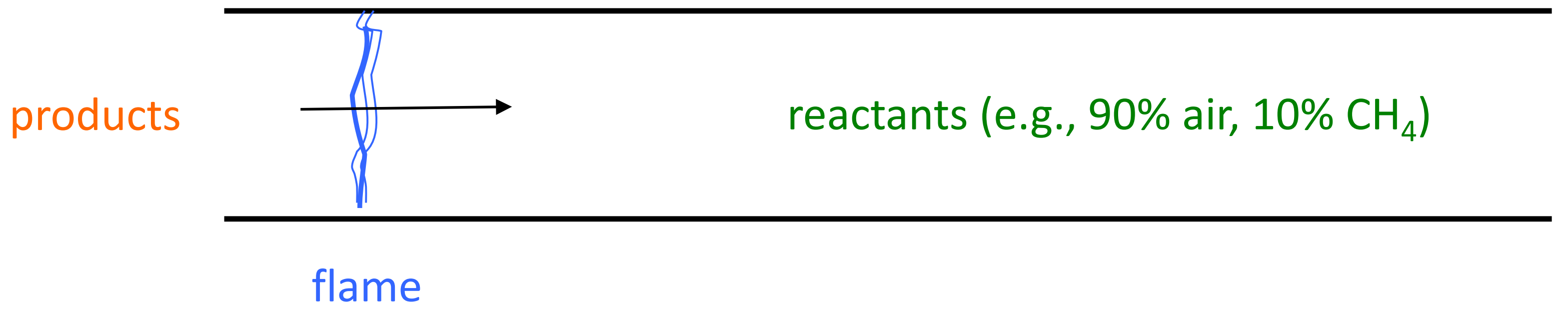
Why?

* G.Holmstedt, et al. IAFSS 1994.

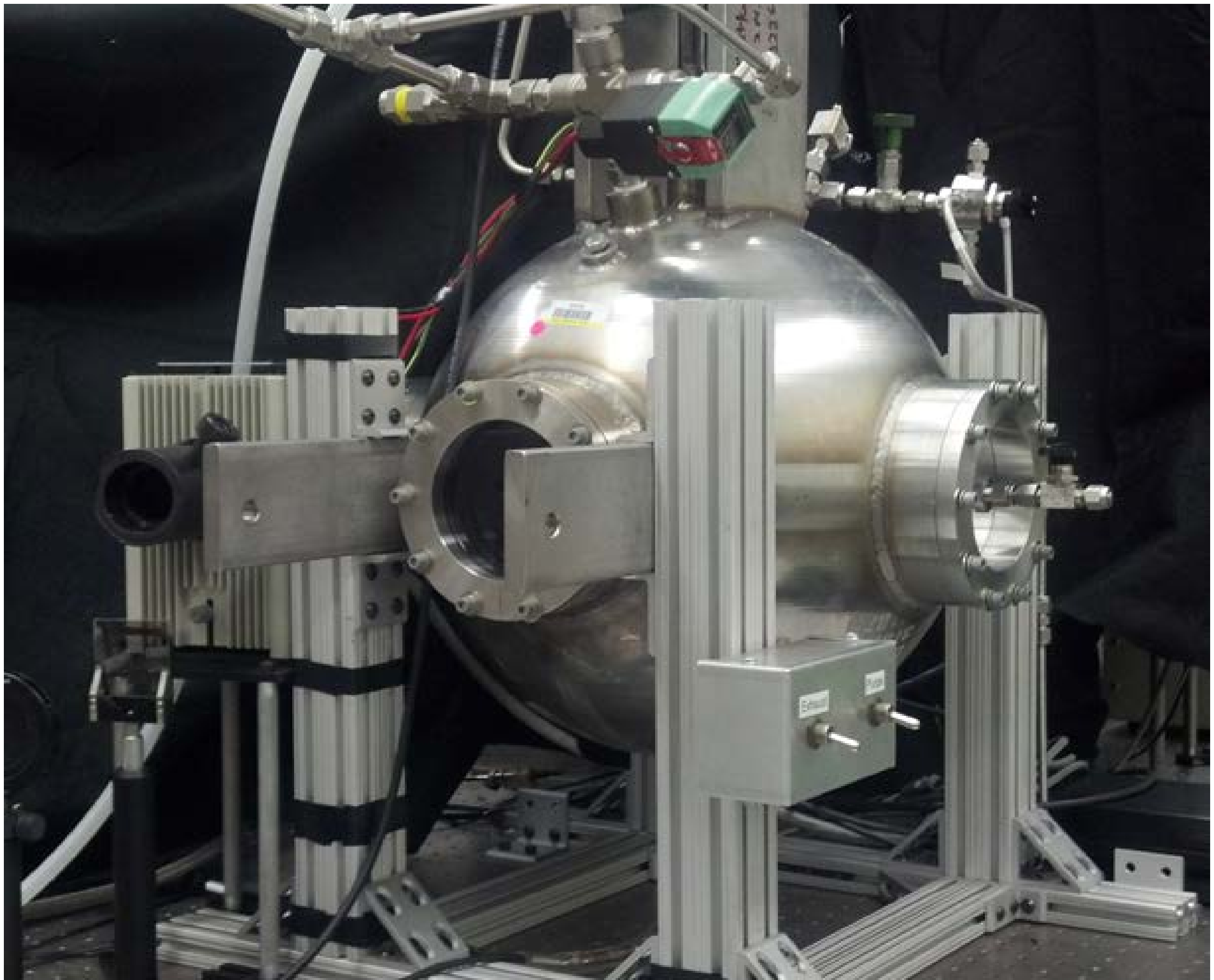
What is burning velocity?

The rate of propagation of a flame front into the quiescent reactants.

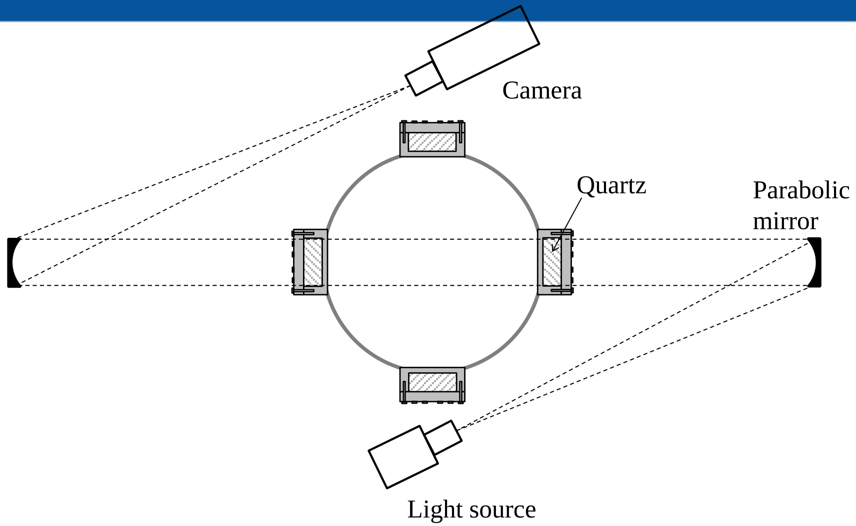
Approximate example: Flame propagation in a tube



