Effect of Cabin Pressure on the Piloted Ignition of Combustible Solids

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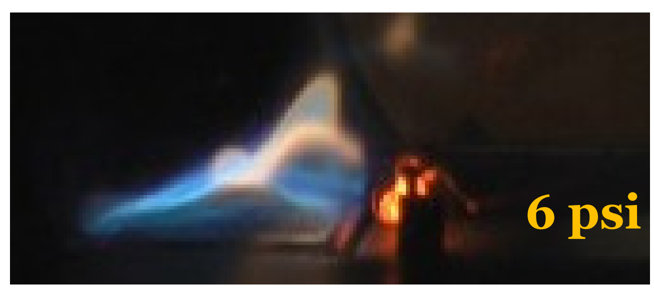
Motivation

- Fires in pressurized vehicles (aircraft, spacecraft or submarines) are extremely hazardous
  - Small compartments
  - Difficulty to escape
- Emphasis on fire **prevention:**
  - Material flammability
  - Effect of environmental conditions (oxygen concentration, pressure, radiant heat flux, etc) on ignition

Today's Talk

- Understand the physical mechanisms responsible for **ignition of solid combustibles** under **low pressure**
- Aircraft cabin pressure is typically pressurized to a "cabin altitude" of 8000 feet or less (~ 75 kPa)
- Are reduced pressure environments a higher fire risk?
  - Piloted ignition experiments with air at low P
    - *Forced Ignition and Spread Test* (FIST) apparatus at UC Berkeley to analyze material flammability
  - Analytical explanation of results



Lower ambient pressure can be found at…

- High Altitude

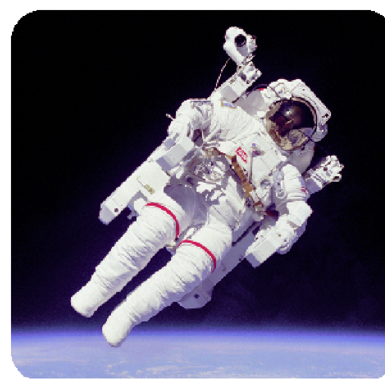
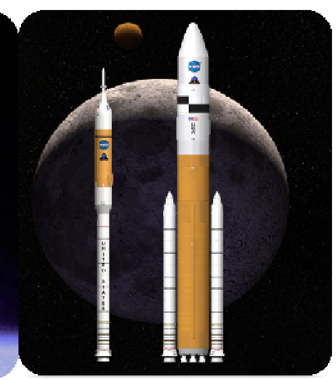
Lhasa, Tibet– 3,650 m
population 250,000

