# Fires - What fundamentals and why?

- The context
- Combustion Science and Fire Science
- Ignition, Flame spread, pool fires.
- Dimensionless numbers and Scaling laws

JGI-Chola workshop, 20 Feb 2014

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# The context

- High rise buildings with individual dwellings of varying content – depending on "richness"
- Houses/apartments fashioned after the west (with larger fraction of wooden panels, flooring, draperies)
- Textile stores, shops – highly loaded "fuel" small spaces
- Poor dwellings closely spaced with thatched roof
- Industries using fuel or producing fuel
- Propellant and explosive based industries (firecracker production facilities)
- Transportation of fuels and chemicals.

# The context…

Beyond “common sense” can we state what “fire loading” of what kind can lead to what problem so that legislation can then take over to prevent occurrences of fire?

Building codes are not static. They must keep pace with new materials and understanding based on experiments, modeling and computations.

It is not material development alone; Ignition, fire spread, flash-over, fire movement out and into building space all matter. These need to be calculated, calibrated with experiments on model situations and used as tools for design.

**Smoke Soot and Fire (reasonably High temp)**

Radiation – small

Radiation – large

Both free convective flows

Questions – what led to ignition; why is the fire spread so intense? – a recent example – train and volvo bus fires.

Not-so-large a fire, but potential for storage related explosive fire

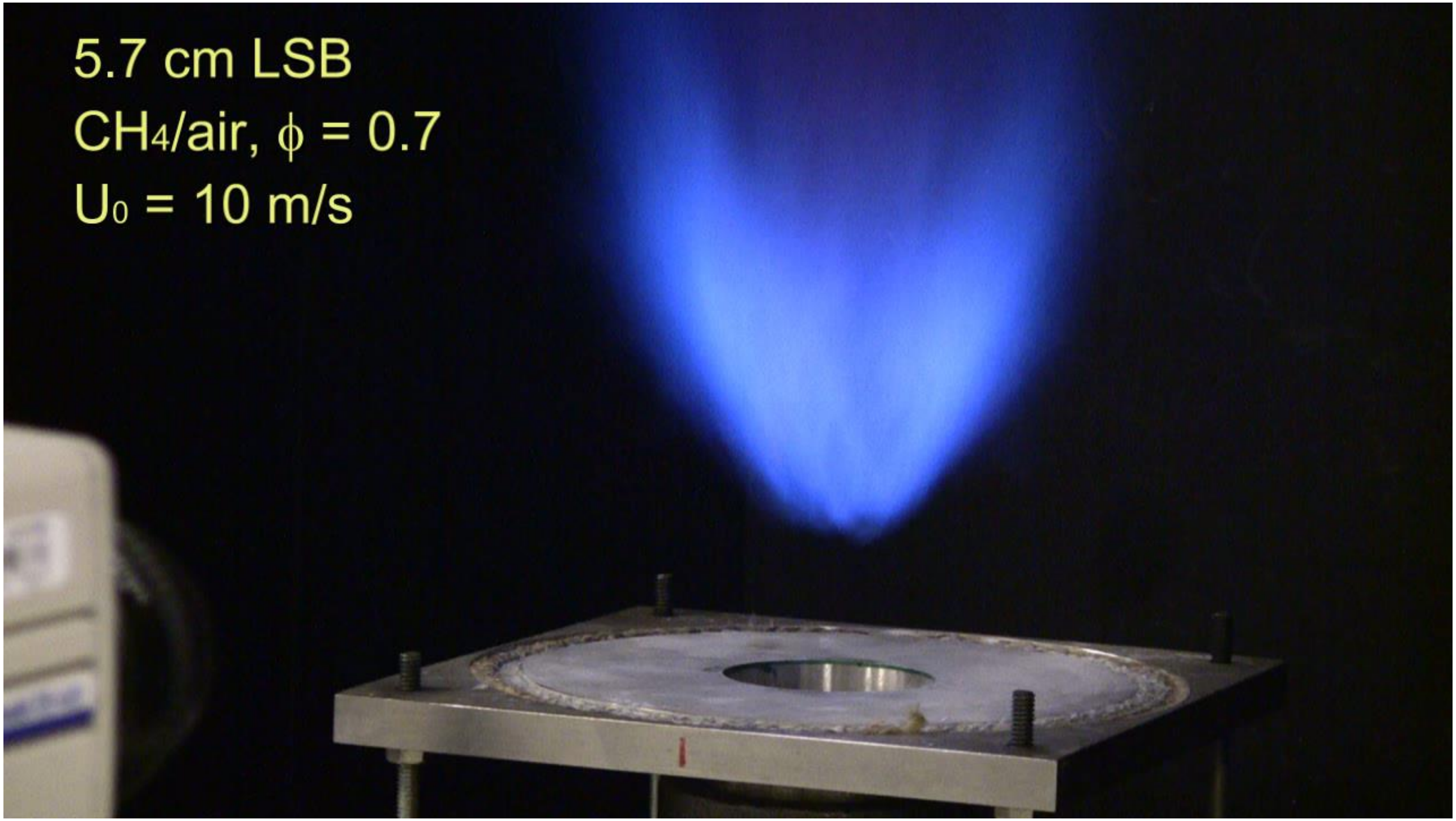
A large industrial fire

Medium-intensity surface fire in an open dry deciduous forest near Chandrapur, Maharashtra

Travelling Fires with a Tornado

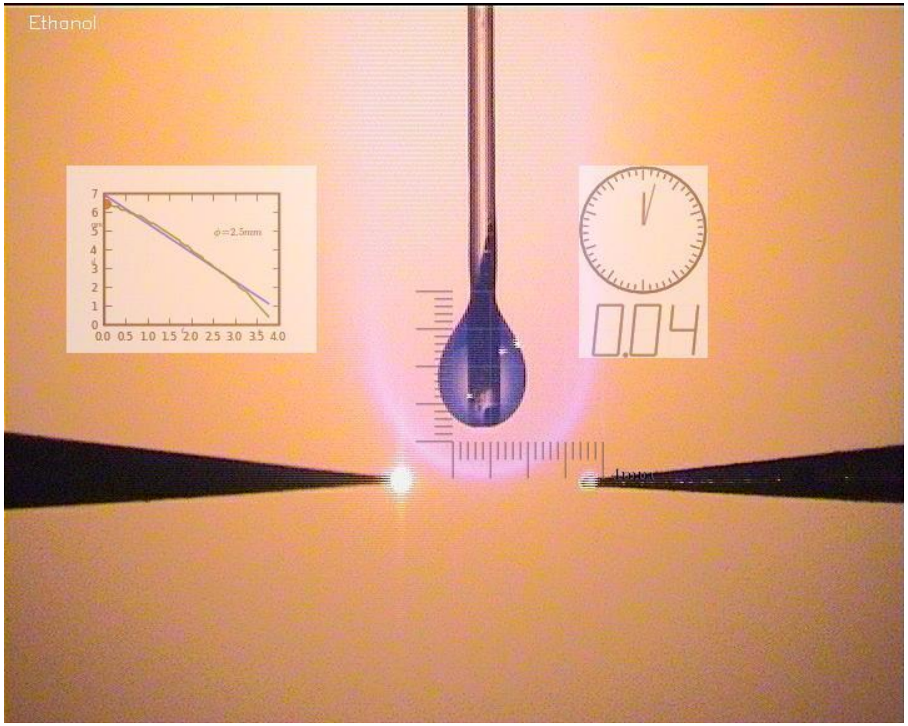
Dispensing fire extinguishing agents with an aircraft