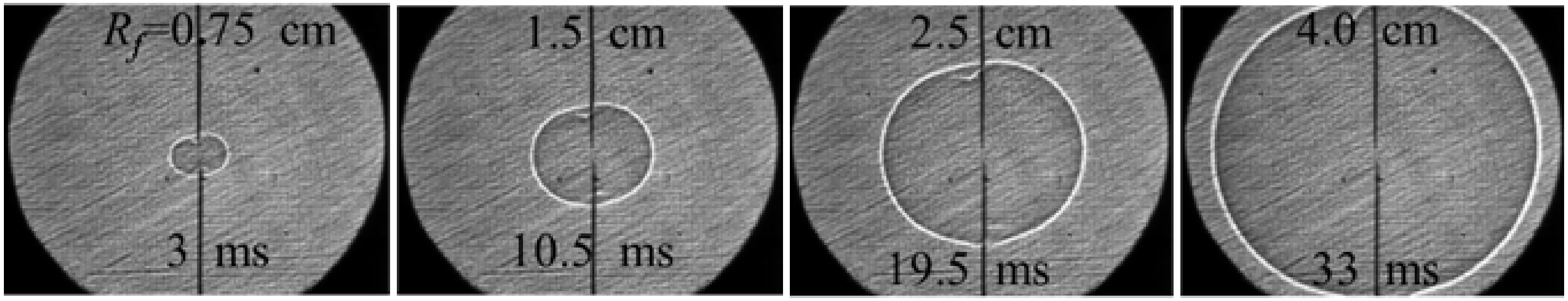
Constant Pressure Method, 30 L chamber:



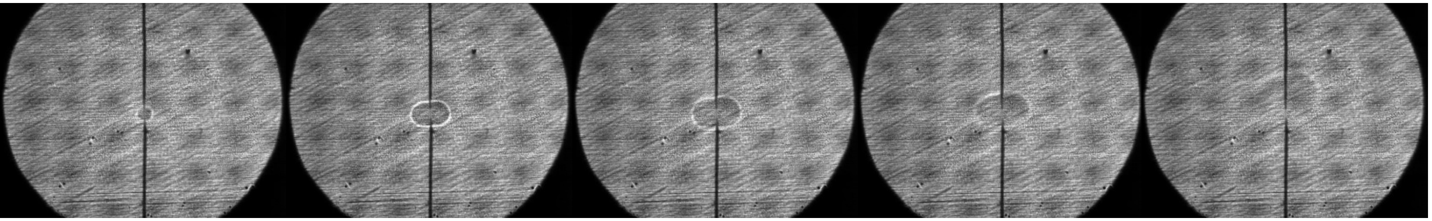
Record flame front position vs. time

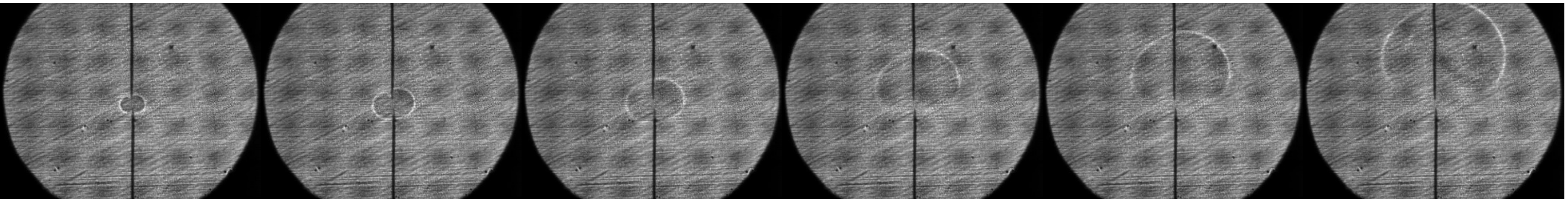


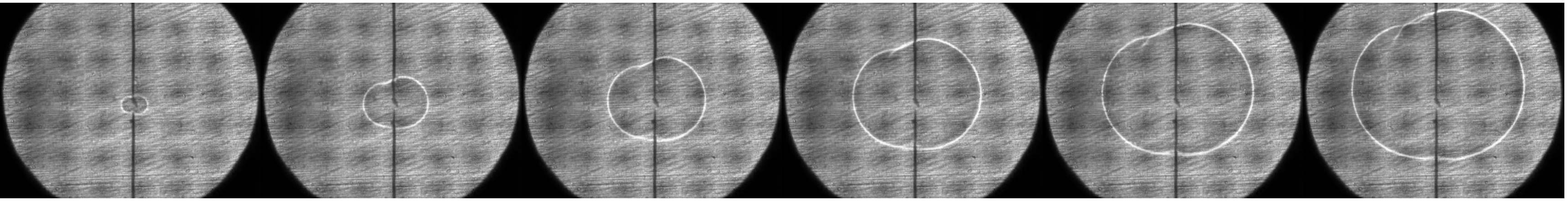
Z-type shadowgraph setup, overhead view.



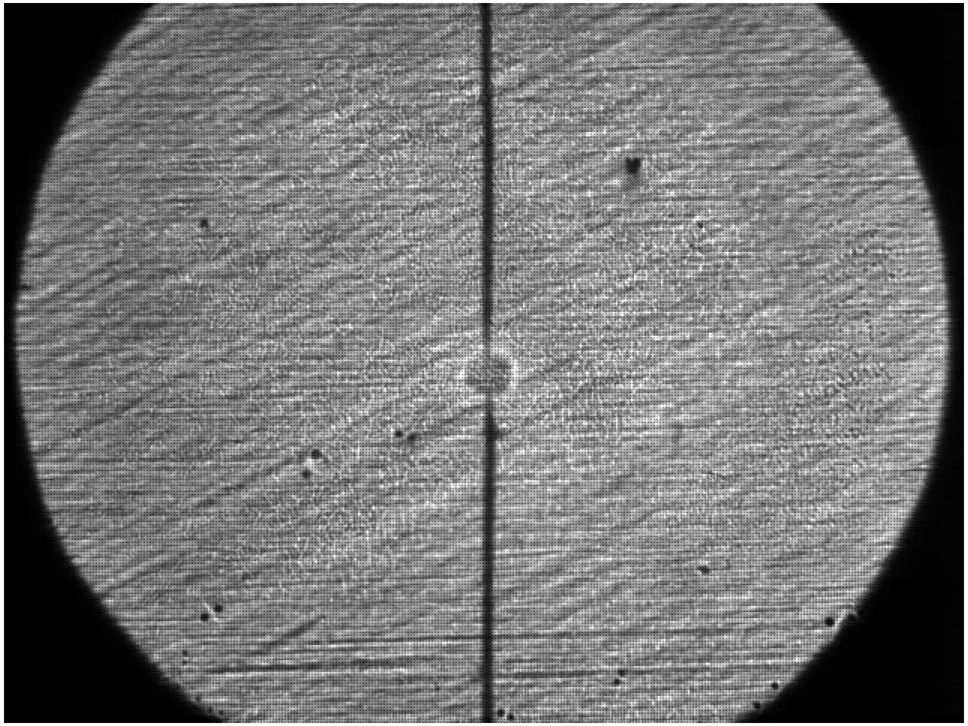
Shadowgraph images of stoichiometric CH_4/air with 1% Halon 1301.