Quito, Ecuador- 2,850 m
population 2M

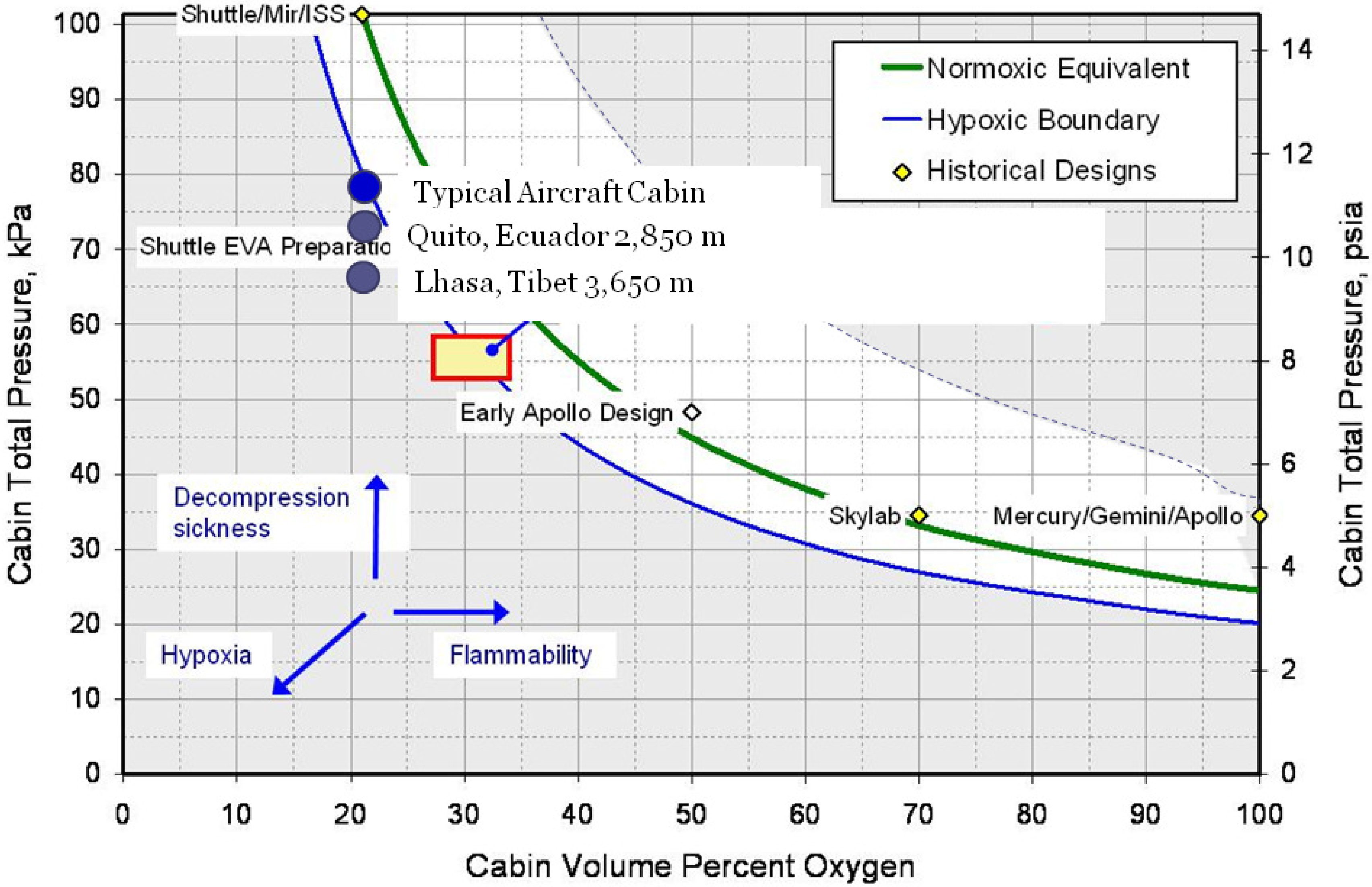
- Inside Aircraft



- Inside Spacecraft

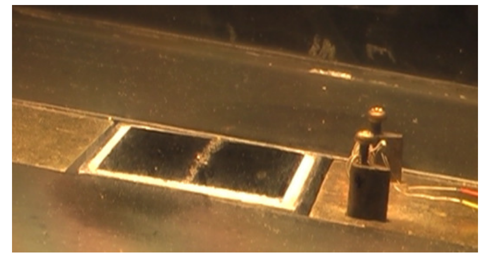
Cabin Environments

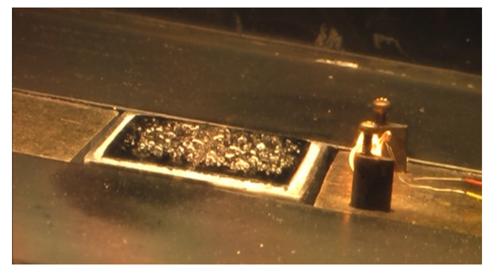


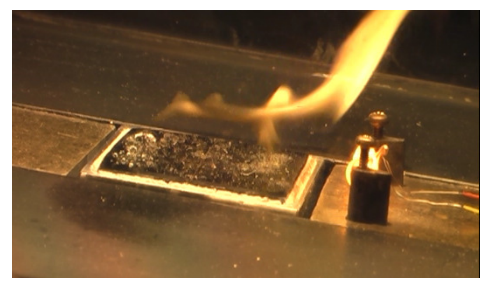
How does a solid fuel ignite?

Piloted ignition process:

1. Solid heating & pyrolysis
2. Mixing of gaseous fuel and air
3. Chemistry: fuel/air mixture reaches lean flammability limit at high temperature igniter
