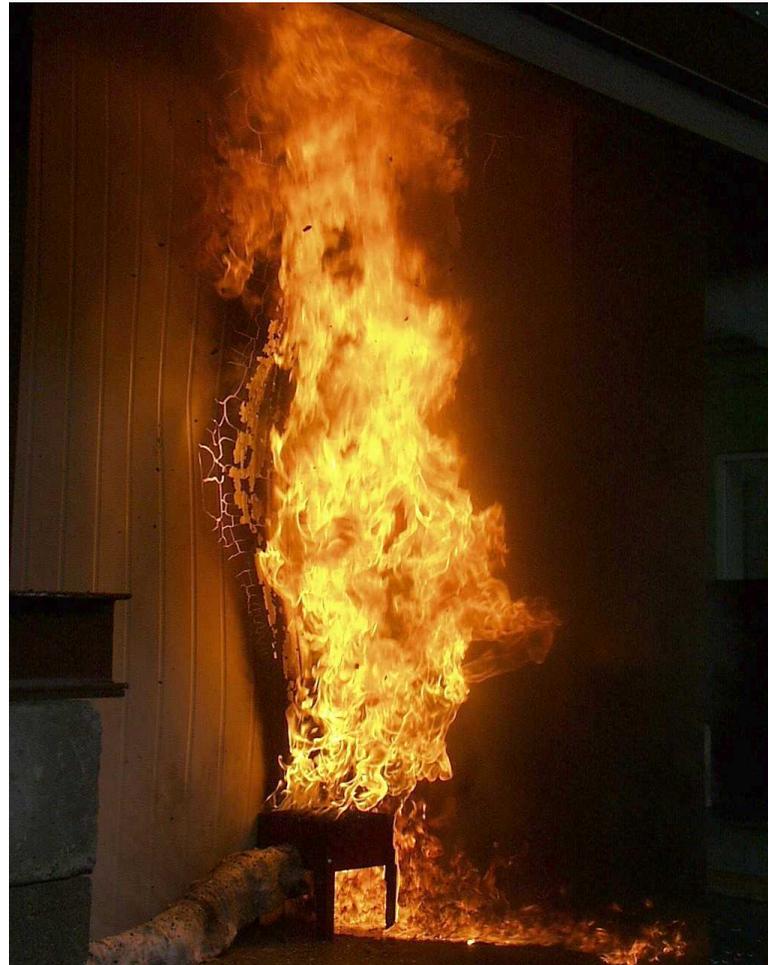


Cambridge 2019 Combustion Summer School

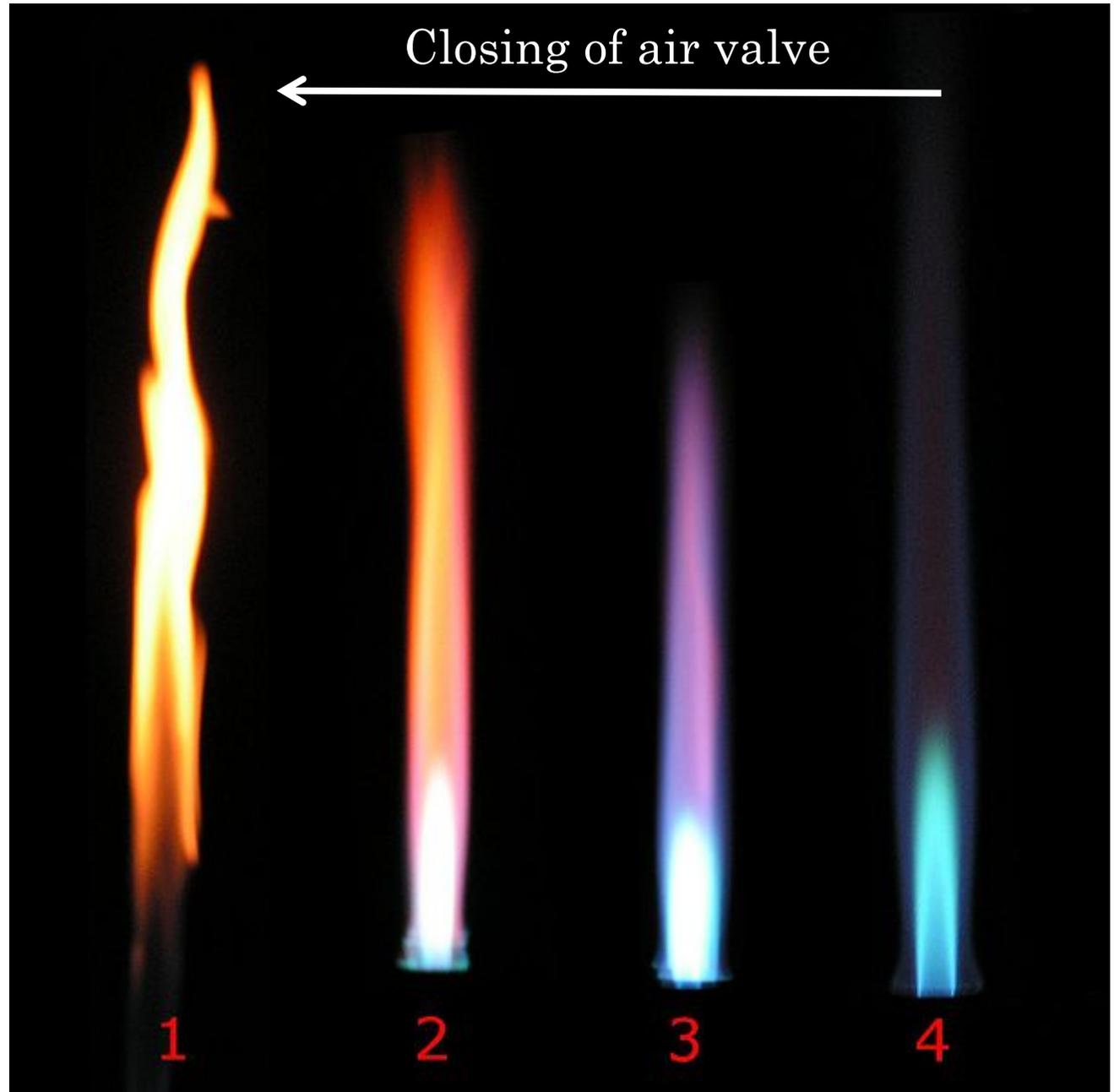
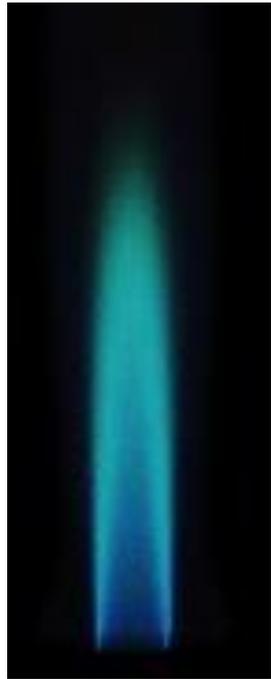
Introduction to Fire Dynamics

taught by Prof Guillermo Rein

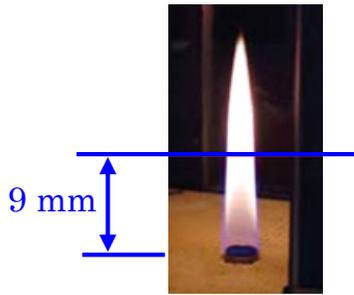
Imperial College
London



Bunsen Burner (Heidelberg, ~1855)