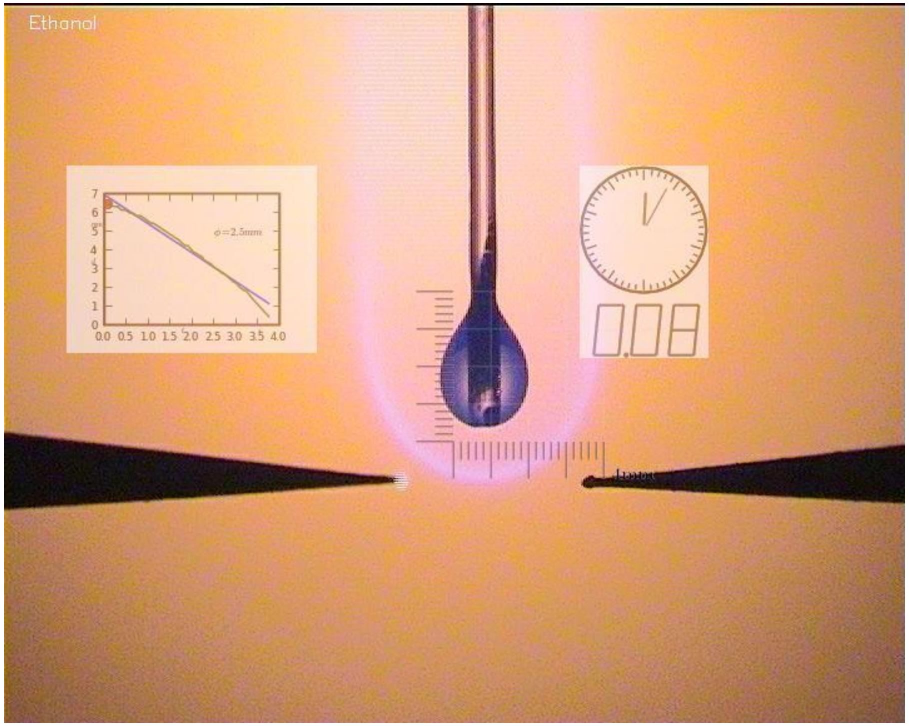

**Oil rig (BP) sinks in Gulf of Mexico after explosion**


5.7 cm LSB
CH4/air, ϕ = 0.7
U0 = 10 m/s

Natural gas – 4 mm nozzle

Natural gas – 8 mm nozzle



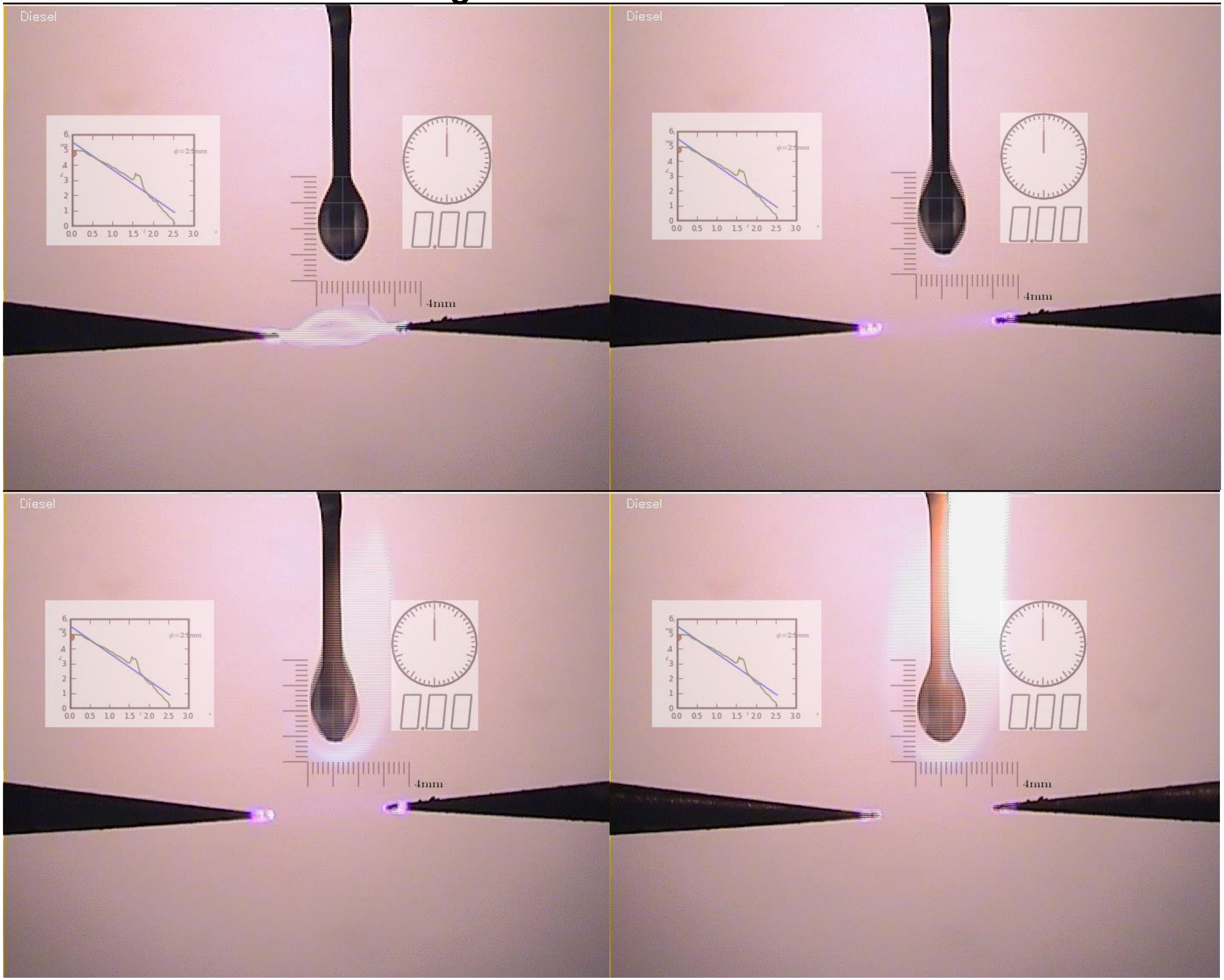



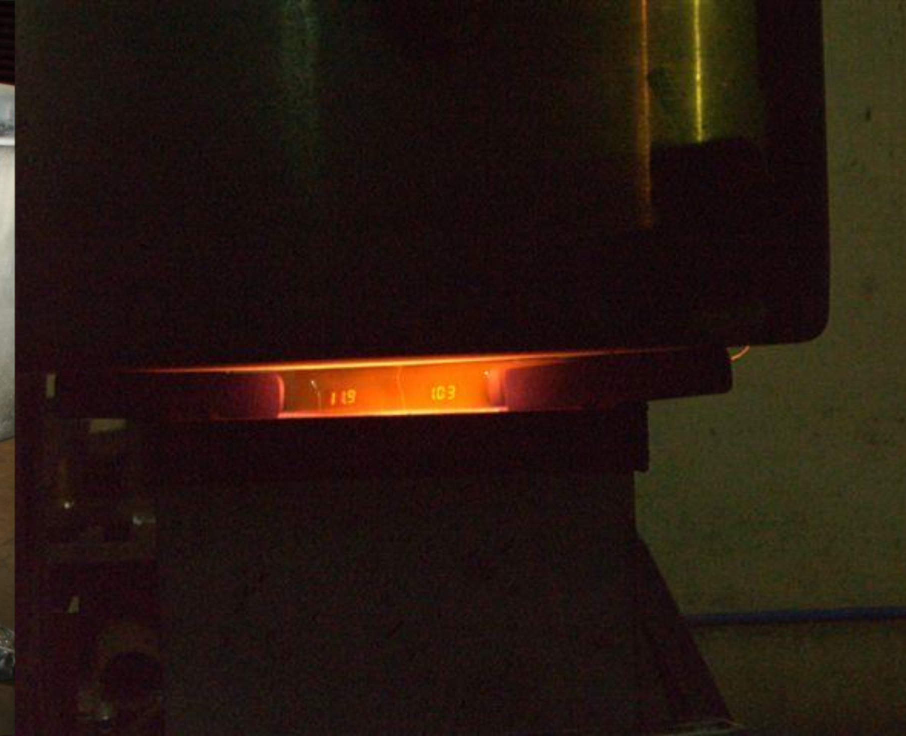

**40 ms+, spark ending**

**80 ms+, 0.5 mm thick flame**

# Ethanol

# Diesel - ignition and combustion




High temperature clean solid fuel combustion

# Gaseous, liquid and solid fuels

## Common questions

- What controls the ignition – gaseous, liquid and solid fuels?
- What is the spread rate or burn rate of the fuels
- What aspects control the extinction phenomena
- How therefore can we engineer materials and operating conditions to prevent fire?

## Approach

- Basic phenomena – mixing (fluid flow related) and chemical reactions and their interactions, vaporization or pyrolysis (for complex liquid or solid fuels)
- In the case of liquid and solid fuels, controlling heat flux to the surface coupled to burn rate should be determined

# On to fundamentals

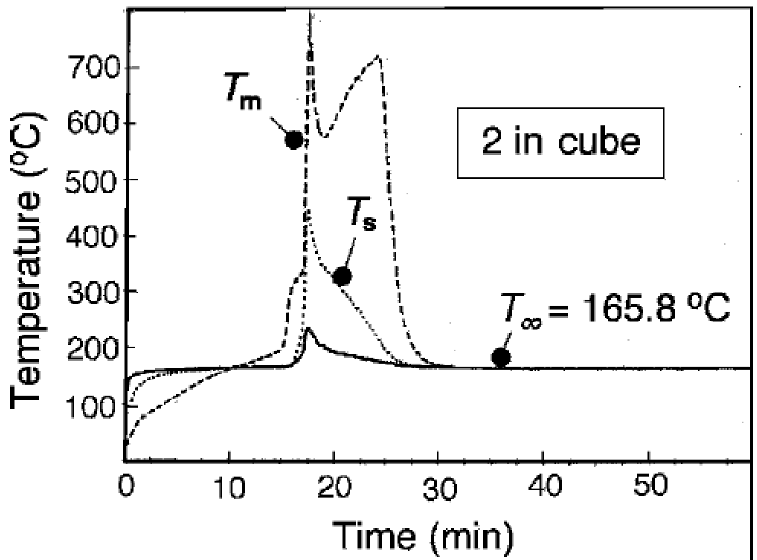
# More on: what is it that is meant by understanding fire behavior?