4. If sufficient pyrolysis gases are generated: a diffusion flame will anchor on solid (burning) → critical mass flux at ignition



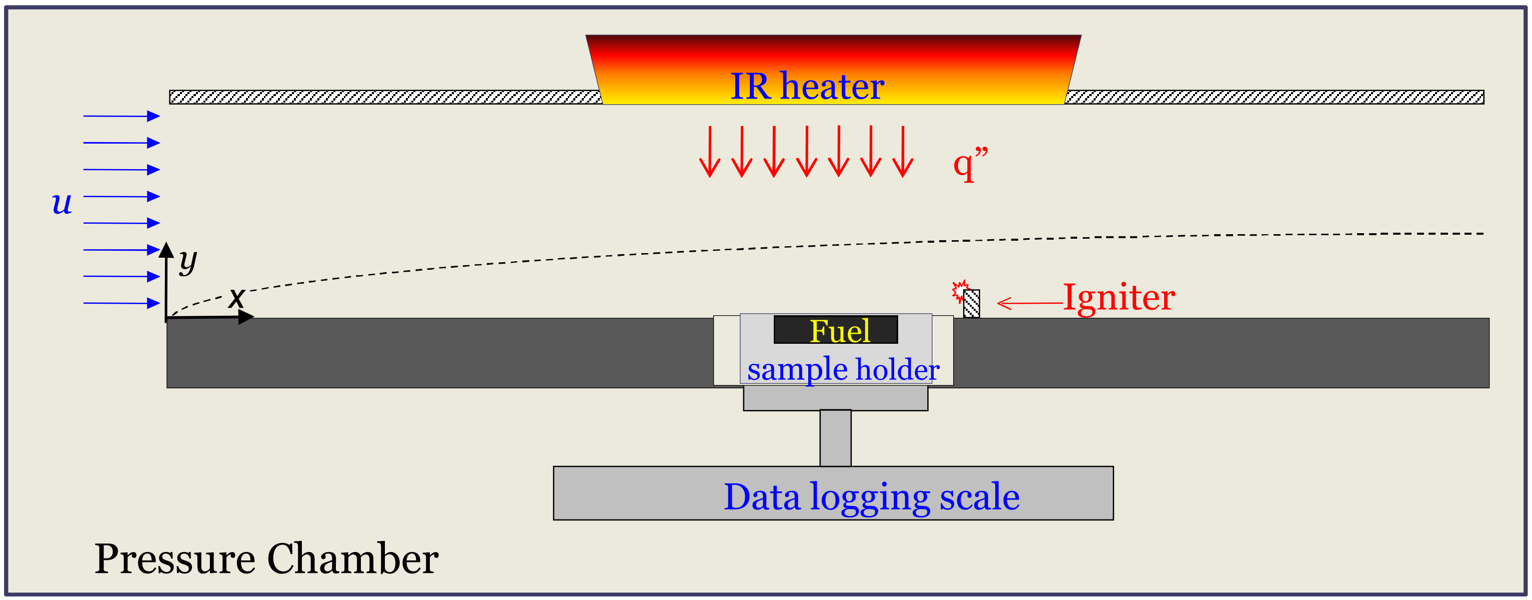




Possible Fire Scenario

- **Heat source: electronic component overheating**
- **Fuel: polymeric materials used in panels, blocks, covers**
- **Ignition source: spark from electrical arching**

Forced Ignition and Spread Test (FIST)



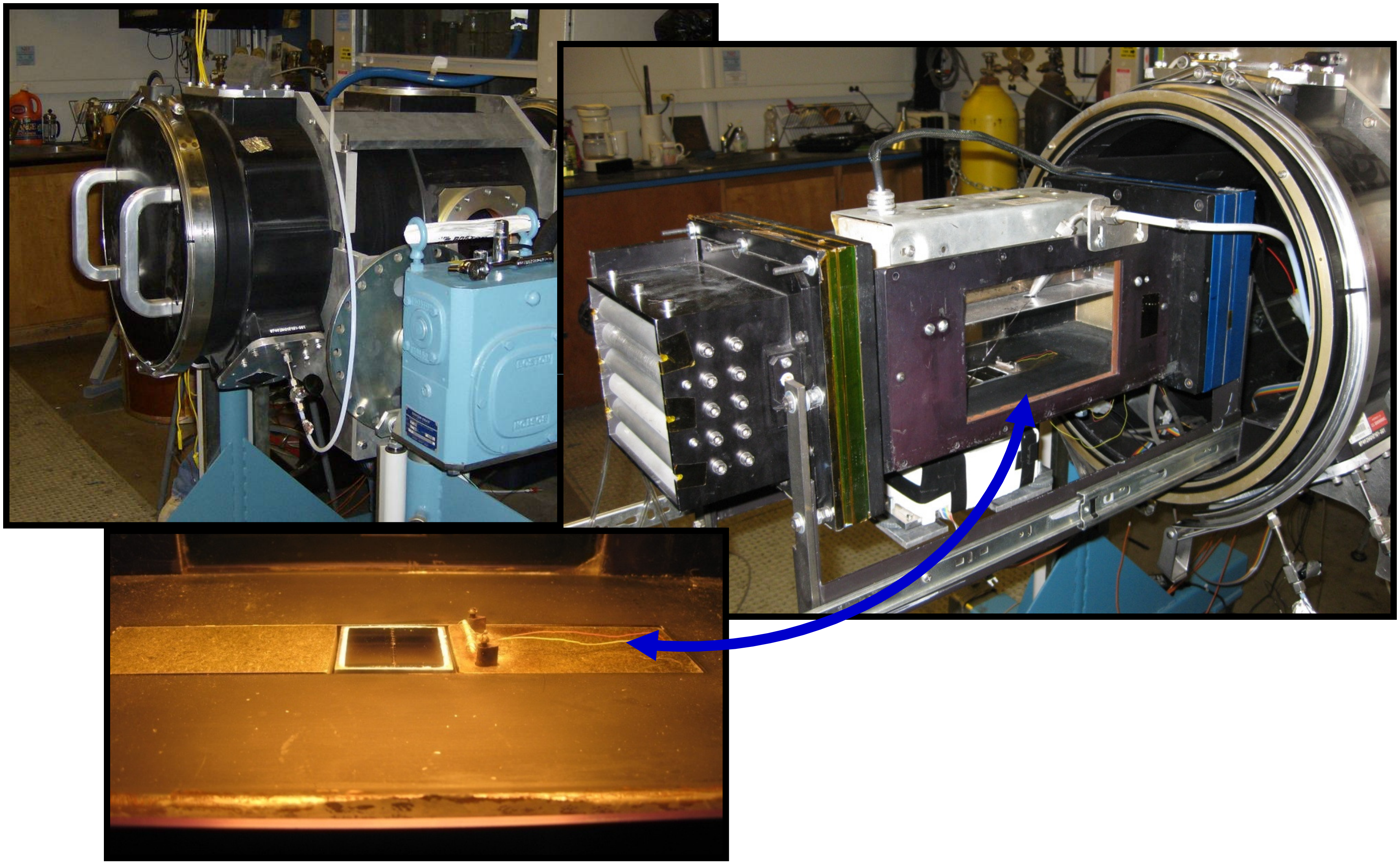
Variables:
-air flow velocity
-incident heat flux
-ambient pressure