Flame Structure



Laminar methane jet flame from a 10 mm orifice

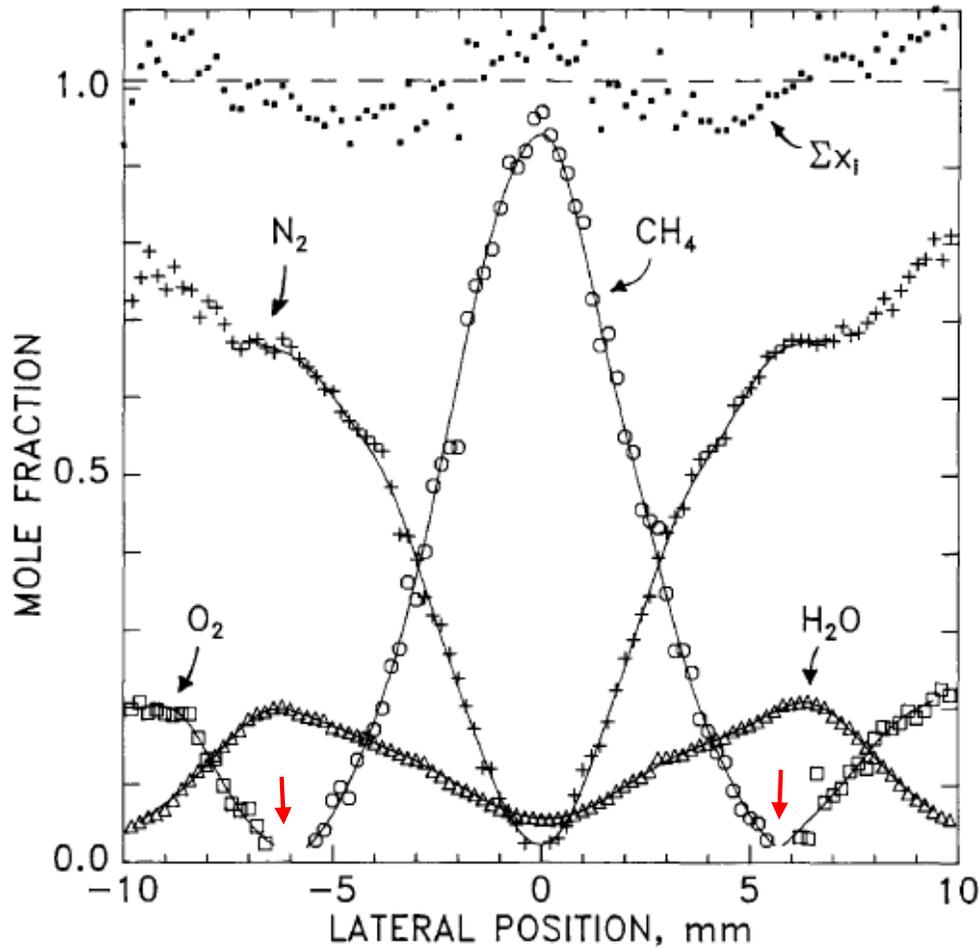


Fig. 9. Mass spectrometric profile measurements of some of the major species: methane, nitrogen, oxygen, and water at a height of 9 mm above the burner. The N_2 profile has not been corrected for the small amount of CO detected at the same mass (see Fig. 10). At the top of the figure the sum of the mole fractions of all the species presented in Figs. 9 and 10 is shown; the dashed line represents the average value of 1.01 ± 0.04 .