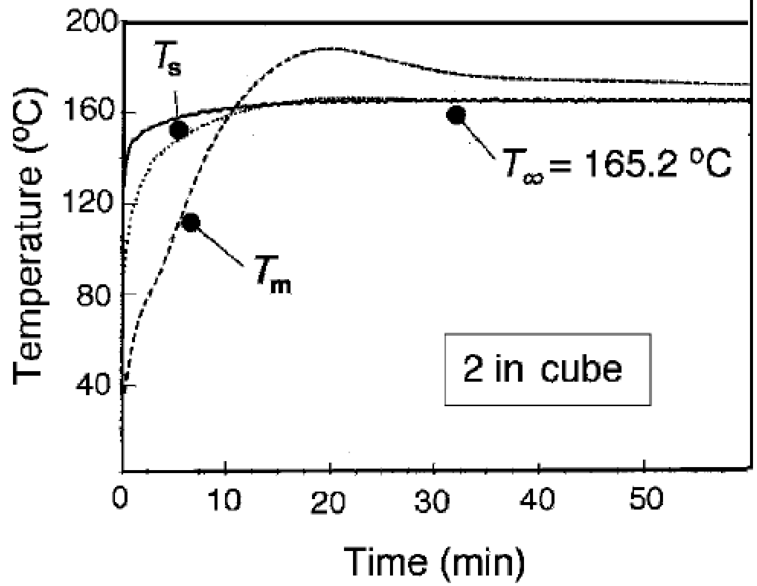
- Examples from some typical situations (Indian as well).
- A half-smoked cigarette is left on a sofa unattended. – would this lead to the start of a fire? If so, can I add a fire retardant to the material of the sofa to delay the ignition? Can I prevent the emission of toxic compounds if ignition takes place at all.
- The valve of a LPG cylinder is stuck in part-open position. It is noticed after the leakage is smelled after a while. Would this lead to a fire? an explosion?
- A large pile of textiles is placed in a large room that has other heat generating processes going on with transfer of heat by convection and radiation to the pile. Would this lead to starting of a fire or is it safe? Is it possible to distinguish between a natural incident and arson?

# Ignition,
# Pool fires.

# Examples….

- A cubical stack of natural foam rubber pillows was stored in a basement near a furnace. That part of the basement could achieve 60 °C. A fire occurs in a furnace area and destroys the building. The night watchman is held for arson. However an enterprising investigator suspects spontaneous ignition – related to the size of the stored material, its properties and the ambient temperature.
- This problem is classical in the area of spontaneous ignition of solids.




The material – compressed cotton block

Note that at 165.2°C, things are "cool"

At 165.8°C, things go overboard – there is ignition.

The cause of this sensitive dependence is
The sensitivity of the chemistry to temperature:

$dT/dt \sim \exp(-E/RT)$

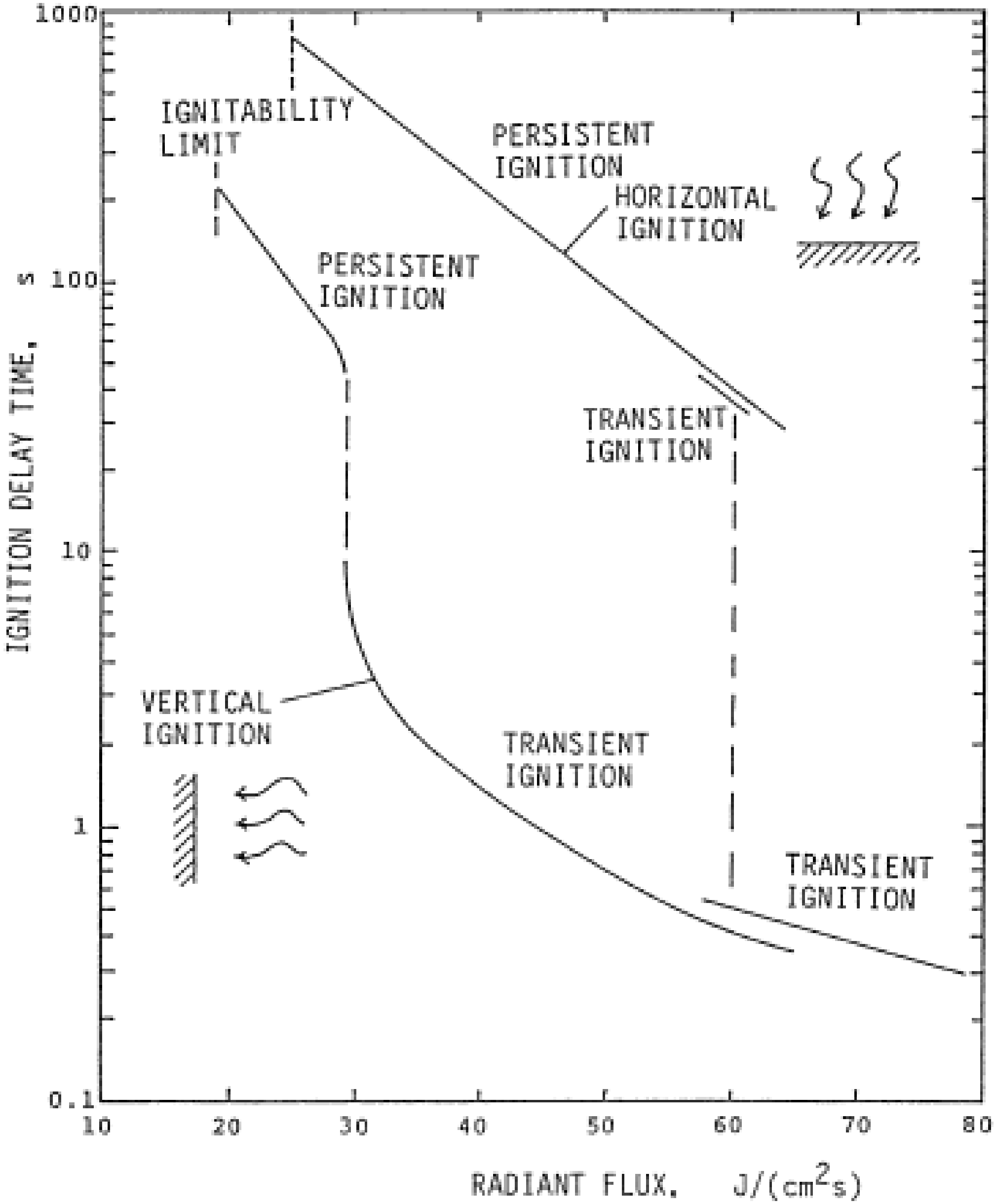



FIG. 1. Ignition delay time for radiative ignition of a slab of polymethylmethacrylate [22].

From:
Hirano,
International
Comb Symp,
2002

# Ignition theory – Time for igniting thin and thick materials

## Analysis

- Thermally Thin

$$t_{ig} = \rho \tau c \frac{(T_{ig} - T_0)}{(\dot{q}''_e - \dot{q}''_{crit})}$$

- Thermally Thick

$$\frac{1}{\sqrt{t_{ig}}} = \left(\frac{\pi}{4} k\rho c\right)^{-1/2} \frac{(\dot{q}''_e - \dot{q}''_{crit})}{(T_{ig} - T_o)}$$

For a thin material, the material can be taken to be at the same temperature throughout and a heat balance at the surface gives:

$$\rho c_p d \frac{\mathrm{d}T}{\mathrm{d}t} = \dot{q}'' = \dot{q}''_e - h_c(T - T_\infty) - \epsilon(T^4 - T^4_\infty)$$

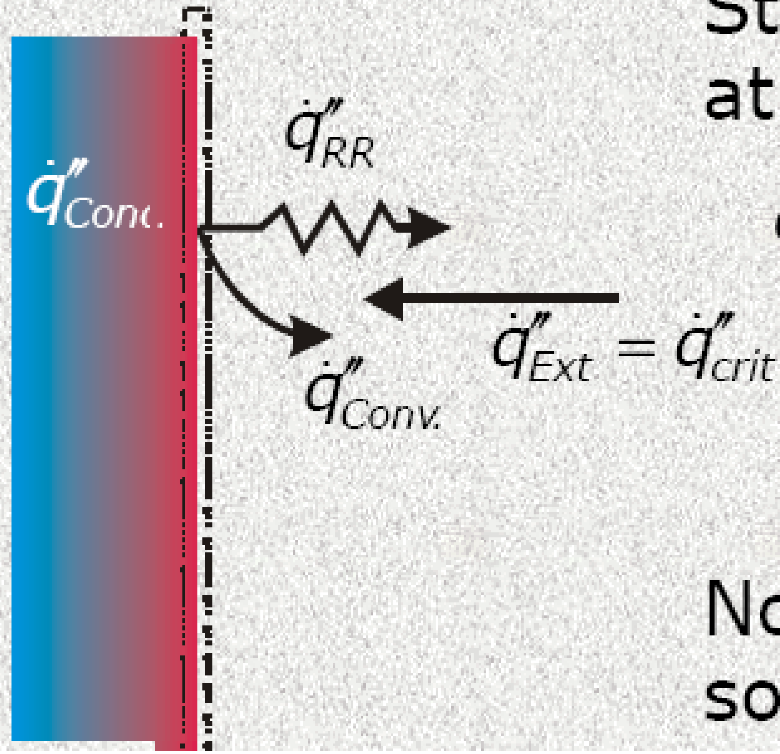
Where $\rho c_p d$ is the mass per unit area. Expressing $dT/dt$ by $(T_{ig} - T_0)/t_{ig}$ and rearranging the terms one gets the expression for ignition time ($t_{ig}$) as indicated earlier with the negative terms Representing heat loss by convection and re-radiation.

$t_{ig}$ = ignition time, $\rho$ = density, $c_p$ = specific heat, $d$ = $\tau$ = thickness;
$T_{ig}$ = Ignition temperature, $T_0$ = ambient temperature,

For the second case, one needs to solve $\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$ with boundary conditions

$x = 0, \quad T = T_s,$ etc and you will get the result.