Material: PMMA

Measure :
-$T_{surface}$ vs. time→ t_{ig}, **time to ignite**

-Mass vs. time → $(dm/dt)|_{tig}$ **mass loss rate at ignition**

FIST Apparatus

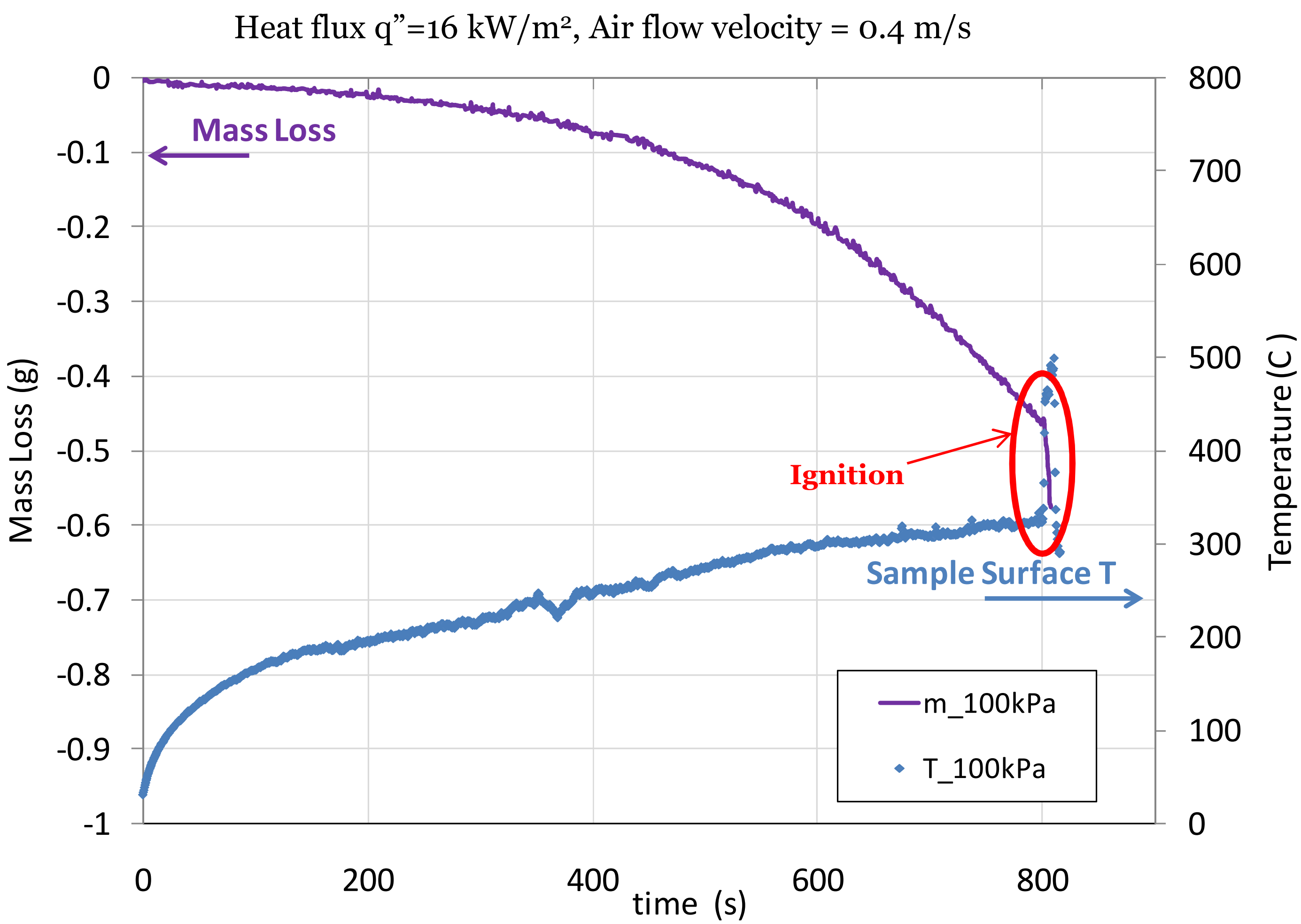


Video of Test

Air velocity =0.4 m/s , q"= 16 kW/m^2, P=12 psi

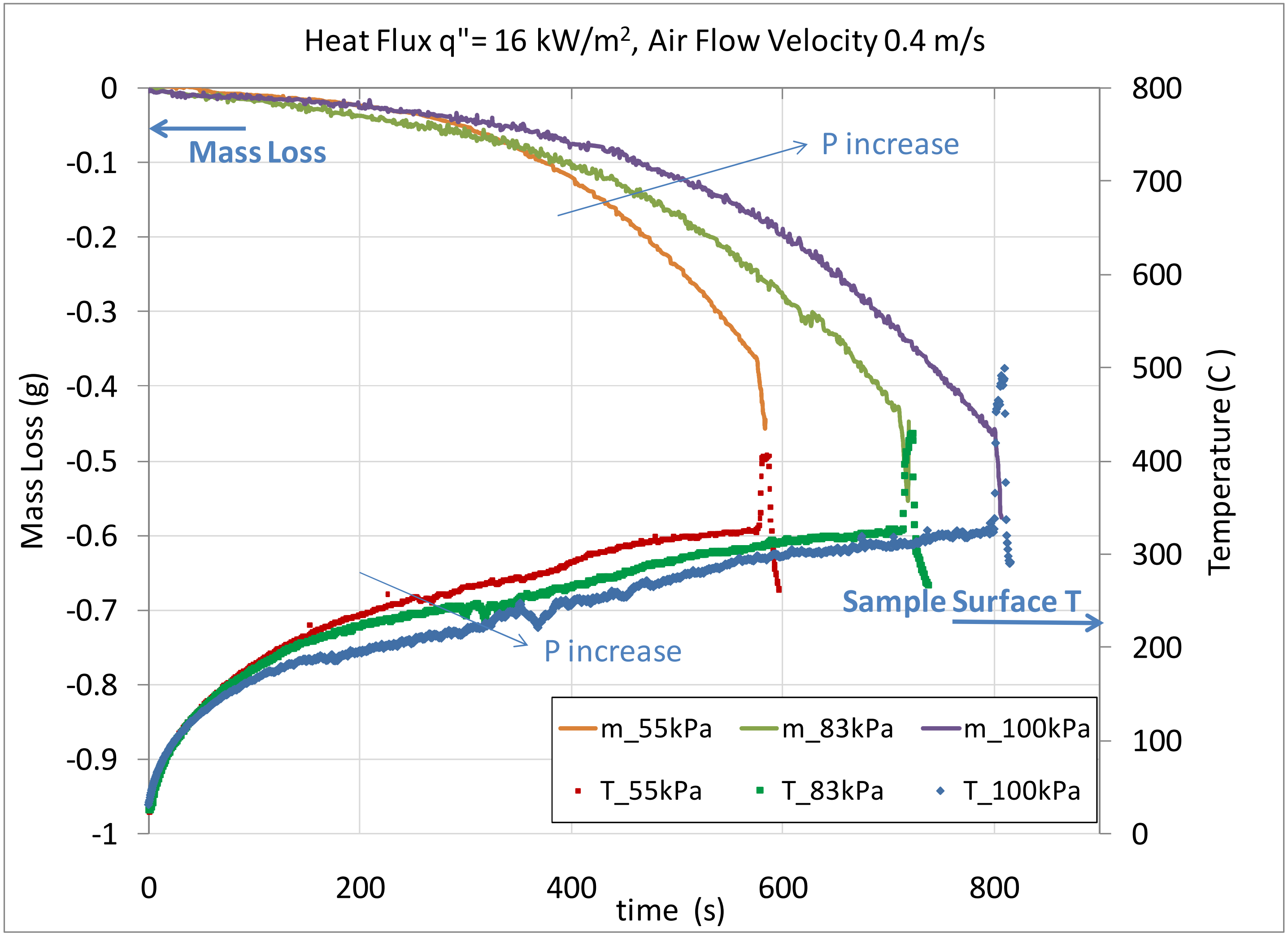
Experiment Example

- 100 kPa & Air (21% O_2 by volume) -Raw Data



Experimental Results

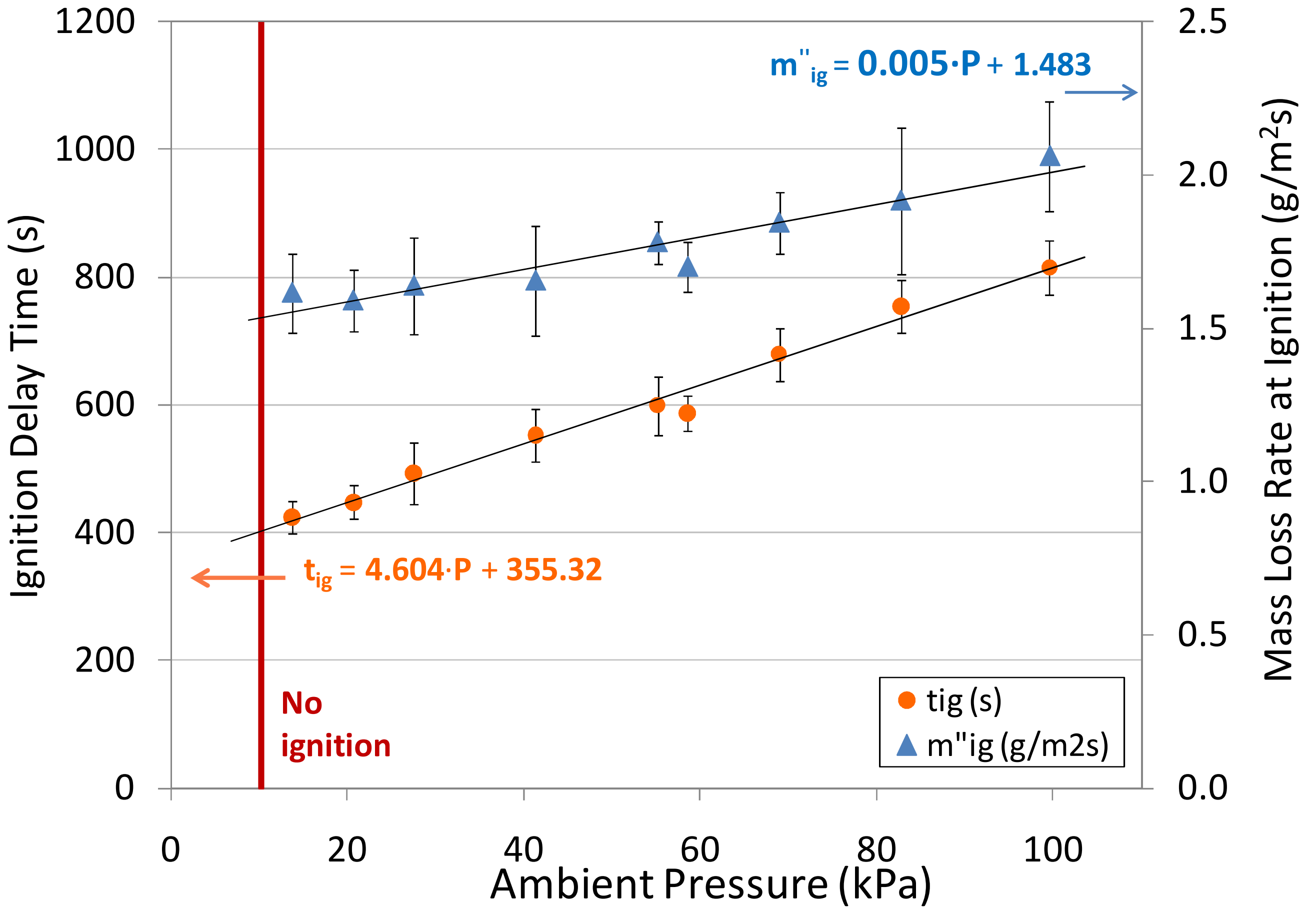
- Pressure Comparison : 55, 83 & 100 kPa (Raw Data)