C_3H_8-CF_3Br-air Premixed Flame φ=0.8



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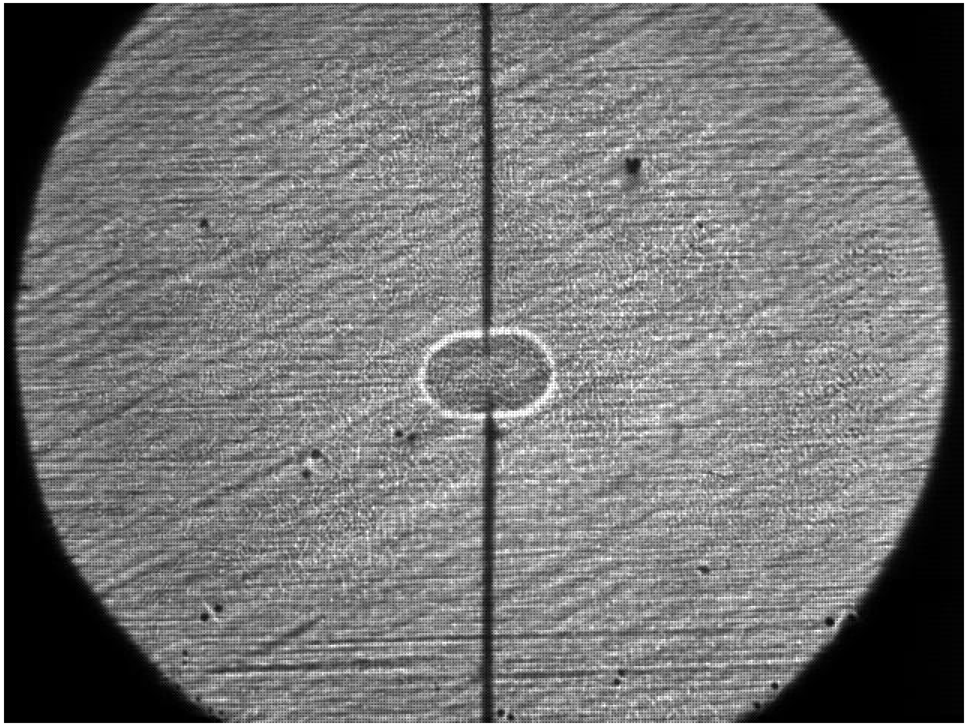
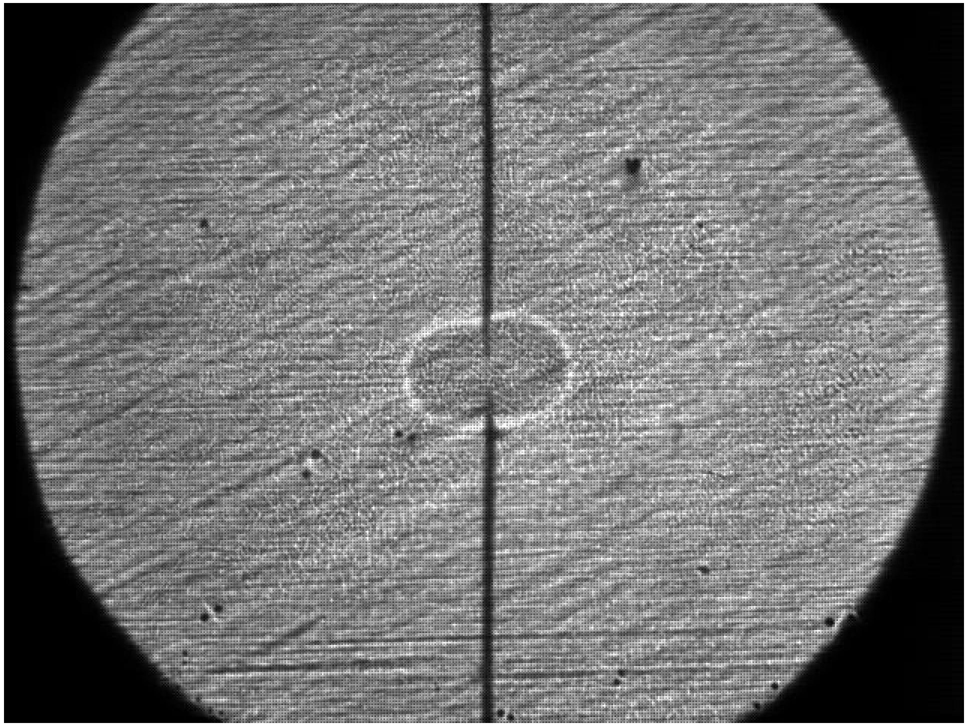
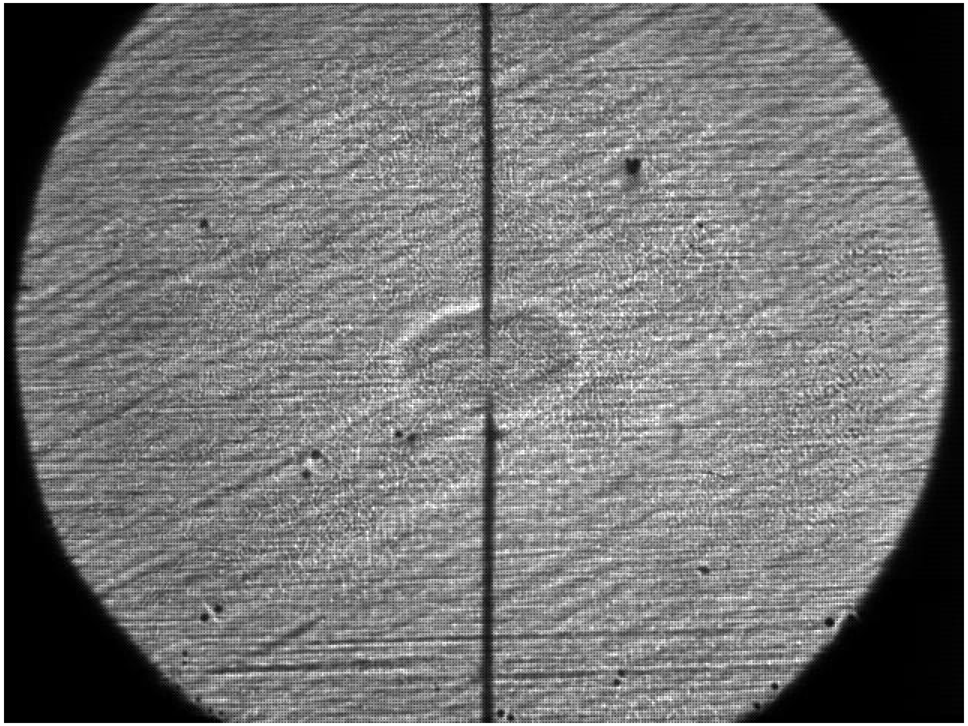