# Estimating the Ignition Temperature




Steady State Energy Balance at Surface

$$\dot{q}''_{crit} = \varepsilon\sigma\left(T_{ig}^4 - T_{\infty}^4\right) + h_c\left(T_{ig} - T_{\infty}\right)$$

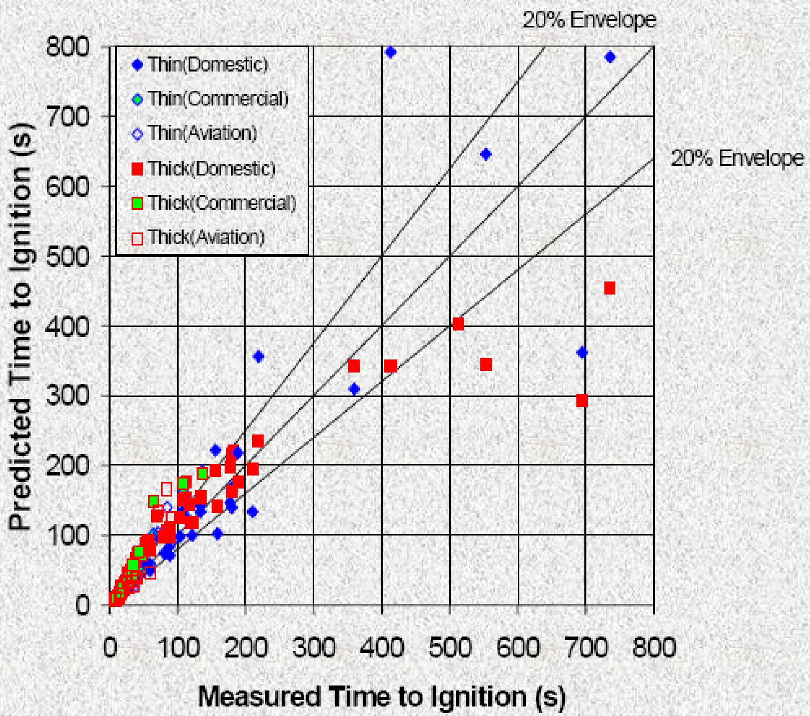
Radiative losses

Convective losses

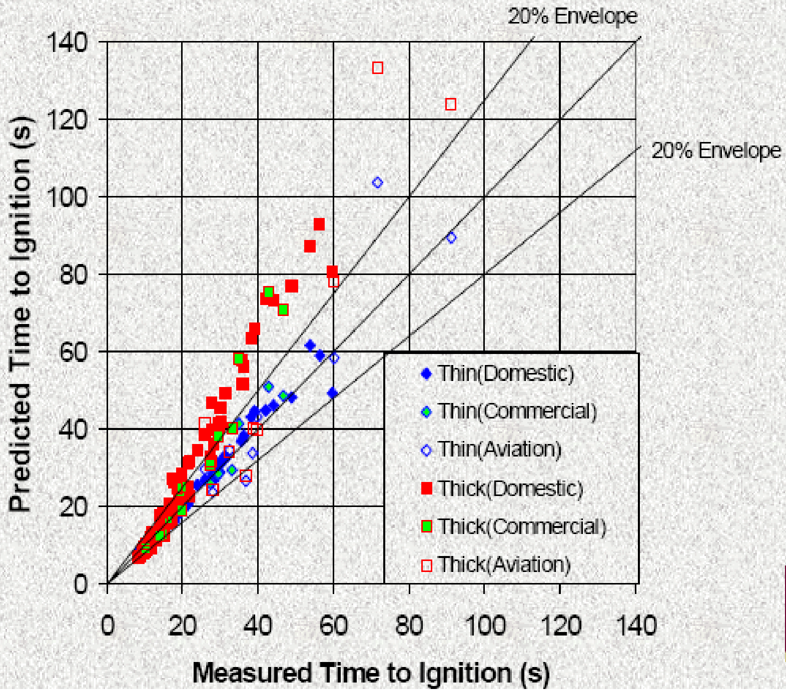
Nonlinear – interative solution

Measure the surface temperature vs. time in tests
Check by varying the radiant flux the flux at which ignition occurs.
Check this formula then.