Experimental Results

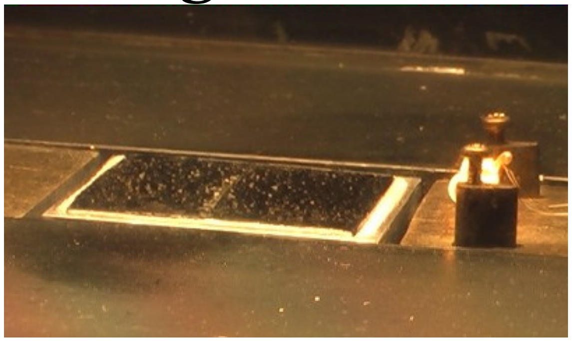
- Ignition Delay & Mass Loss Rate at Ignition vs. Total Pressure

Air (21% O_2 by volume) at 0.4 m/s , q"=16 kW/m²

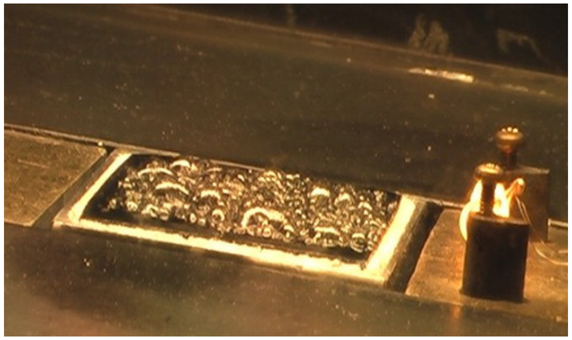


Visual Observations

- Different surface behavior: bubble formation, size and bursting characteristics



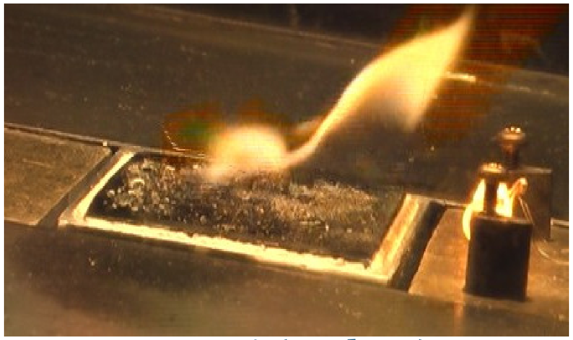
3 psi (21 kPa)



12 psi (83 kPa)

- Flame establishment over solid surface also different

3 psi (21 kPa)



12 psi (83 kPa)

Effect of Pressure (Part1)

- Ignition delay time, t_{ig} :
  - $t_{ig} = t_{heating} + t_{mixing/transport} + t_{induction}$

- Heating time: convective heat loss over flat plate
  - Forced flow: $h \propto \mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}$
  - Natural convection: $h \propto Gr^{1/4}\,\mathrm{Pr}^{1/4}$
  - Mixed flow $h \propto \mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}\sqrt[4]{1+\frac{Gr}{\mathrm{Re}^2}\mathrm{Pr}^3}$

Re= ρUL/μ , Re~ P
Pr≠f(P)
Ideal gas: Gr ~ P^2

→ **h~$P^{1/2}$**

As pressure decreases, convective heat loss of material to surroundings is lower → heats more rapidly

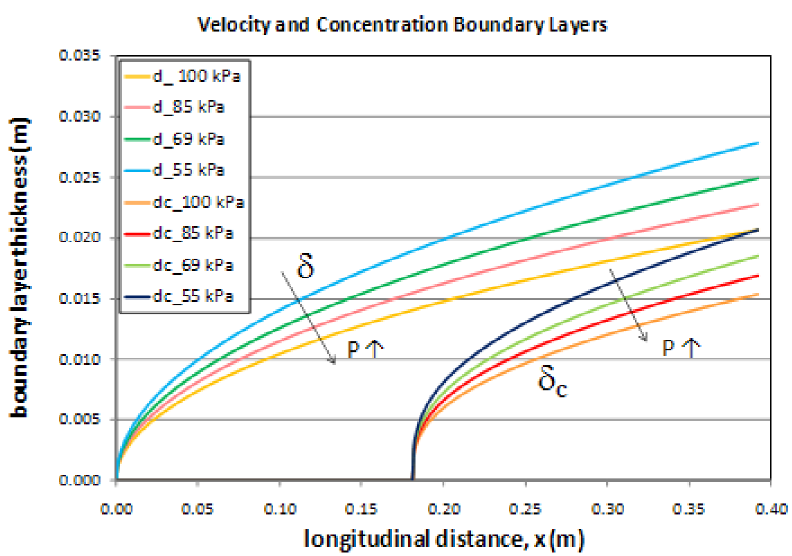
Effect of Pressure (Part 2)

- Mixing/transport time: Mass loss rate at which a flammable concentration (LFL) is obtained at the pilot

Simplified Analysis : Boundary Layer – Integral Method

- 3rd order polynomials for velocity, temperature and species profiles: $\frac{u}{U_\infty} = \frac{3}{2}\frac{y}{\delta} - \frac{1}{2}\left(\frac{y}{\delta}\right)^3$ $\quad \frac{T - T_0}{T_\infty - T_0} = \frac{3}{2}\frac{y}{\delta_T} - \frac{1}{2}\left(\frac{y}{\delta_T}\right)^3$ $\quad \frac{Y_F - Y_{FO}}{Y_{F\infty} - Y_{FO}} = \frac{3}{2}\frac{y}{\delta_c} - \frac{1}{2}\left(\frac{y}{\delta_c}\right)^3$

- Integrate BL Eqns.→ analytical expressions for hydrodynamic, thermal and concentration BL thicknesses:



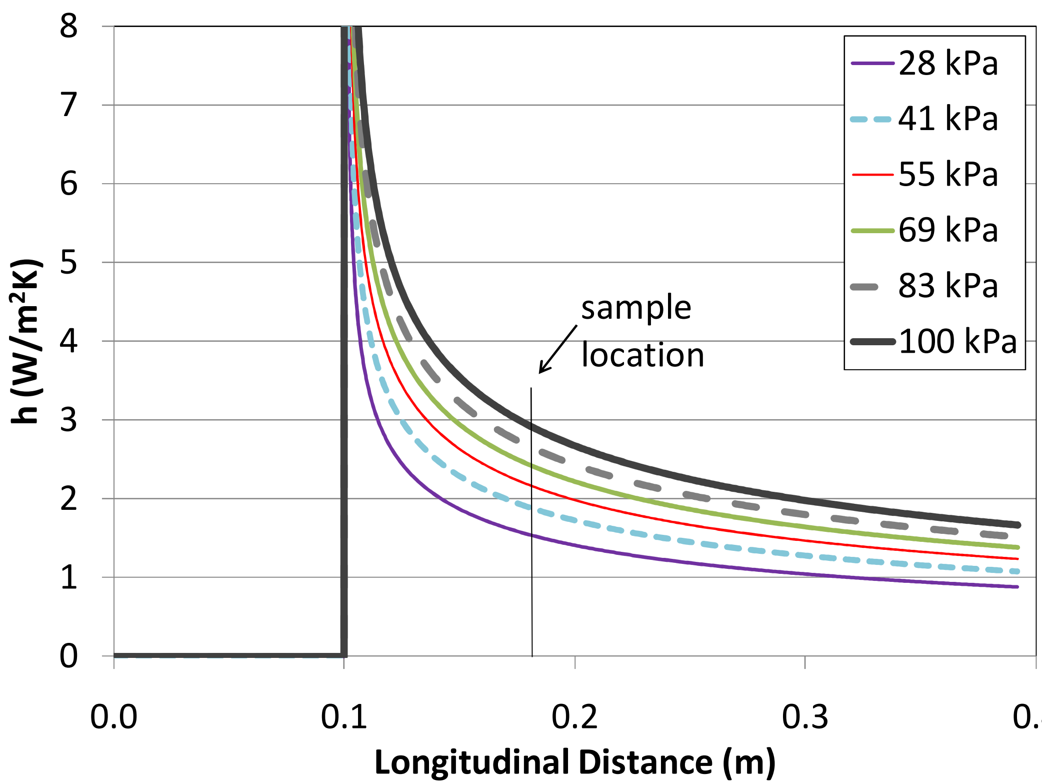
$$\delta = \sqrt{\frac{280}{13}\frac{\nu x}{U_\infty}} \approx 4.64\sqrt{\frac{\nu x}{U_\infty}}$$

$$\delta_T = \left[\frac{10\alpha x \delta}{U_\infty}\left(1 - \frac{x_T}{x}\right)\right]^{1/3}$$

$$\delta_c = \delta\left\{\frac{13D}{14\nu}\left[1 - \left(\frac{x_c}{x}\right)^{3/4}\right]\right\}^{1/3}$$

Simplified Analysis
Heat Transfer Coefficient

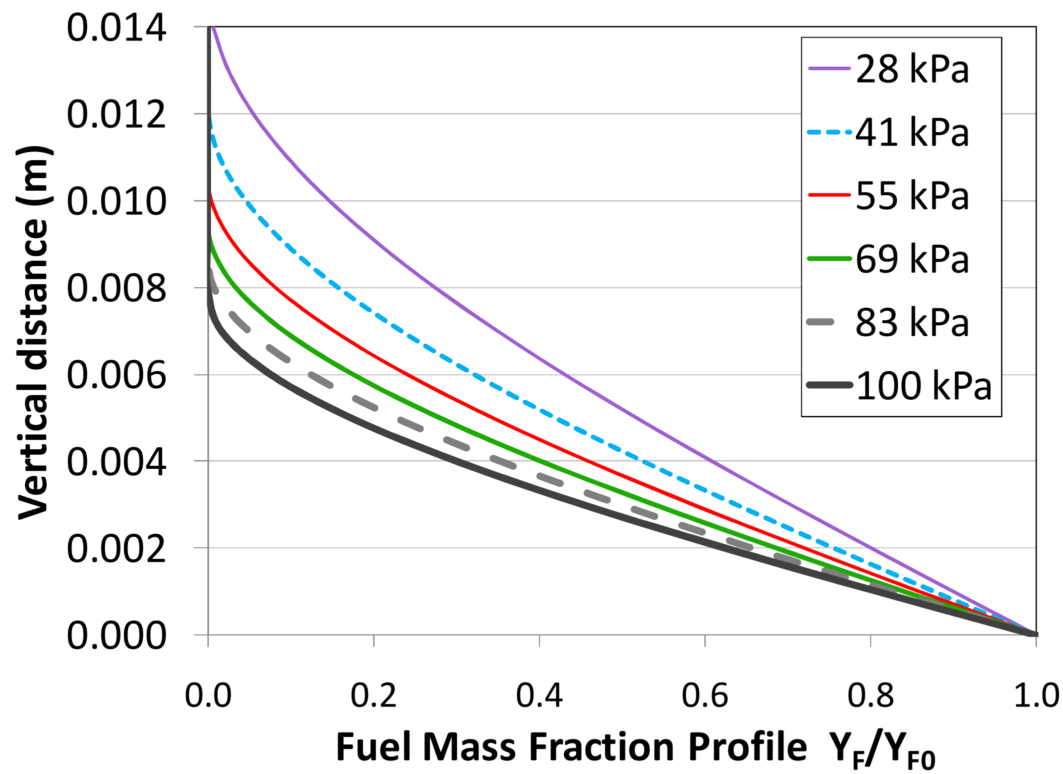
- $h \approx k/\delta_T$
- At the sample location, h decreases by 13% when the pressure is reduced from 100 kPa to 75 kPa



Simplified Analysis
Species Concentration

- Reduced pressure leads to a thicker species boundary layer

$$\frac{Y_F}{Y_{F0}} = 1 - \frac{3}{2}\frac{y}{\delta_c} + \frac{1}{2}\left(\frac{y}{\delta_c}\right)^3$$