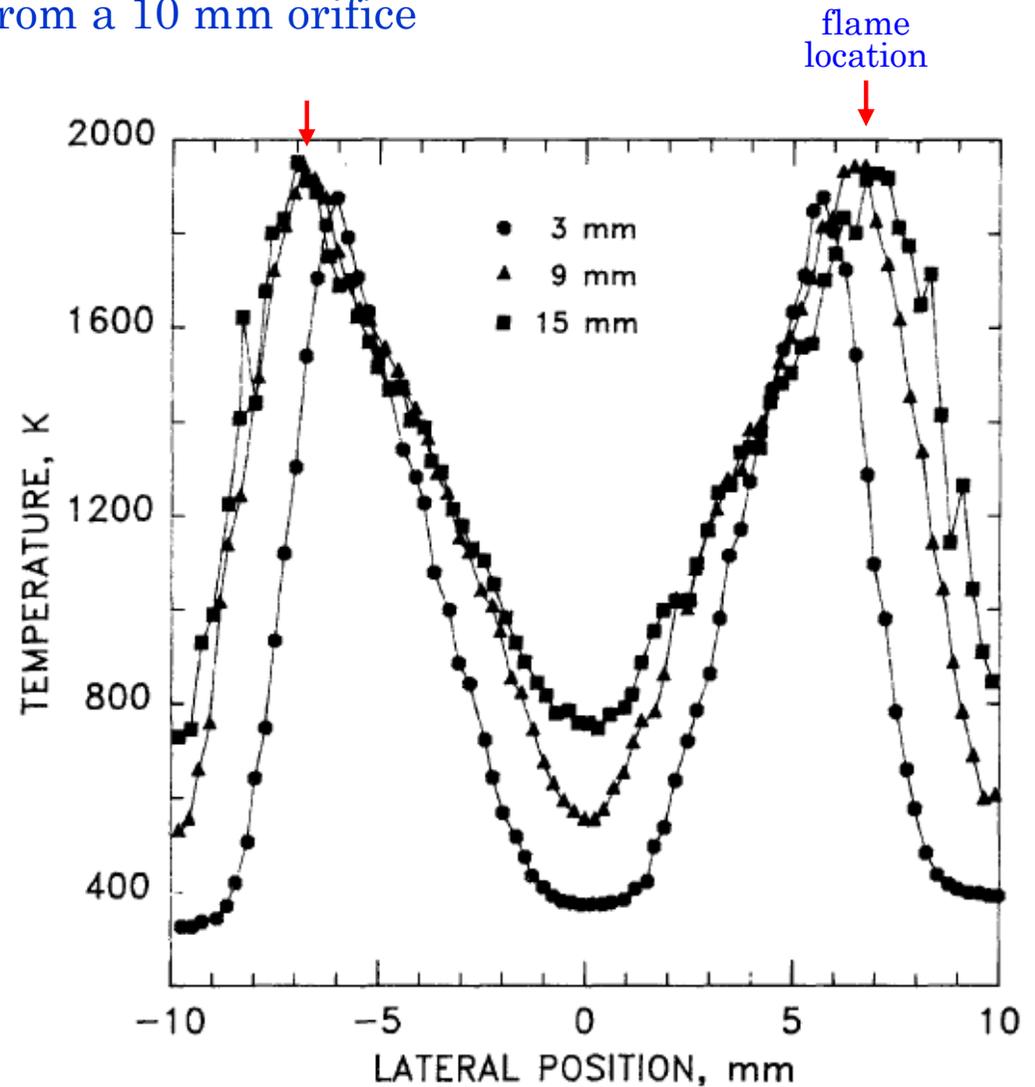


Fig. 2. Thermocouple temperature profiles at heights of 3, 9, and 15 mm above the burner; the data are not corrected for radiation losses (see Table I). At the right-hand side of the figure the temperature values in the air flow are erroneously high due to heating of the thermocouple via conduction along the thermocouple supports.



from Smyth et al, CNF 1985



<https://www.youtube.com/watch?v=QwoghxwETng>

Objective of this lecture

- Provide an **introduction to fire dynamics** to the class, mechanical engineers working on combustion science.
- We assume substantial knowledge on **combustion**, a key thermochemical process of fire.
- We will study how flames and fire evolve, making emphasis on **fire growth and compartments**.