# Results 7kW/m²≤q″e ≤40kW/m²

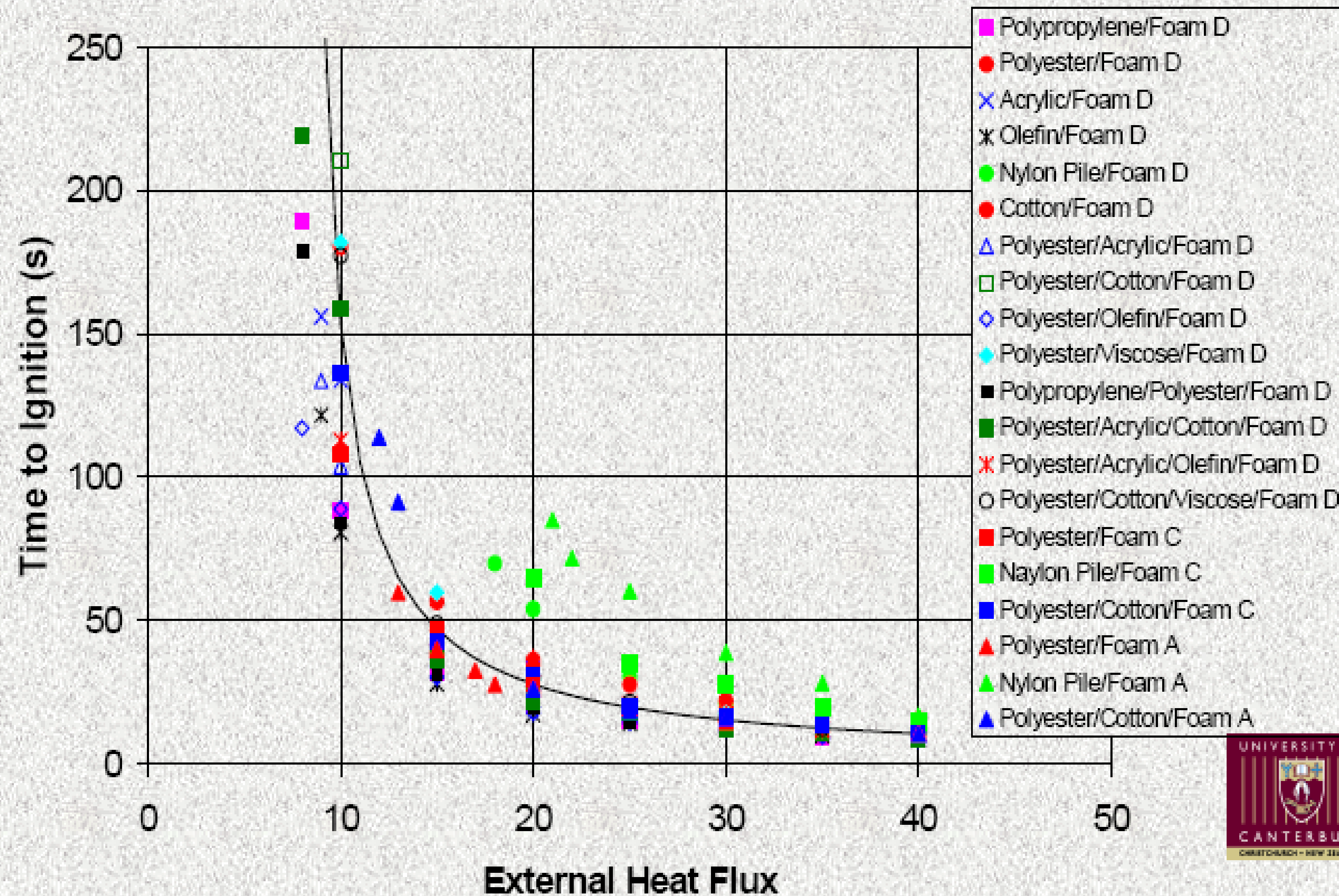



# Results 15kW/m²≤q″e ≤40kW/m²



$$t_{ig} = \frac{338}{(\dot{q}_e'' - 7.8)}$$

# Generic Results

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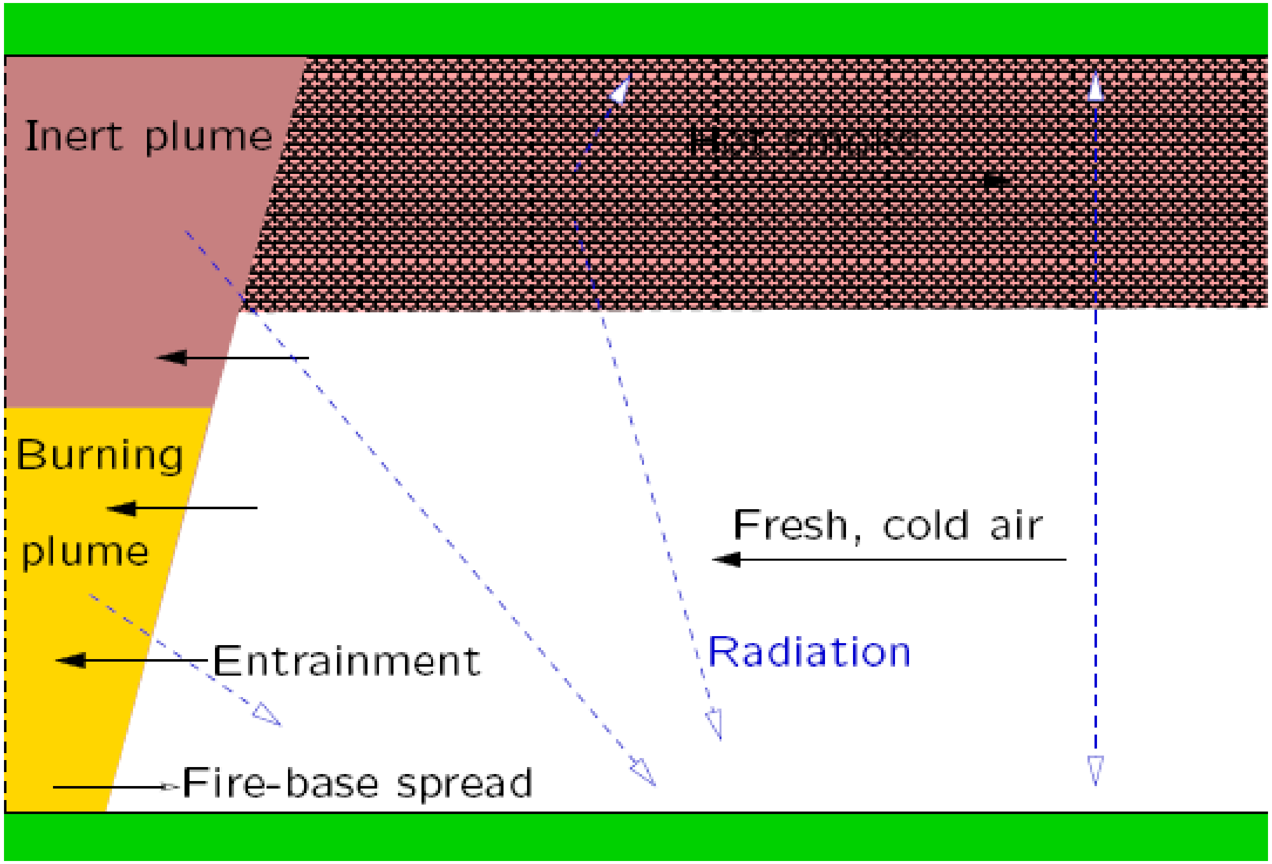
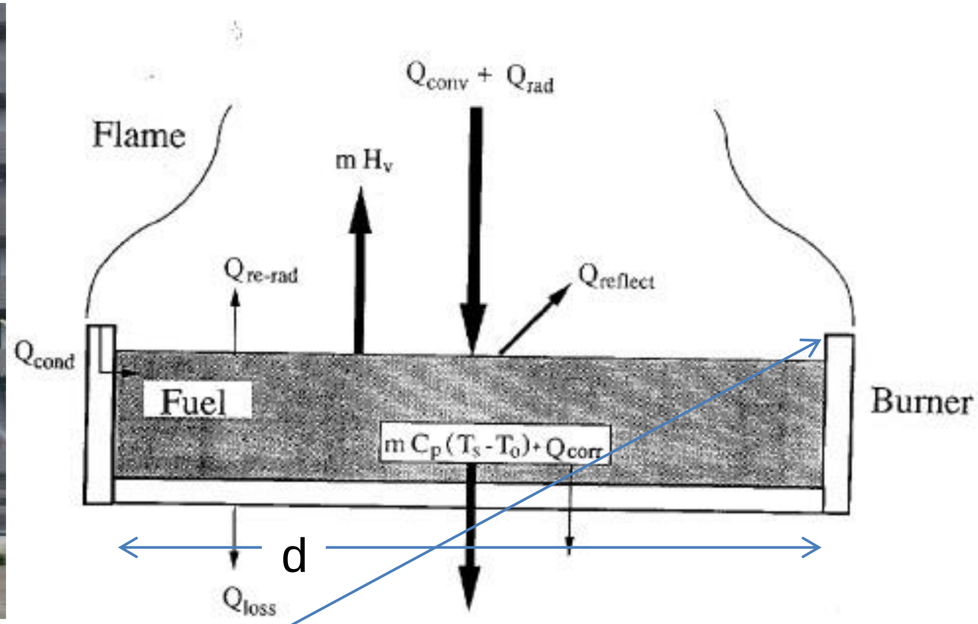
# The principal mechanisms in a fire




Whether inside the flame/fire or outside, heat balance occurs because of convection – radiation - re-radiation - gasification with solid/liquid fuels




$$\rho_l \dot{r} L_s = \sigma (T_f^4 - T_s^4)(1 - exp\{-\beta kd\})(1\text{-}4h_t/d)$$

$$\rho_l \dot{r} = [\sigma T_f^3 / c_p] \quad [c_p(T_f - T_s)/L_s] \, (1 - exp\{-\beta kd\})(1\text{-}4h_t/d)$$

$$\rho_l \dot{r} = [\sigma T_f^3 / c_p] \quad B \, (1 - exp\{-\beta kd\})(1\text{-}4h_t/d)$$

Radiation extinction coefficient

$$\rho_l \dot{r} / B = [\sigma T_f^3 / c_p] \, (1 - exp\{-\beta kd\})(1\text{-}4h_t/d)$$

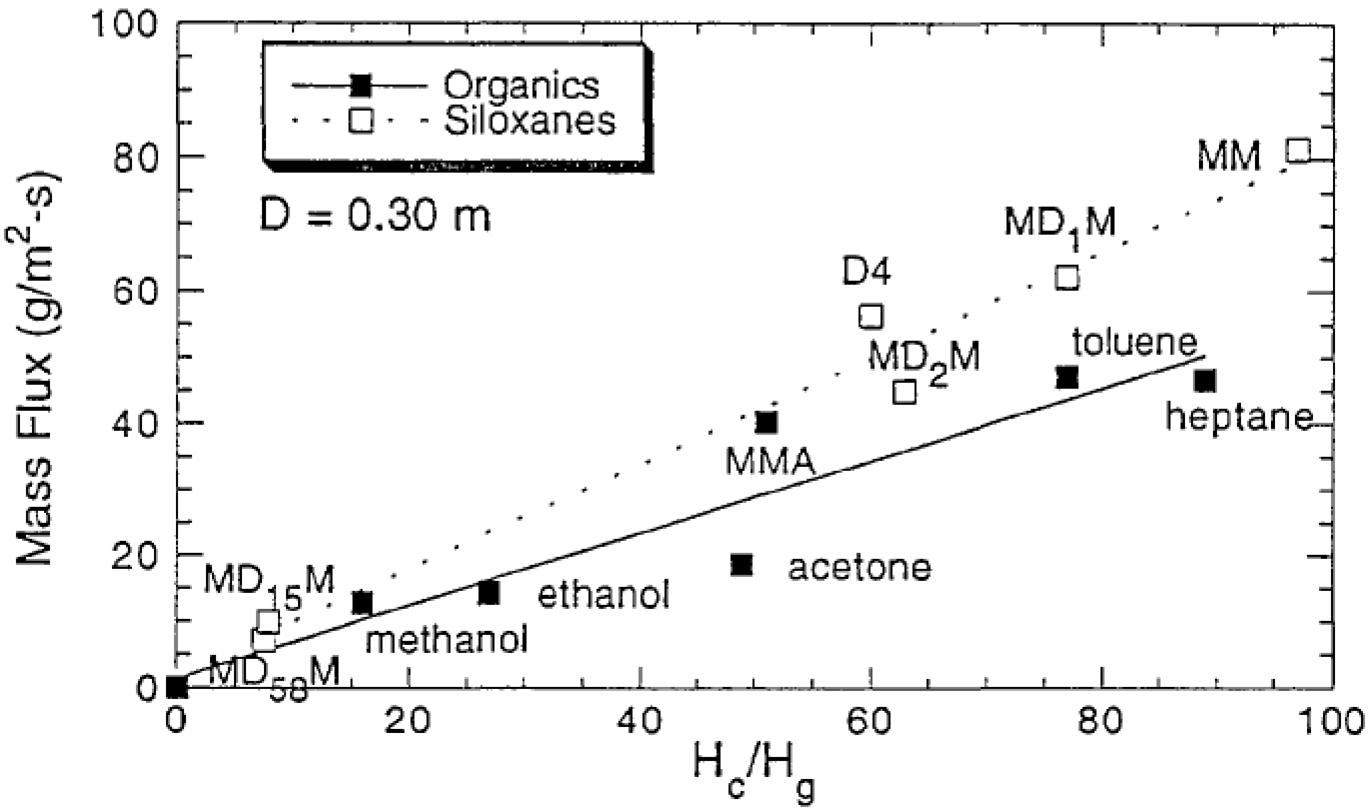



**Figure 11** The measured fuel mass flux as a function of the fuel B number for a number of hydrocarbons and siloxanes burning in a 0.3 m burner.