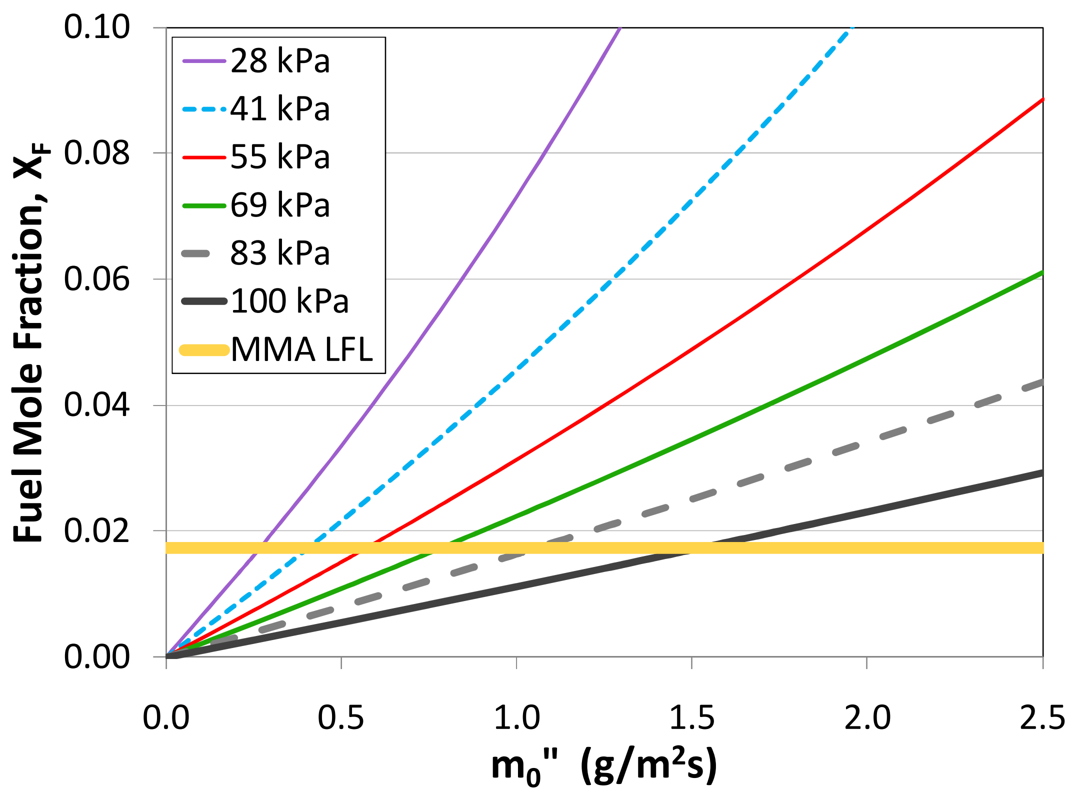


Simplified Analysis

- To determine mass loss rate:

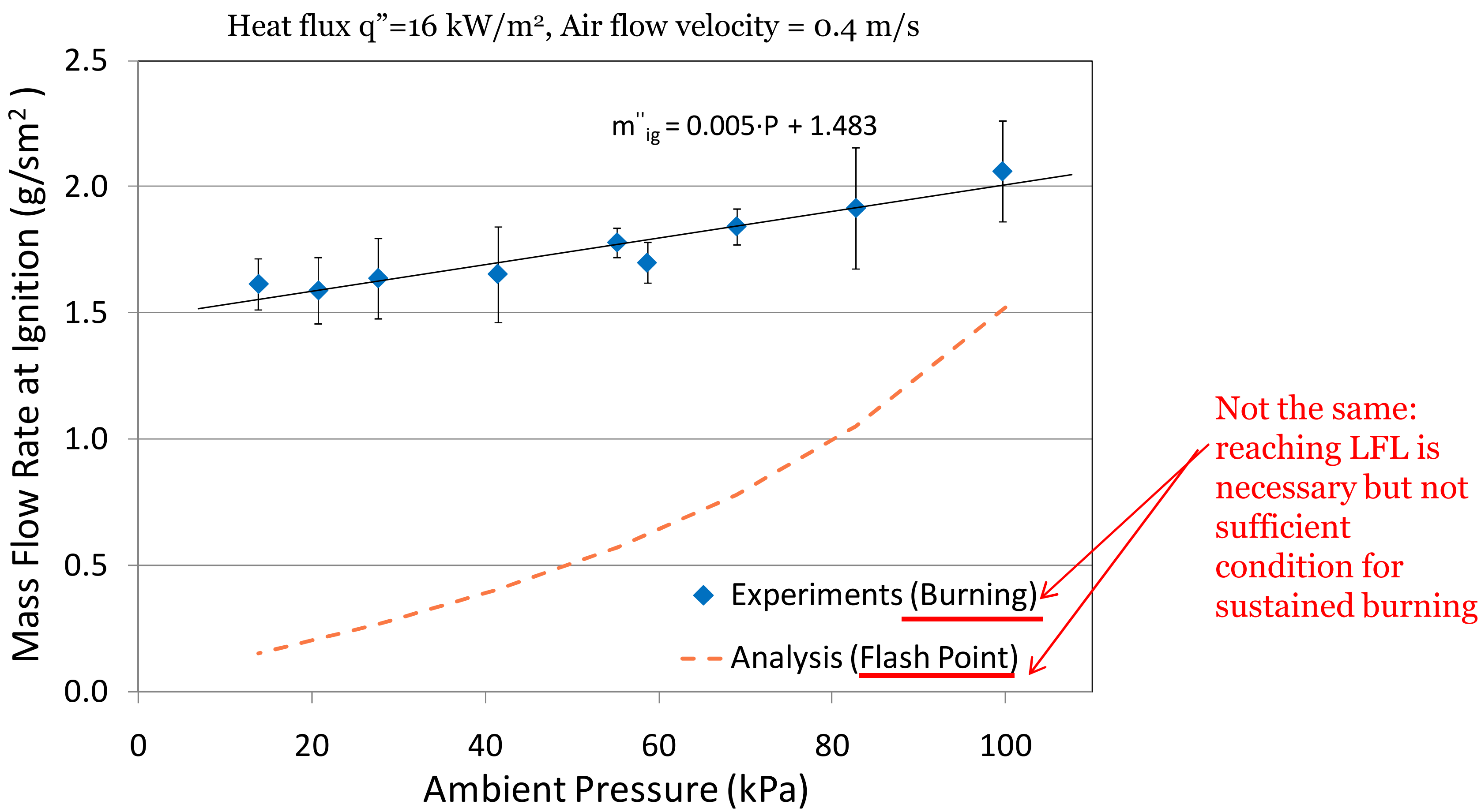
$$\dot{m}'' \approx -\rho D\left(\frac{\partial Y_F}{\partial y}\right)_y = \frac{3}{2\delta_c}\rho D Y_{F0}\left(1-\left(\frac{y}{\delta_c}\right)^2\right)$$

- At lower P, required mass flow rate of fuel to reach lean flammability limit at igniter location is reduced