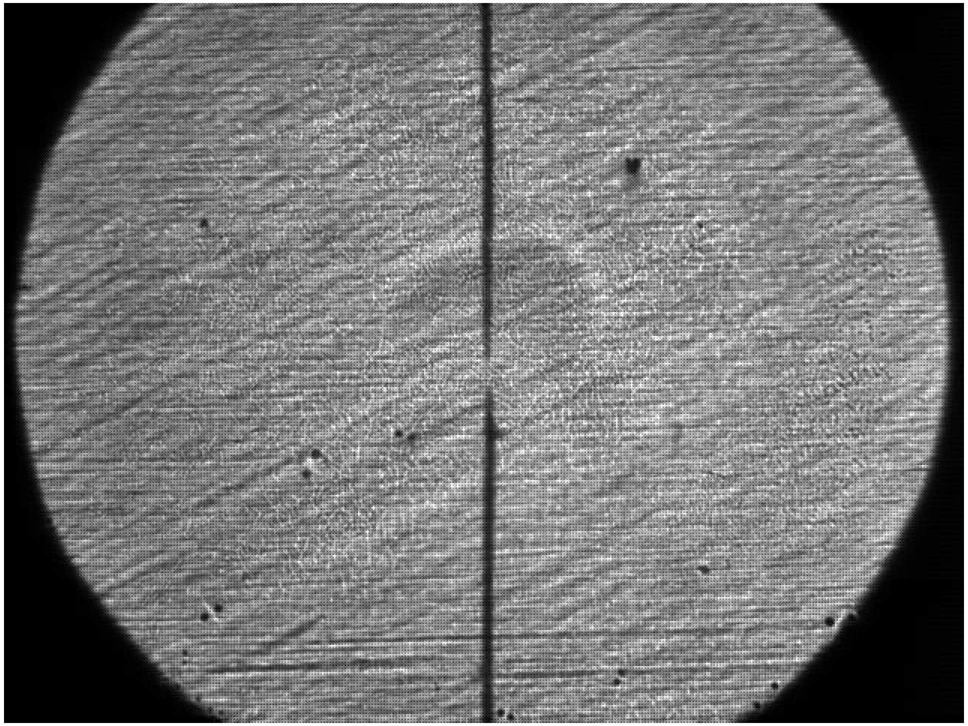
C_3H_8-CF_3Br-air Premixed Flame φ=0.8



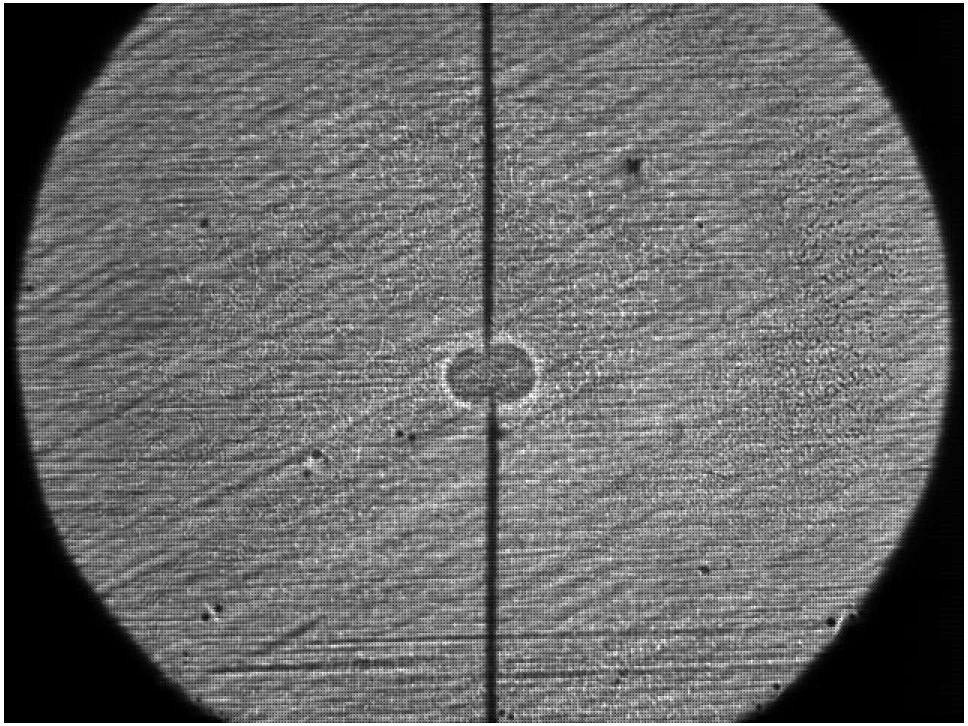
C_3H_8-CF_3Br-air Premixed Flame φ=0.8



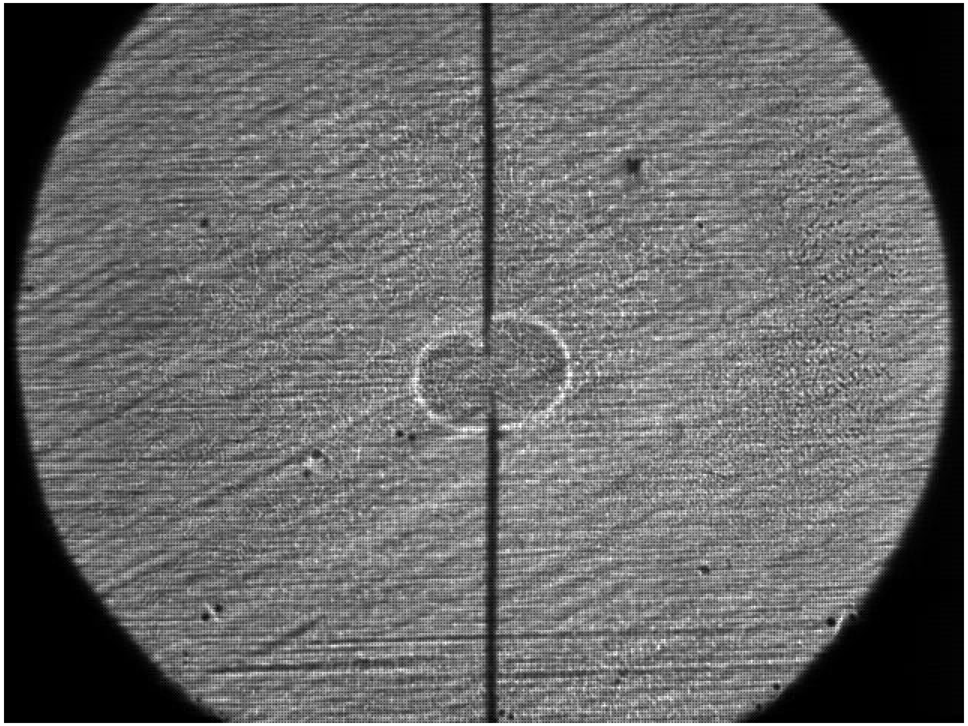
C_3H_8-CF_3Br-air Premixed Flame φ=0.8



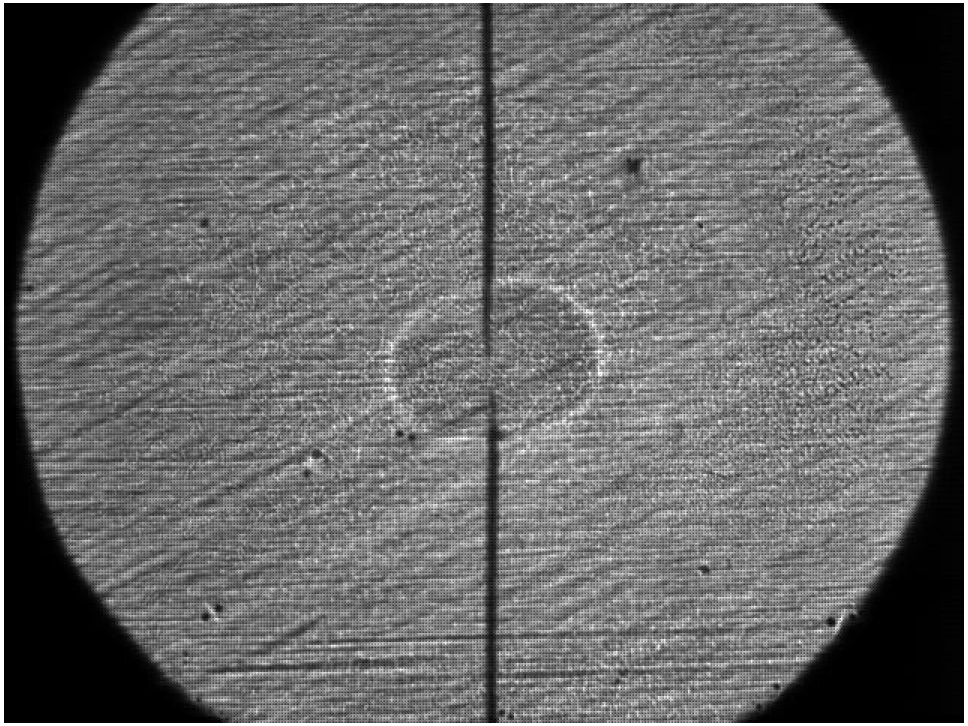