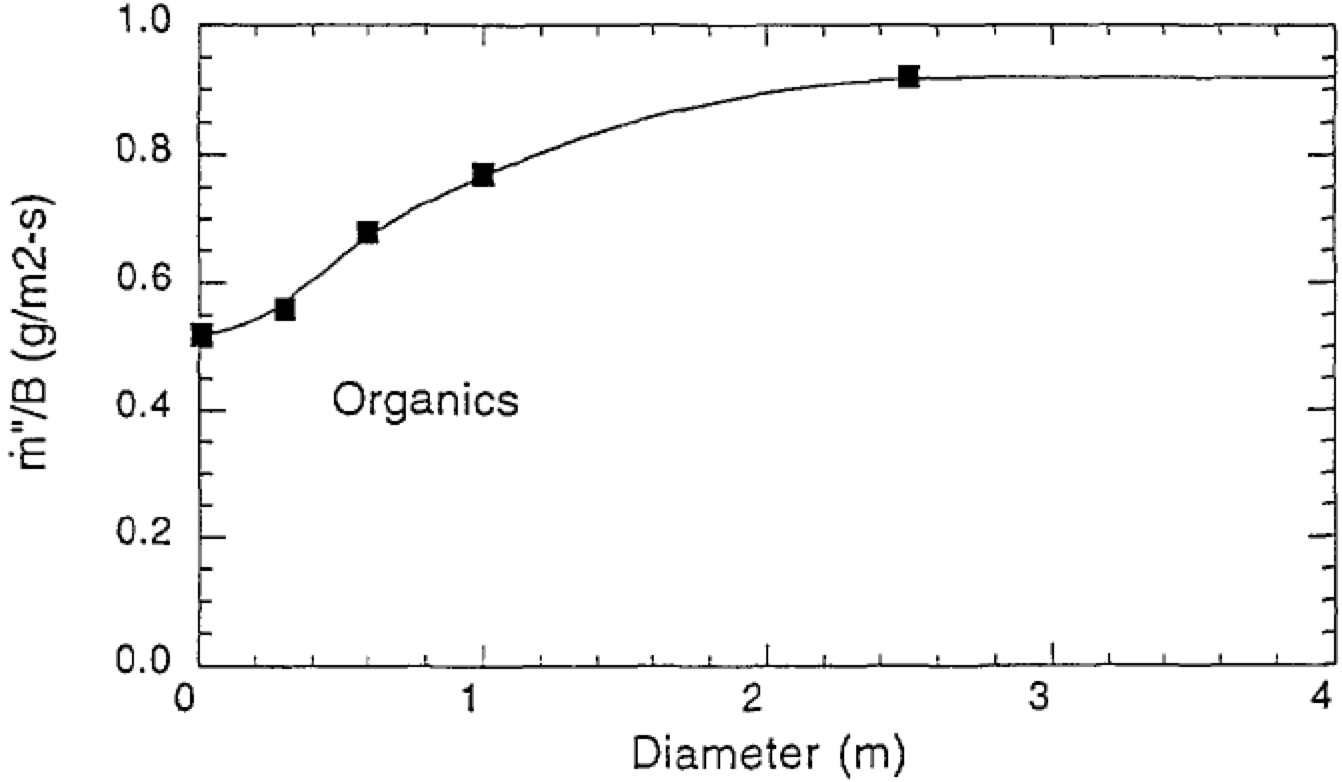



**Figure 12** The ratio of the fuel mass flux to the fuel B number ($\dot{m}''/B$) as a function of pool diameter for hydrocarbon fires.

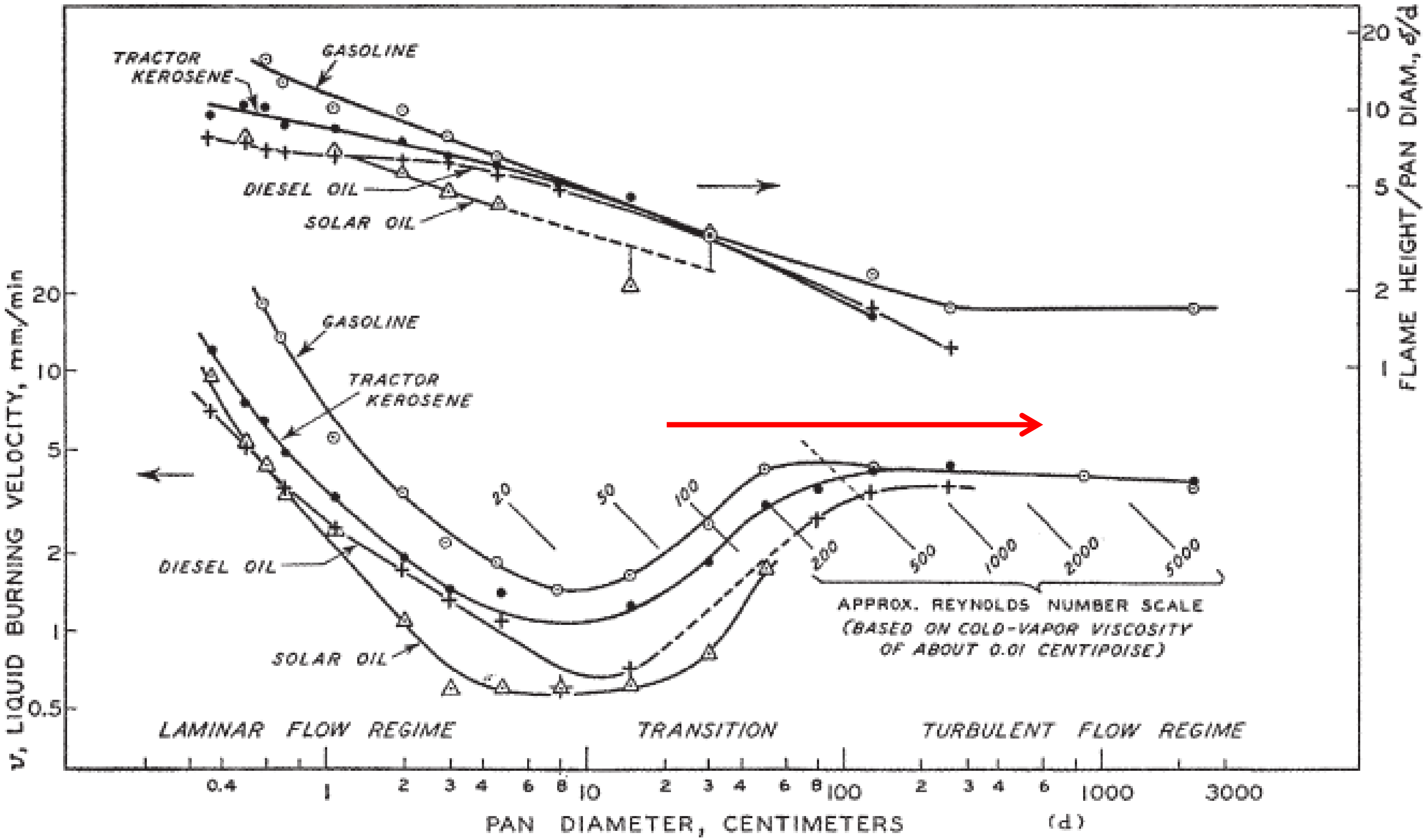



Figure 1: Correlation by Hottel [1] of burning rate and flame height from pool fires as a function of pan diameter.

$$\rho_l \dot{r} / B = [\sigma T_f^3 / c_p] \; (1 - \exp\{-\beta k d\})(1 - 4h_t/d)$$

*Valid over the red arrow range*

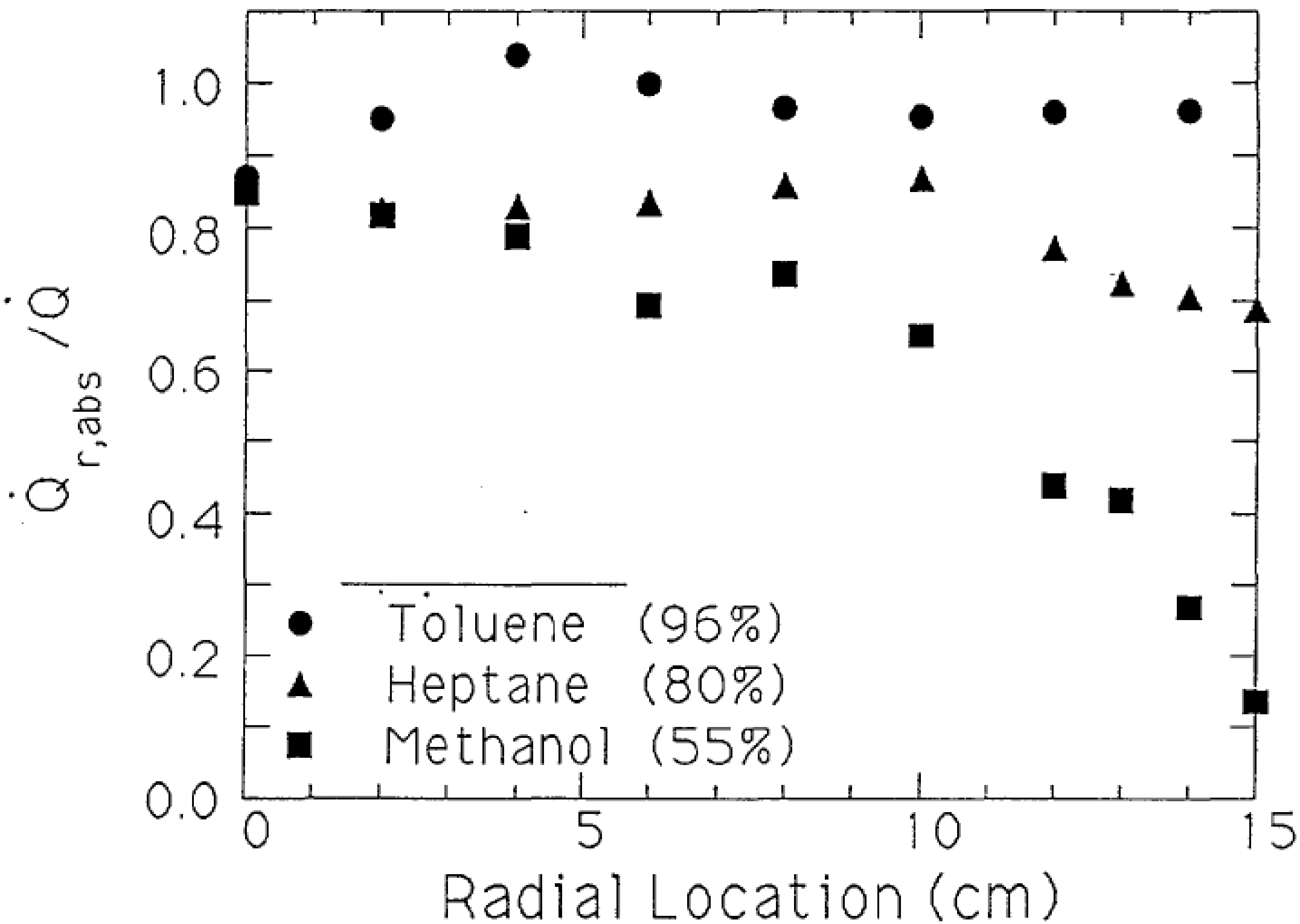



**Figure 10** The normalized absorbed radiative heat flux as a function of location on the surface of 0.30 m pool fires. Numbers in parenthesis indicate the percentage of heat feedback due to radiation.