Fire Dynamics is the foundation of Fire Engineering

just as

Thermodynamics is the foundation of Mechanical Engineering,

Structural Mechanics is the foundation of Civil Engineering

and

Chemical kinetics is the foundation of Chemical Engineering

but

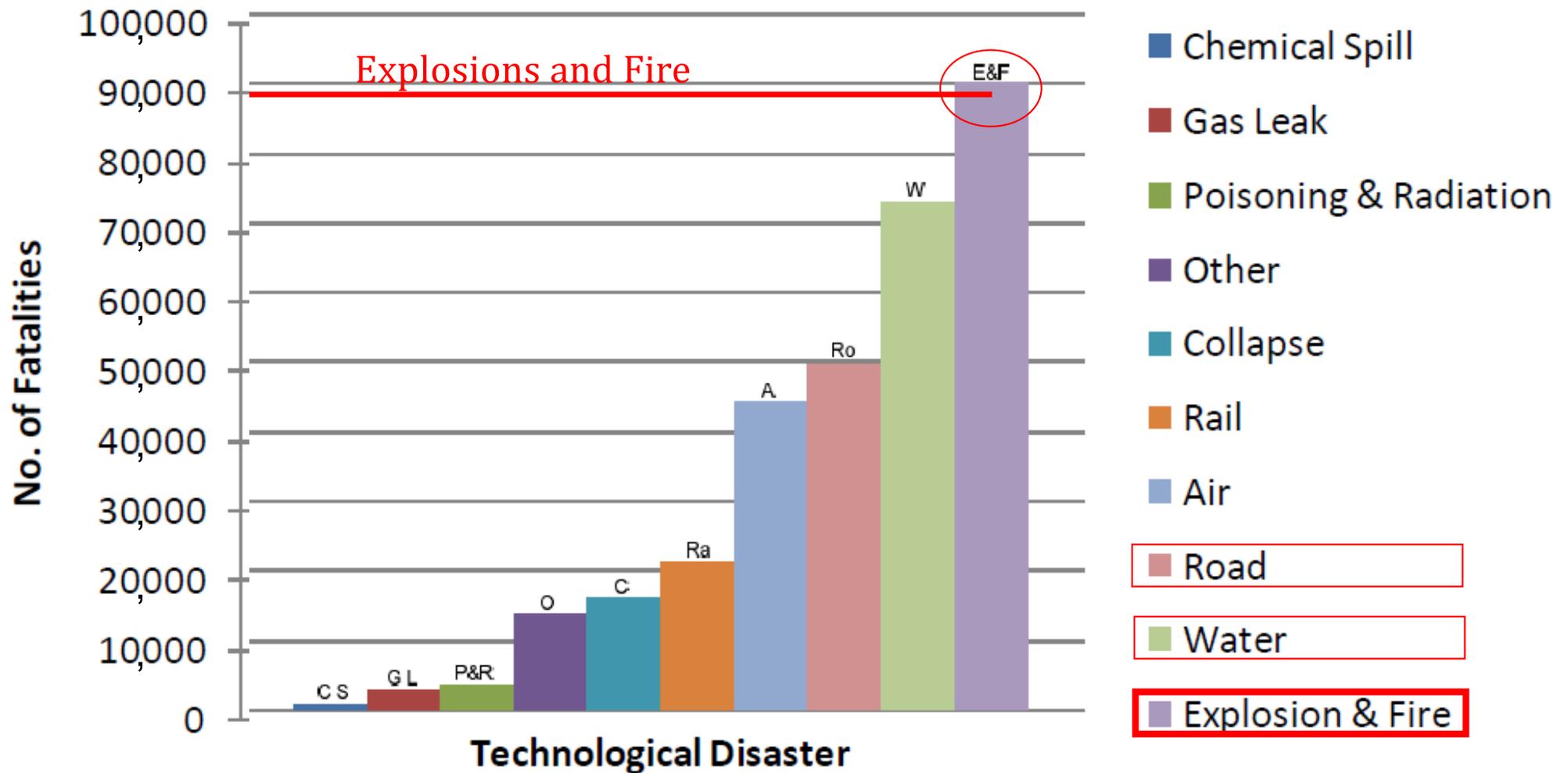
Fire Dynamics is an amalgam of Thermodynamics, Chemical kinetics and Structural Mechanics.

adapted from Prof. Dougal Drysdale

Fire Phenomena



Technological Disasters 1900-2010



NOTE: Immediate fatalities as a proxy to overall damage. Disaster defined as >10 fatalities, >100 people affected, state of emergency or call for international assistance.