CH_4-CF_3Br-air Premixed Flame φ=1.2



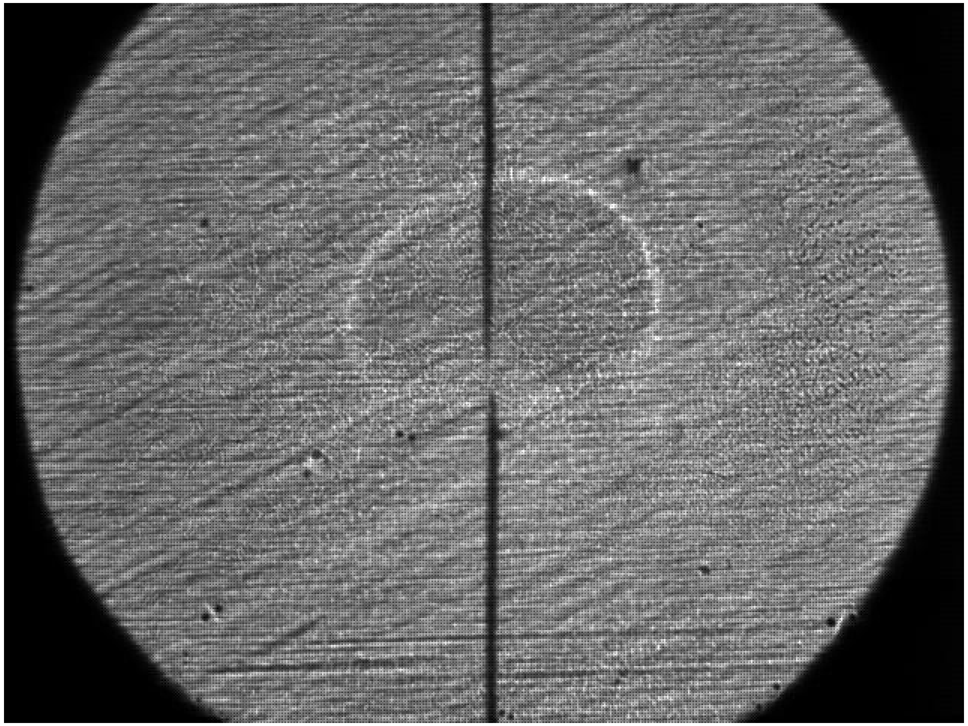
CH_4-CF_3Br-air Premixed Flame φ=1.2



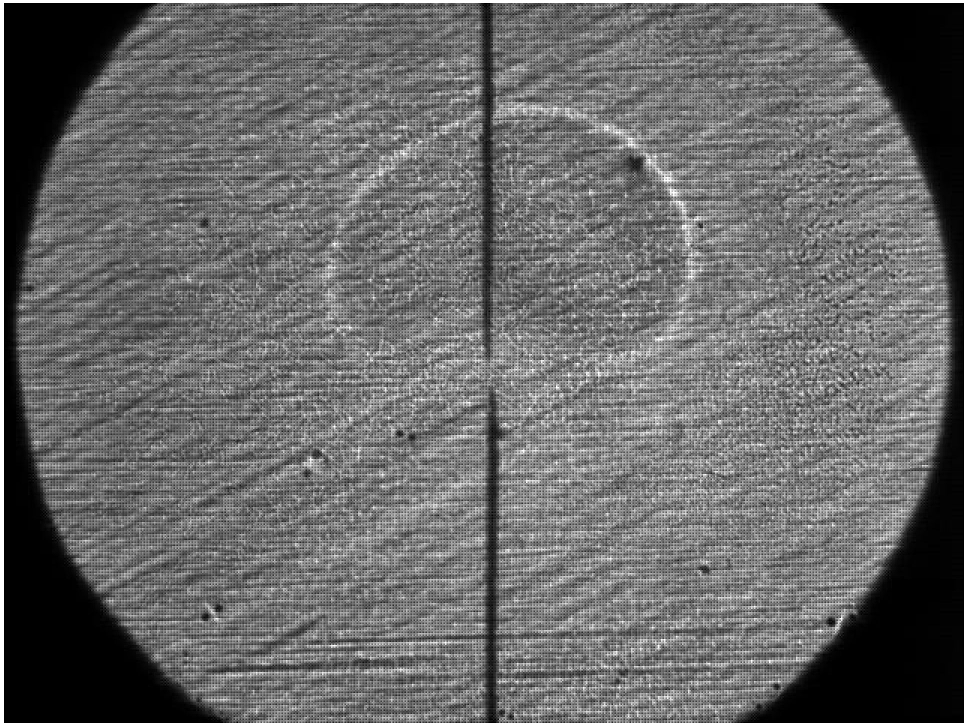
CH_4-CF_3Br-air Premixed Flame φ=1.2



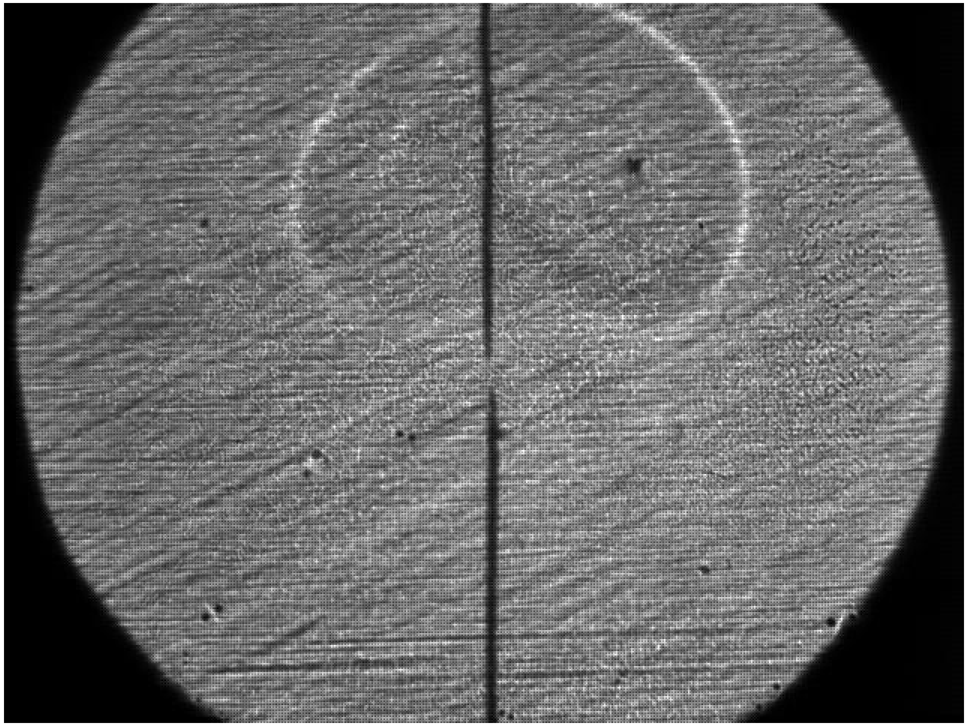