# Polymeric fuels…

| Feature | | POM | PMMA | PP | PS |
|---|---|---|---|---|---|
| Flame base, | m | 0.305 square | 0.305 x 0.31 | 0.305 square | 0.305 square |
| Base area, | $m^2$ | 0.093 | 0.095 | 0.093 | 0.093 |
| Mass burn flux, | $g/m^2s$ | 6.5 | 10.5 | 8.5 | 14.5 |
| $A/F]_{stoich}$ | - | 4.6 | 8.3 | 14.8 | 13.0 |
| Surface temp, | °C | 312 | 385 | 479 | 438 |
| Heat of Combustion, | MJ/kg | 15.5 | 24.9 | 43.4 | 39.8 |
| Heat of phase change, | MJ/kg | 2.43 | 1.61 | 2.03 | 1.76 |
| Transfer No, B | - | 1.23 | 1.57 | 1.16 | 1.44 |
| Combustion completeness, | % | 100 | 85 | 87 | 57 |
| Radiation fraction, | % | 15 | 34 | 38 | 35 |
| Theoretical. Heat release, | kW | 9.3 | 24.8 | 34.3 | 53.7 |
| …rate | $kW/m^2$ | 100 | 222 | 321 | 329 |
| Convective heat flux, | $kW/m^2$ | 17.5 | 7.6 | 6.8 | 2.9 |
| Radiative heat flux, | $kW/m^2$ | 5.0 | 20.1 | 28.7 | 37.2 |
| Surface re-radiation, | $kW/m^2$ | 6.7 | 10.7 | 18.2 | 14.6 |
| Gasification flux, | $kW/m^2$ | 15.8 | 17.0 | 17.3 | 25.5 |
| Flame radiation temp, | K | 1400 | 1400 | 1350 | 1190 |

Poly oxymethlyene (POM) through Polymethyl methacrylate (PMMA), Poly Propylene (PP) to Polystyrene (PS)

**A/F increases, Radiation fraction, sooting tendency Increase.**

**Effective radiation temperature decreases…** From De Ris, Comb symp, 1978

# Flame heights:

## The equations of fluid motion, scaling and dimensionless numbers

$$(\rho u)_x + (\rho v)_y = 0$$

$\rho U/H \sim \rho v/\delta$; Hence, $v \sim U\,\delta/H$

$$\rho u(u)_x + \rho v(u)_y = [\mu\ (u)_y]_y + g_o \cos\phi\ (\rho_\infty - \rho)$$

$\rho U^2/H \sim \rho U v/\delta \sim \mu U/\delta^2 \sim g\ (\rho_\varpi - \rho)$

Balancing first two gives a result same as earlier

Balancing first or second and third term we get $\delta^2 \sim \mu\ H / \rho\ U \sim \nu\ H/U \sim \nu\ H^2/U\ H$

or $\delta/H \sim \sqrt{1/Re}$ where Re = Reynolds number = $U\ H/\nu$ with $\nu = \mu/\rho$

If we want skin friction we write →

$\mu(u)_y \sim \mu\ U/\delta$  $c_f = \mu(u)_y/(\rho U^2/2) \sim 2\sqrt{1/Re}$,

where $c_f$ is the skin friction coefficient. This result is standard for laminar flow and the actual result after analysis/calculation is $c_f/2 = 0.332/\sqrt{Re}$

For free convection problems,

$\rho U^2/H \sim g(\rho_\varpi - \rho) \rightarrow U^2 \sim g H (\rho_\varpi - \rho)/\rho$ or

$U^2 \sim g H (T - T_\varpi)/T_\varpi \qquad U \sim \mathrm{Sqrt}\,(g H \beta(T - T_\varpi))$;

Balancing 3 and 4th terms gives

$\delta \sim \mathrm{Sqrt}[\mu U/ g(\rho_\varpi - \rho)] \sim \mathrm{Sqrt}[(\mu/\rho)U/ g\beta(T - T_\varpi)]. \qquad \beta = 1/T$

Replacing U, we get $\delta/H \sim [v^2/g H^3\beta(T - T_\varpi)]^{(1/4)} \sim 1/Gr^{(1/4)}$

Skin friction for free convective flow and heat transfer coefficient follow one another. $c_f = \mu(u)_y/(\rho U^2/2)$; $St = k(T)_y/\{\rho U c_p (T_w - T_\varpi)\}$,

Comparing we get $c_f/2 \sim St/Pr$, $Pr = \mu c_p/k$

Also traditionally one uses $Nu = h H/k$ [with $h = q''/(T_w - T_\varpi)$] $= H/\delta \sim Gr^{(1/4)}$

St = Stanton number, Nu = Nusselt number.

The Reynolds number of free convective flow is (Grashoff number)$^{0.5}$. When free-forced convection issues are important, the number to use is $Re^{0.5}/Gr^{0.25}$. See how nicely you get the results very simply!

# Flame heights - 1

- Fires always move up – this is because, hot gases are lighter and gravity "wishes" to arrange the hot fluid to be above the cold fluid because hot fluid is lighter than the coldfluid. The three quantities in understanding their behavior are inertial force, force due to buoyancy and viscous force.
- If the flame is present due to flow of gases at significant velocities, then inertial effects can be expected to dominate. If viscous forces match them, then Reynolds number plays a role.
- If buoyant forces match them, we have a new number – Froude number defined by $Fr = U^2/gH$; $Fr \gg 1$ implies momentum dominated flame; $Fr \ll 1$ implies buoyancy dominated flame. When buoyancy matches viscous force, Grashof number is more appropriate to describe the flow
- In free flows – large fires liquid pan fires, forest fires, start of fires in buildings, not influenced by walls and surfaces, Froude number is a more appropriate descriptor.

# Flame heights -2

$$Fr = U^2/gH$$

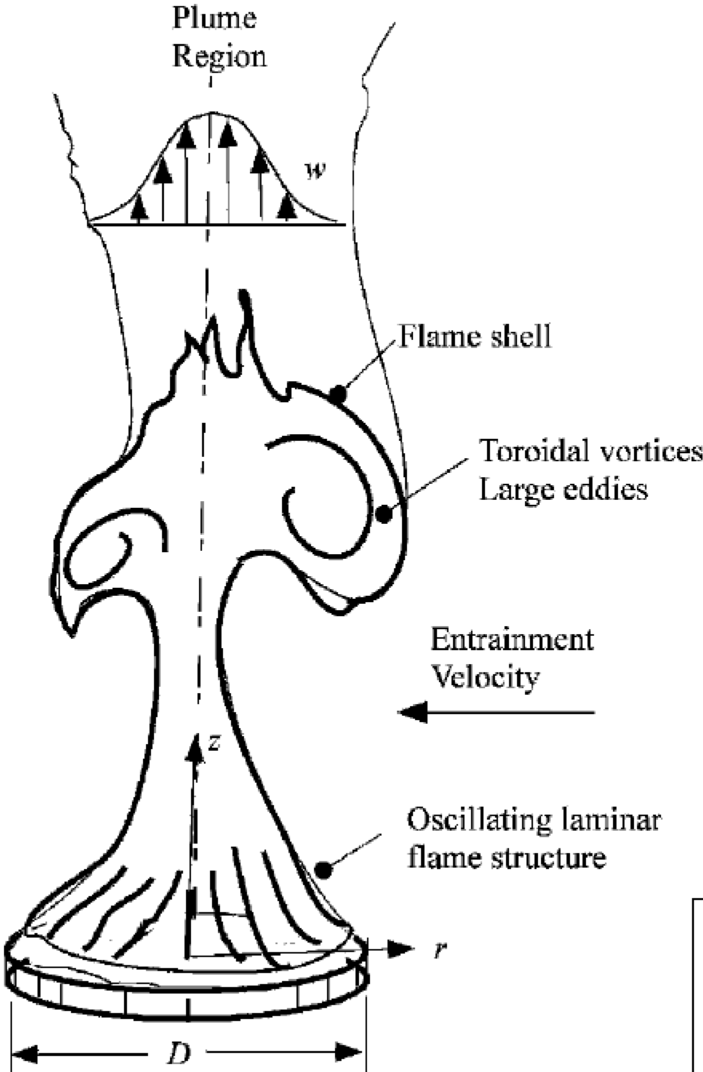
1. A measure of U can be obtained in pan fire for instance (also in others) by $\dot{m}H_c = \rho U(\pi D^2/4)H_c = Q$, the heat release rate (kW) where D is the pan size, $H_c$ is the heat of combustion. Therefore, $U \sim Q/[\rho(\pi D^2/4)H_c]$.
2. If we introduce this into Froude number expression, we get,