Comparison of *Trends*

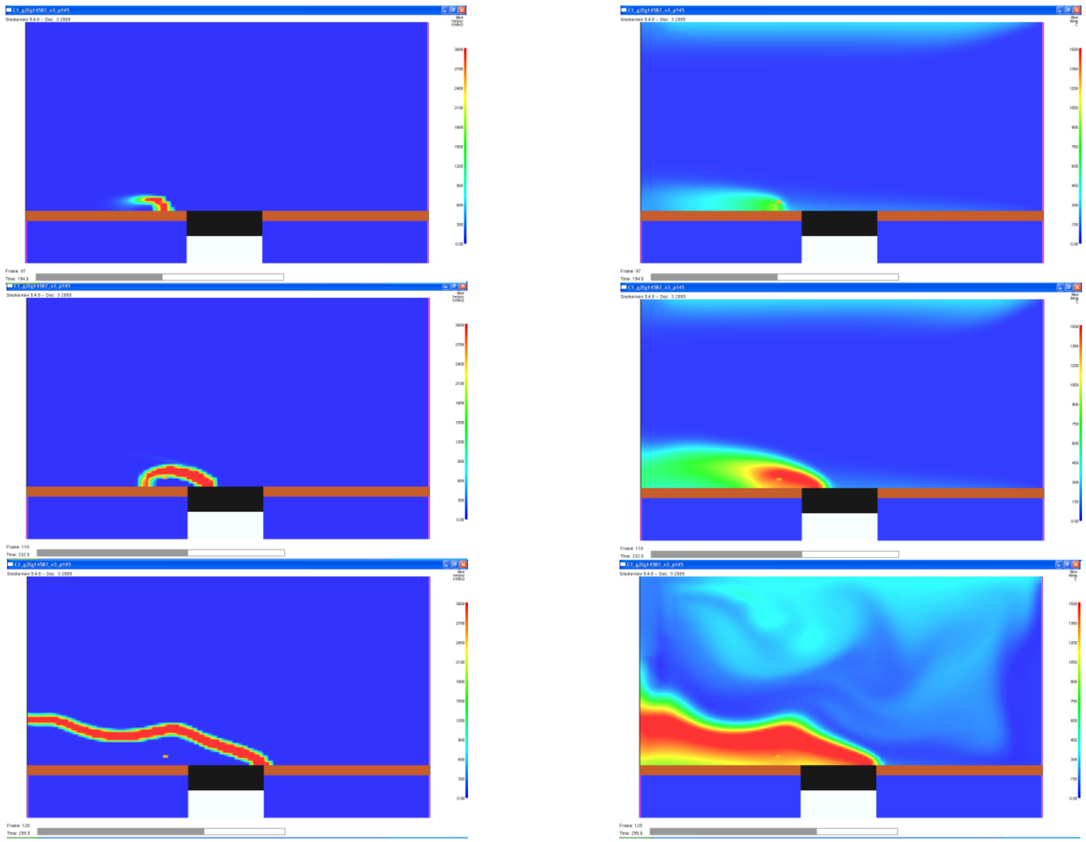
- Mass Loss Rate at Ignition vs. Pressure



Current Work

Fire Dynamics Simulator (FDS) 2D model

- PMMA is irradiated under a prescribed heat flux → the solid decomposes and the products of the pyrolysis ignite in the gas phase.



Premixed flame appears in the gas phase

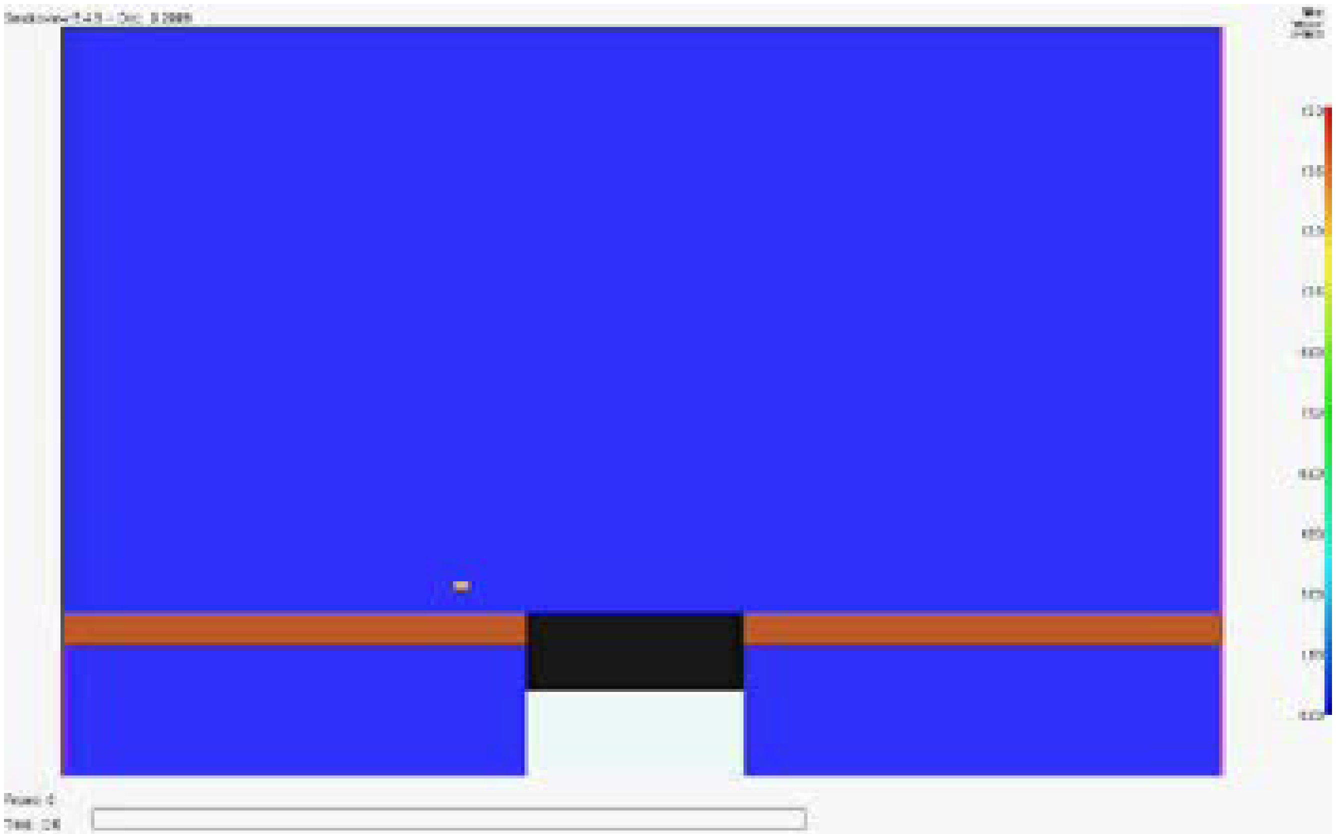
Flame 'jumps' on to solid fuel surface

Diffusion flame anchored on solid surface travels

HRR **Temperature**

Current Work

- Fire Dynamics Simulator (FDS) 2D model
  - Heat release rate/volume:



Summary & Conclusions

- Experimental results from piloted ignition show that t_{ig} & m''_{ig} decrease with pressure:
  - At 75 kPa , Δt_{ig} = - 15%
    $\Delta m''_{ig}$ = -7%
- A theoretical explanation provides insight on the effect of pressure on:
  - Heat transfer coefficient
  - Mass loss rate required to reach a flammable mixture
- Next steps include developing a numerical model using FDS to compare to experiments
- Overall, **a reduction in ambient pressure leads to an increased fire risk**

Acknowledgements

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