CH_4-CF_3Br-air Premixed Flame φ=1.2



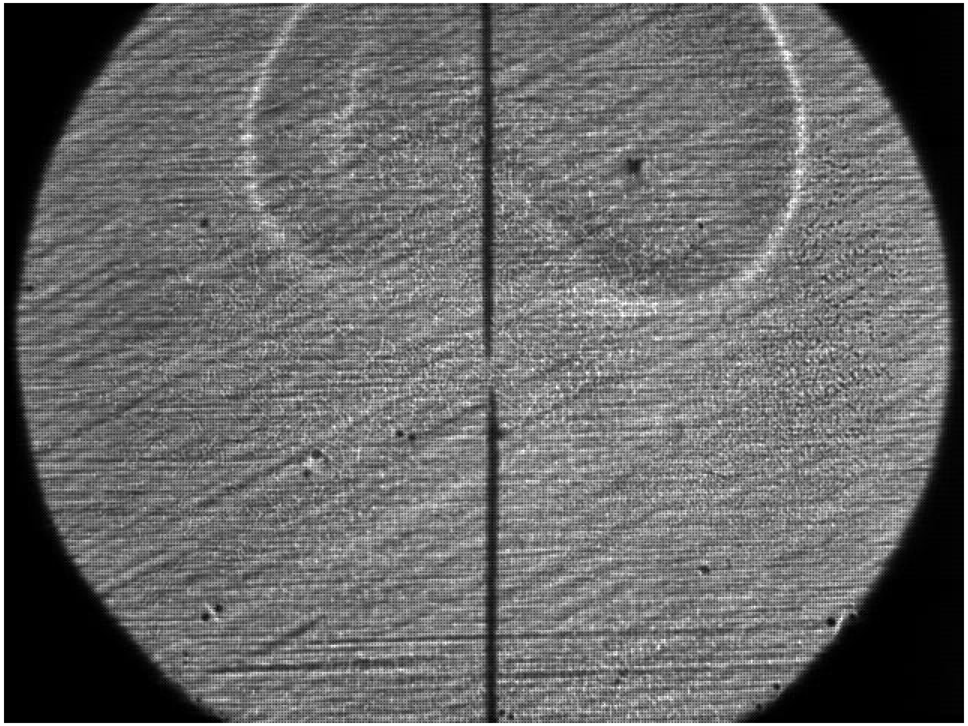
CH_4-CF_3Br-air Premixed Flame φ=1.2



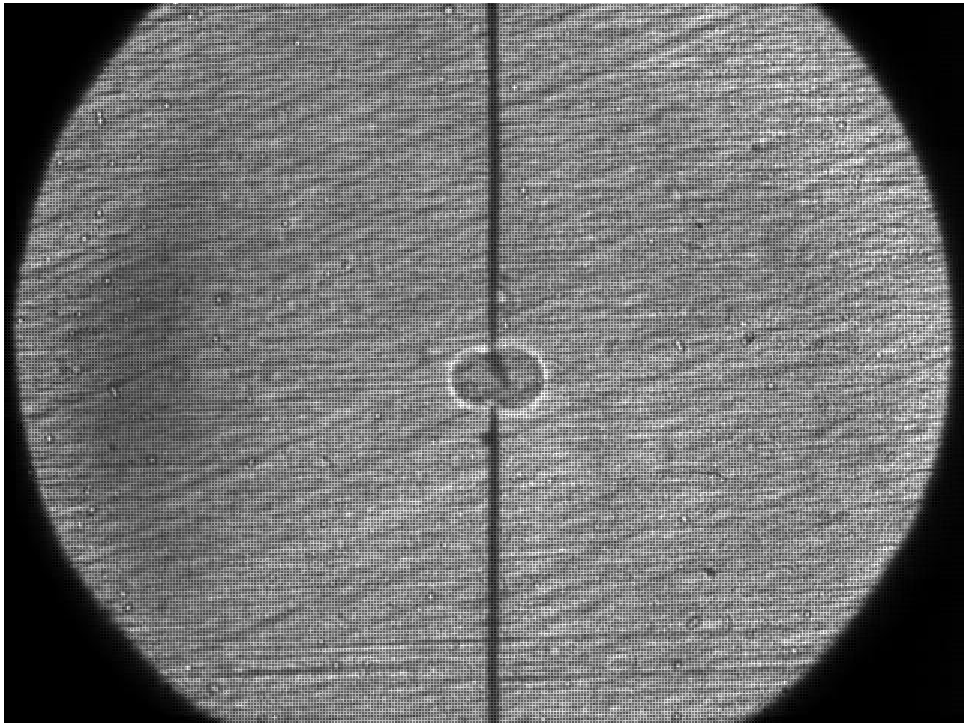
CH_4-CF_3Br-air Premixed Flame φ=1.2



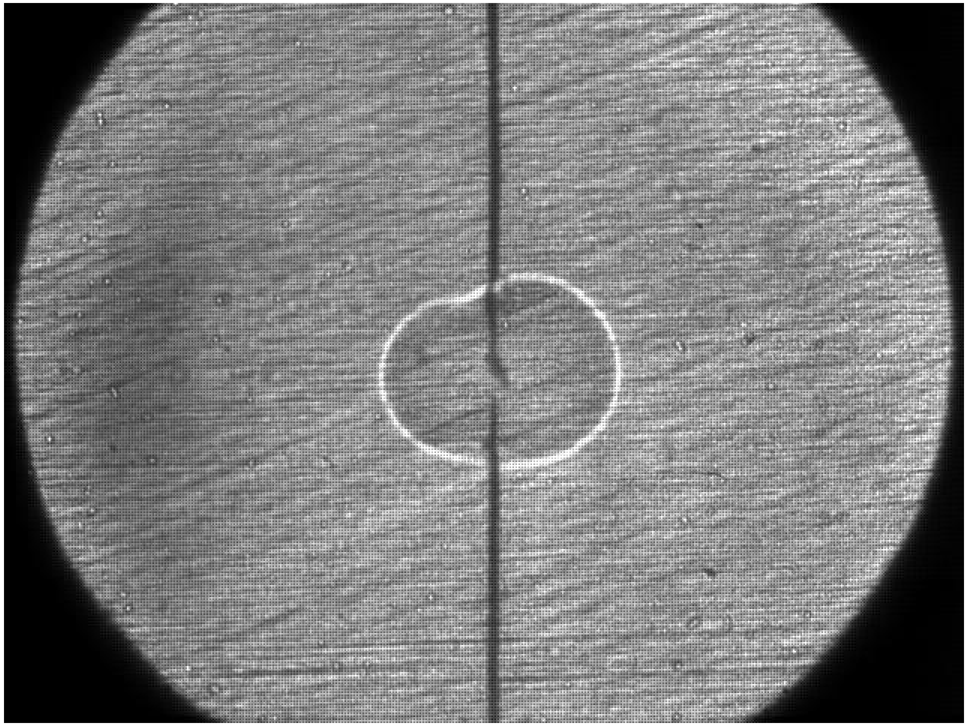
CH$_4$-CF$_3$Br-air Premixed Flame φ=1.2