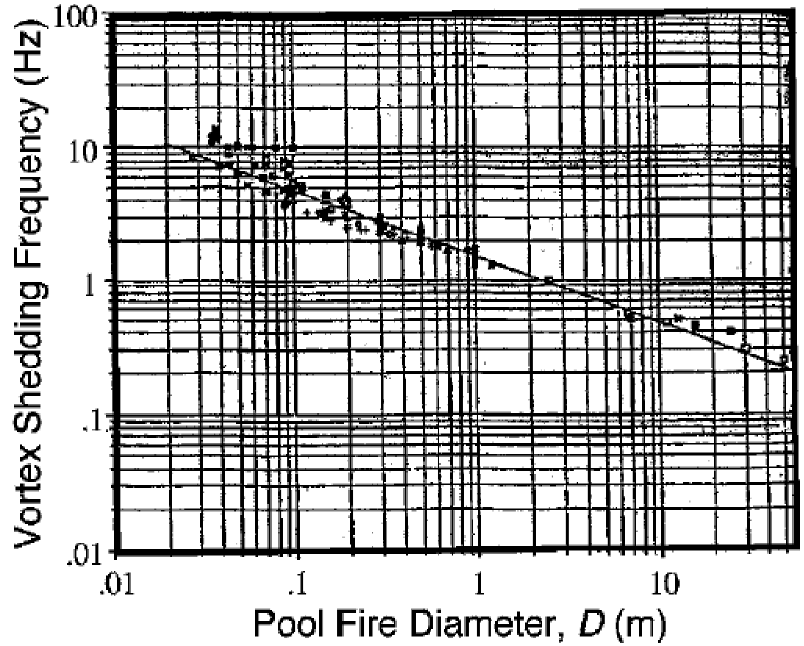
$$\sqrt{Fr} = Q/[\rho(\pi D^2/4)\, H_c \sqrt{gH}$$

3. When the buoyant jet flame occurs over the pan, the height H can be shown to scale with D as H ~ D for turbulent flows. This then gives

$$\sqrt{Fr} = Q/[\rho(\pi D^{2.5}/4)\, H_c \sqrt{g}$$

4. We can expect that the height of the flame, $h_f$ (same as H in the above relation) can replace D and the scaling $h_f/Q^{(2/5)}$ should be appropriate.
5. If there are any flame oscillations they are governed by a frequency, f (Hz, 1/s), the process is controlled by gravity with a linear scale given by D, then the time scale of the oscillation is $\sqrt{D/g}$ (s). This implies that $f\sqrt{D/g}$ is a natural dimensionless number (Strohaul number, St). Or rather $f \sim St\sqrt{g/D}$

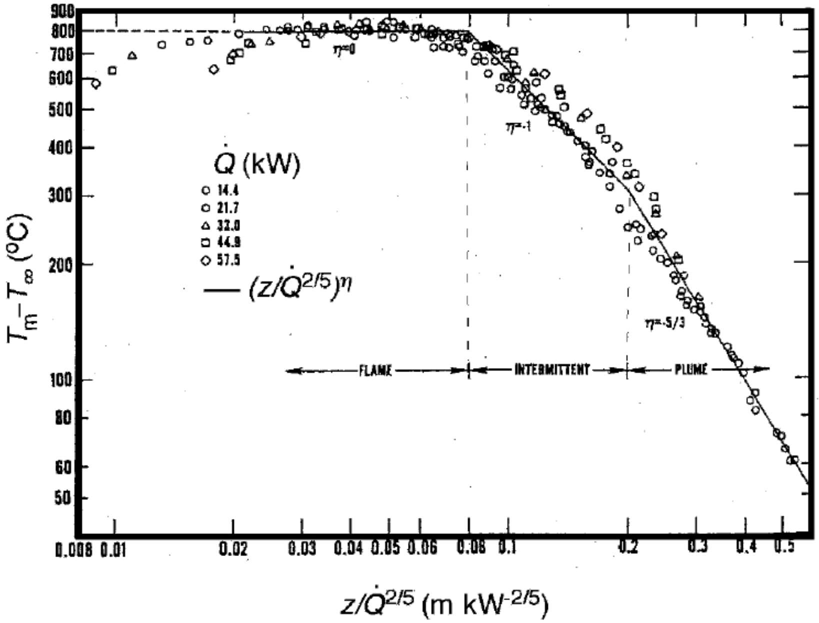


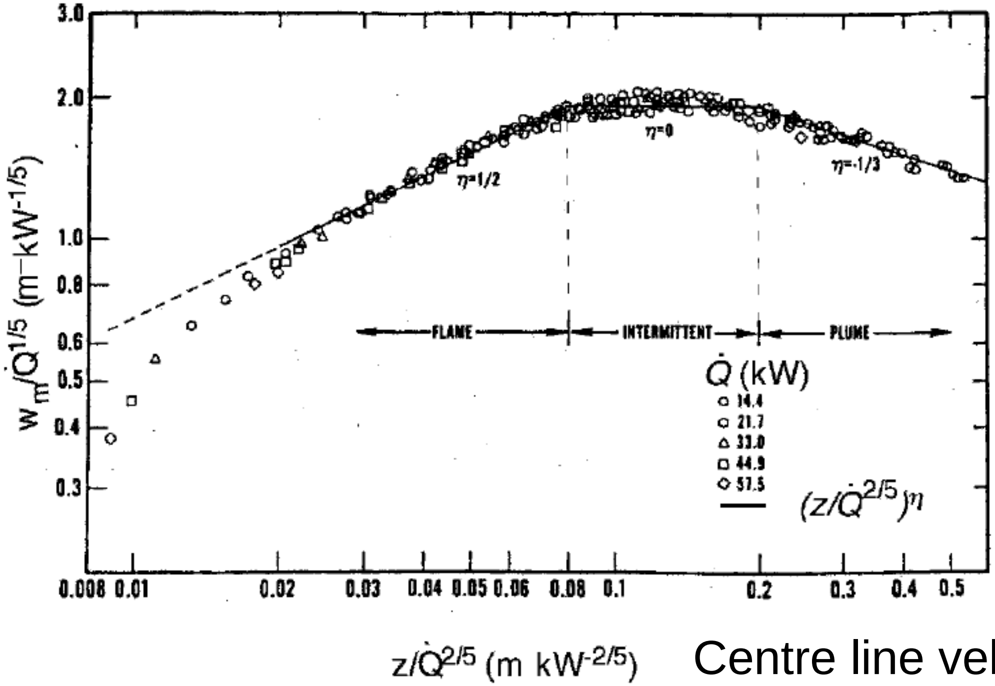

Experiments show f = 0.5 $\sqrt{g/D}$

$$\frac{\dot{m}_e}{\rho_\infty \sqrt{g}\, D^{5/2}} = C_e \left(\frac{z}{D}\right)^{1/2} \left[1 + 2C_\ell \left(\frac{z}{D}\right)\right]^2$$

$\dot{m}_e$ = entrainment mass flow rate

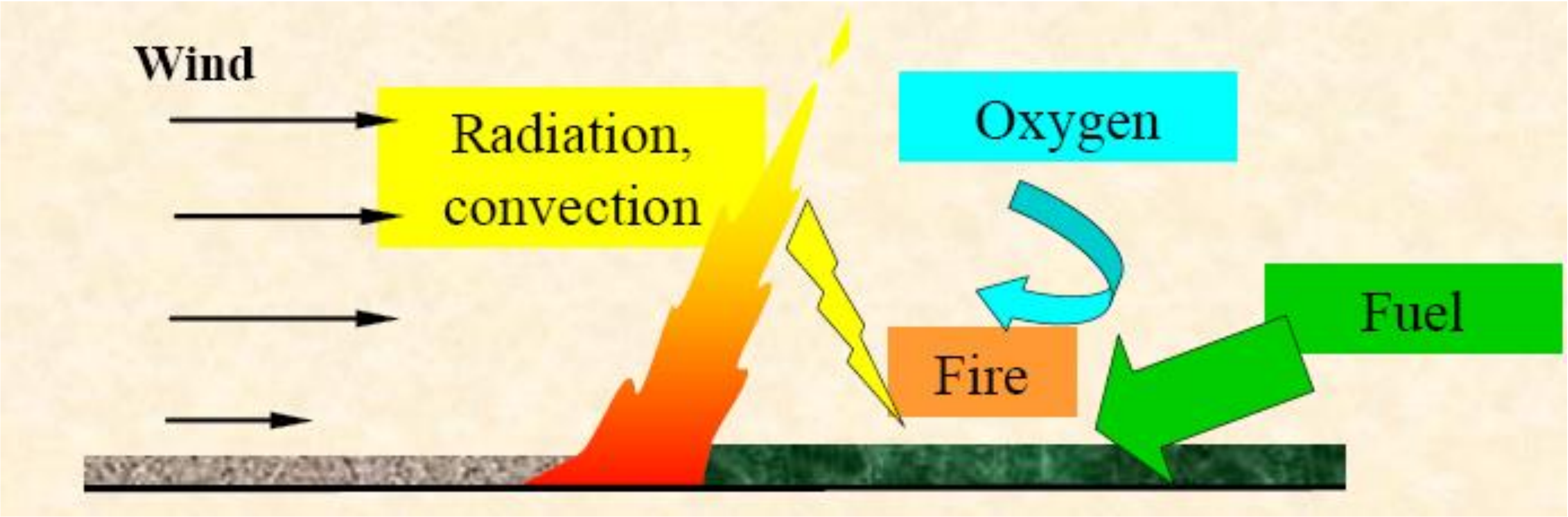



Centre line temperature




Centre line velocity

# Fire spread mechanisms



The end?