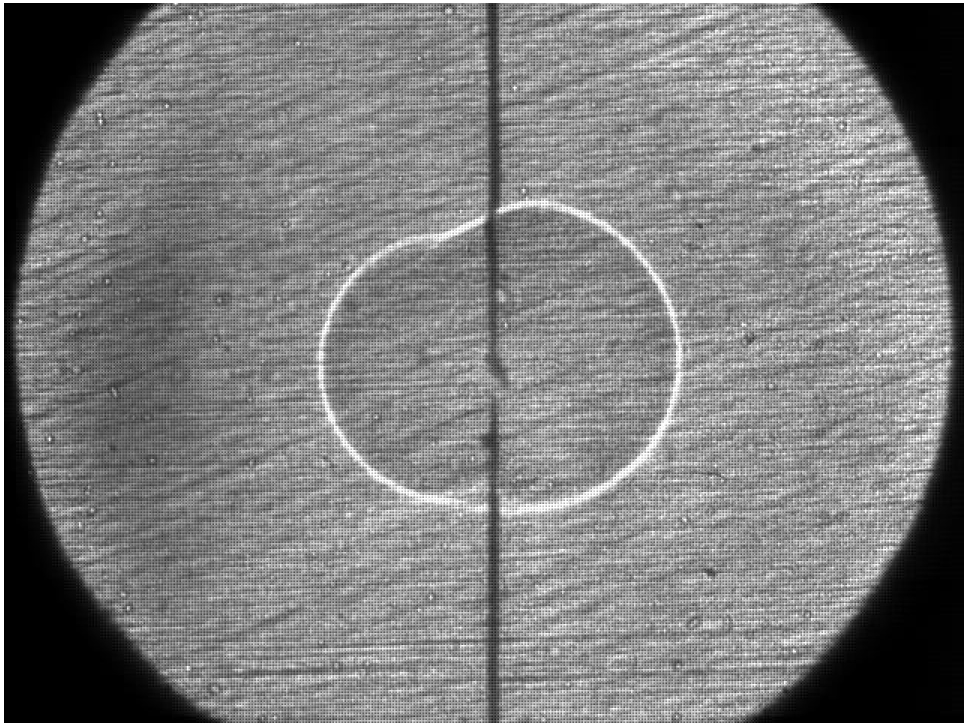
CH_4-2-BTP-air Premixed Flame φ=0.6



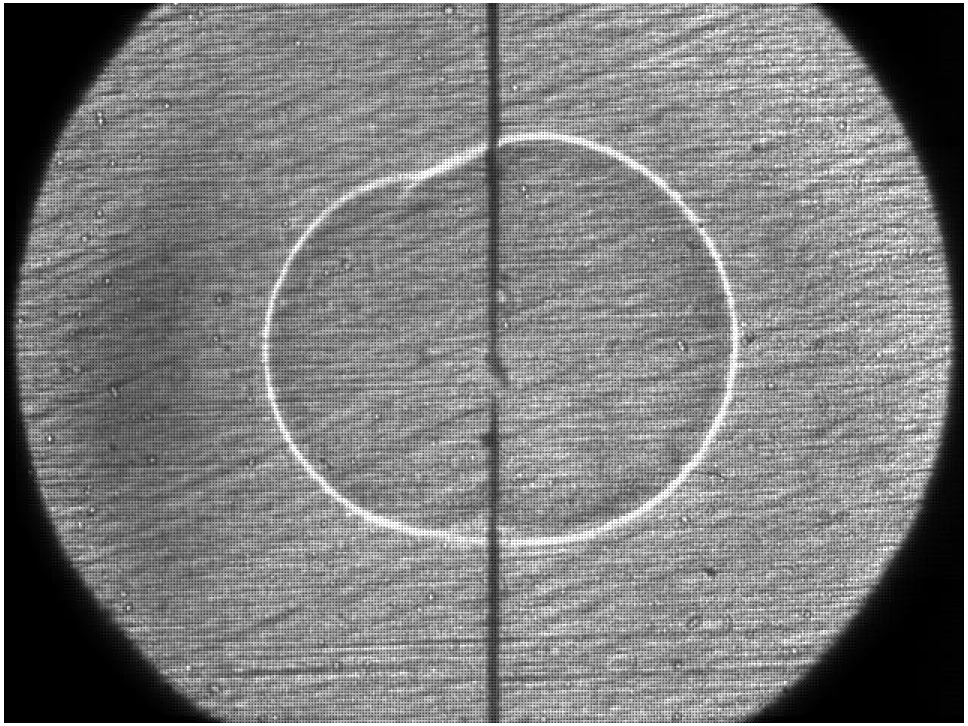
CH_4-2-BTP-air Premixed Flame φ=0.6



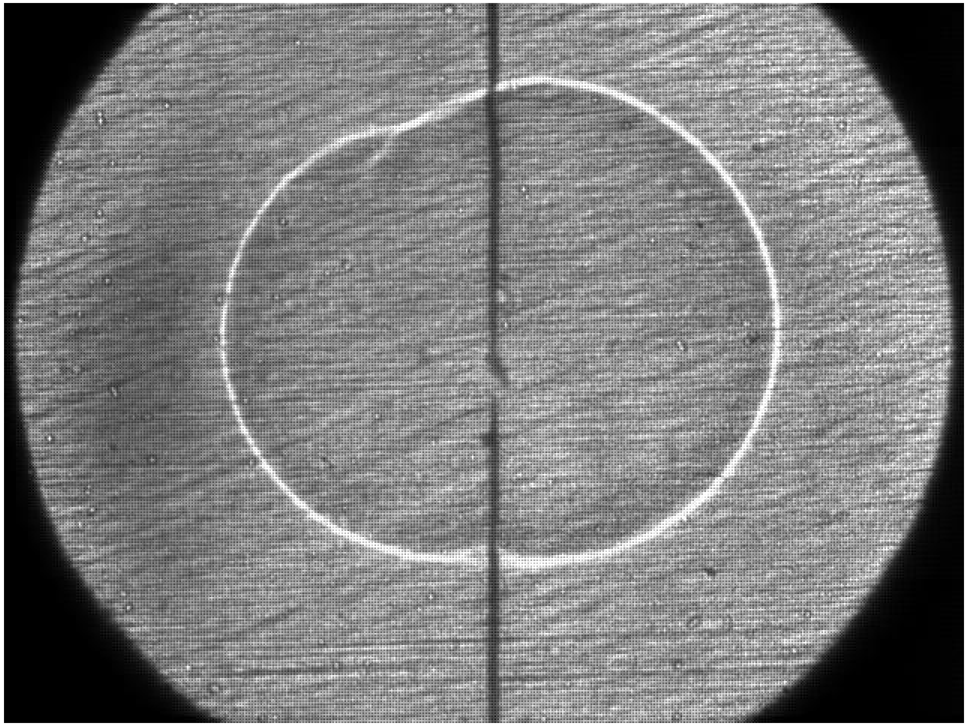
CH_4-2-BTP-air Premixed Flame φ=0.6



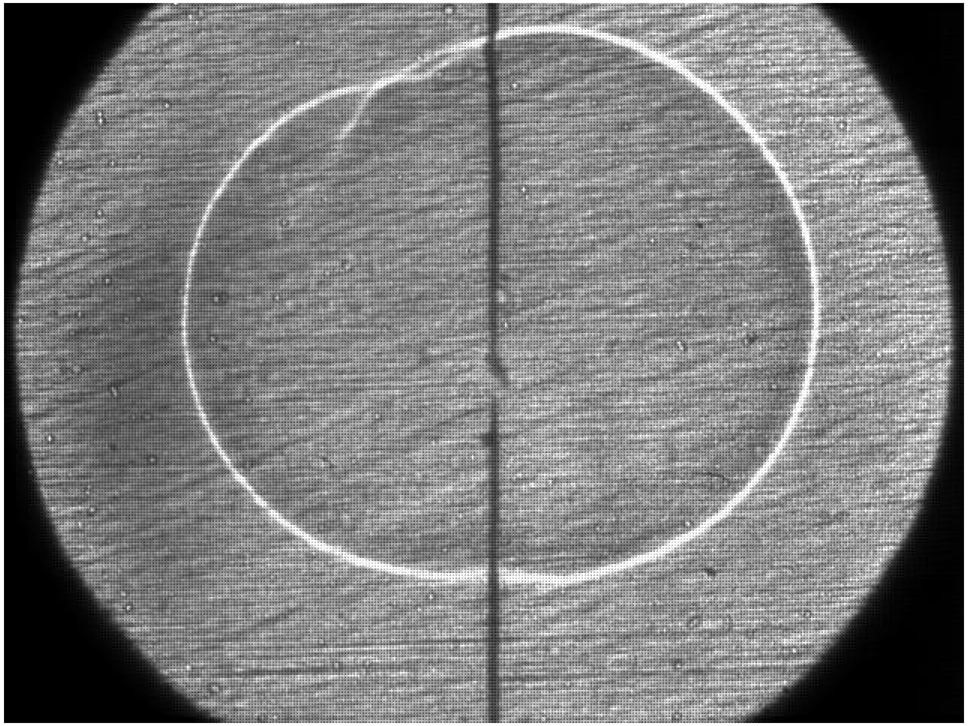
CH$_4$-2-BTP-air Premixed Flame φ=0.6



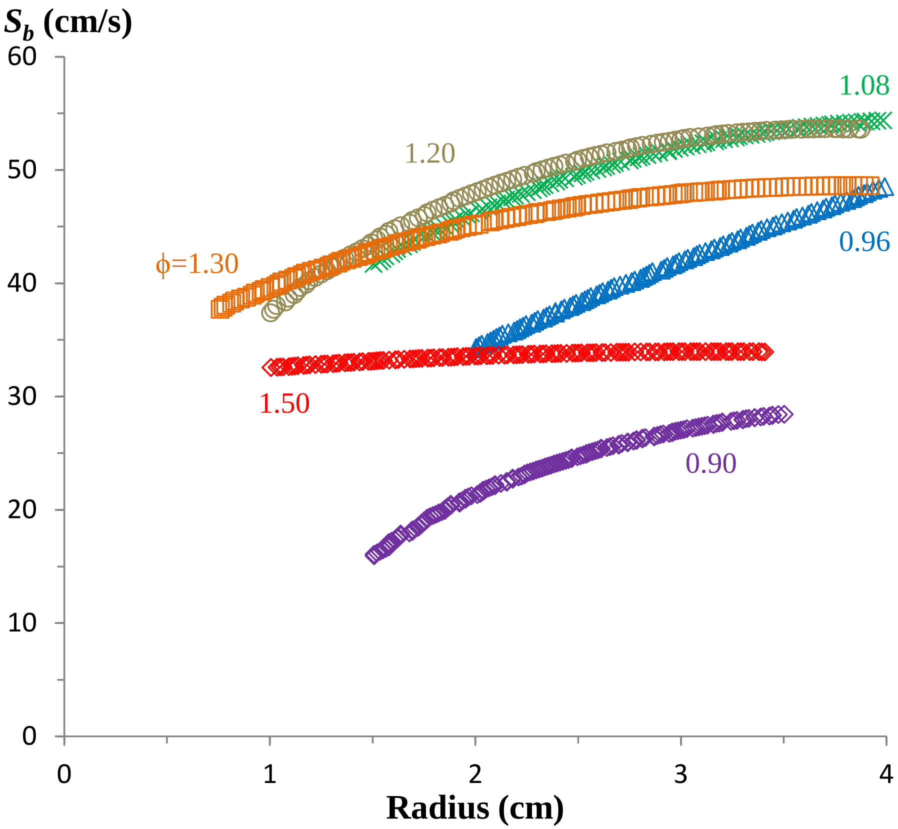
CH_4-2-BTP-air Premixed Flame φ=0.6



CH_4-2-BTP-air Premixed Flame φ=0.6



R32-air mixtures: Burned gas velocity changes as the flame radius changes (stretch effect).



Why is the Laminar Burning Velocity LBV Useful (i.e., is a Good Metric for Assessing Fire Risk)?

1. A single parameter that combines the effects of energy release, heat and mass transfer, and overall reaction rate.

$$S_L^o = (\alpha \, \omega_i)^{½}$$

S_L^o –burning velocity (1-D, planar, steady, laminar)

α : thermal diffusivity $=\lambda/\rho C_p$

ω_i : overall reaction rate = $[f][ox]Ae^{-E_a/RT}$

2. Predictions of turbulent flame speed are based on the laminar flame speed, so over pressure hazard and explosion hazard are both tied to S_L^o.

3. LBV is being adopted in codes and standards by industry.

Conclusions:

1. The determination of “Flammability” is device dependent.
2. Stable flames depend upon a fast enough chemistry to keep up with the flow field.
3. The flow field depends upon the test configuration (fluid flows, buoyancy, configuration, turbulence, etc.)
4. The speed of the chemistry depends upon the rate of reaction of the fuel with air. This depends upon the:
    - a.) concentration and types of reactants (fuel(s), air, impurities, etc.)
    - b.) reaction temperature, which depends upon the:
        - i.) initial temperature,
        - ii.) heat of combustion
        - iii.) heat capacity of the burned gases
        - iv.) radiation heat losses

5. Flame stretch (i.e., diverging streamlines through the reaction zone) can affect flame stability.

6. Turbulence affects the mixing of reactants, the transport rates of reactants into the flame, and the effective area of the flame boundary, and can increase flame propagation rate by orders of magnitude.

Publications:

Burrell, R., Pagliaro, J.L., and Linteris, G.T., "Effects of stretch and thermal radiation on difluoromethane-air burning velocity measurements in constant volume spherically expanding flames," *submitted to Proceedings of the Combustion Institute*, Dec. 2017.

Pagliaro, J. L., Linteris, G. T., "Burning velocities of marginally flammable refrigerant-air mixtures," in: *Proceedings of the 2016 Eastern States Section Meeting of the Combustion Institute, Princeton, NJ, March 13-16, 2016*, The Combustion Institute, Pittsburg, PA, 2016.

Talks:

"Burning velocities of marginally flammable refrigerant-air mixtures," Invited Plenary lecture at the 2016 Eastern States Section Meeting of the Combustion Institute, Princeton, NJ, March 13-16, 2016

"Sustainable Refrigerants: A Combustion Problem," Invited talk at the Institute of Combustion Technology, RWTH Aachen University, Aachen FRG, Sept. 15, 2016.

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