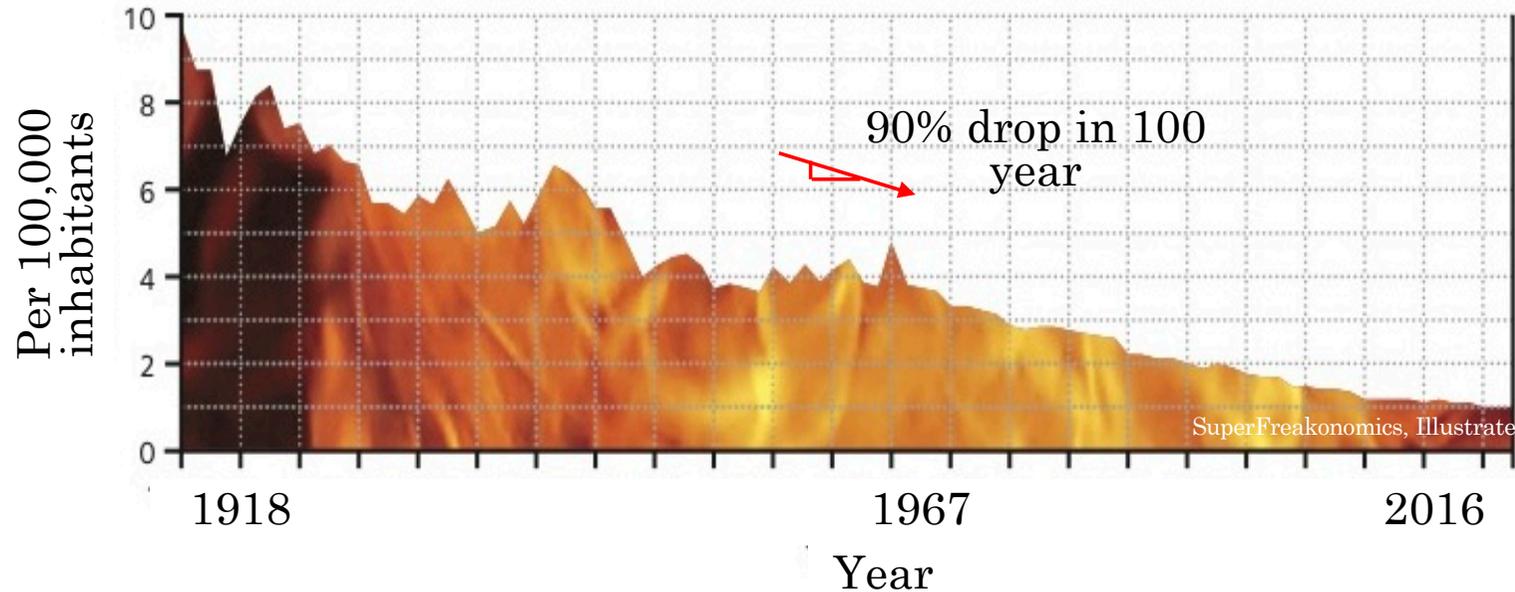


EM-DAT International Disaster Database, Université catholique de Louvain, Belgium. www.emdat.be

Jocelyn Hofman, Fire Safety Engineering in Coal Mines MSc Dissertation, University of Edinburgh, 2010

Building Fires

USA data: Fire deaths vs. time



- Despite tremendous progress in protecting lives from fire, it is still causing 5% of injury-related deaths worldwide (war causes 2%).
- Fighting fires is costly (UK £7 billion/yr).

UK statistics

- Fire fatalities per year ~320 (pre-Grenfell)
- Direct fire costs ~ £2 billions
- Indirect costs ~ £5 billions

The annual total cost of fire in UK is **£7 billion**
(for comparison, UK budget on education is £34
billions)

Fire Engineering

Fire Engineers make the world safer from fire: protecting people, their property, and the environment.

Layers of Protection (after Prof Drysdale):

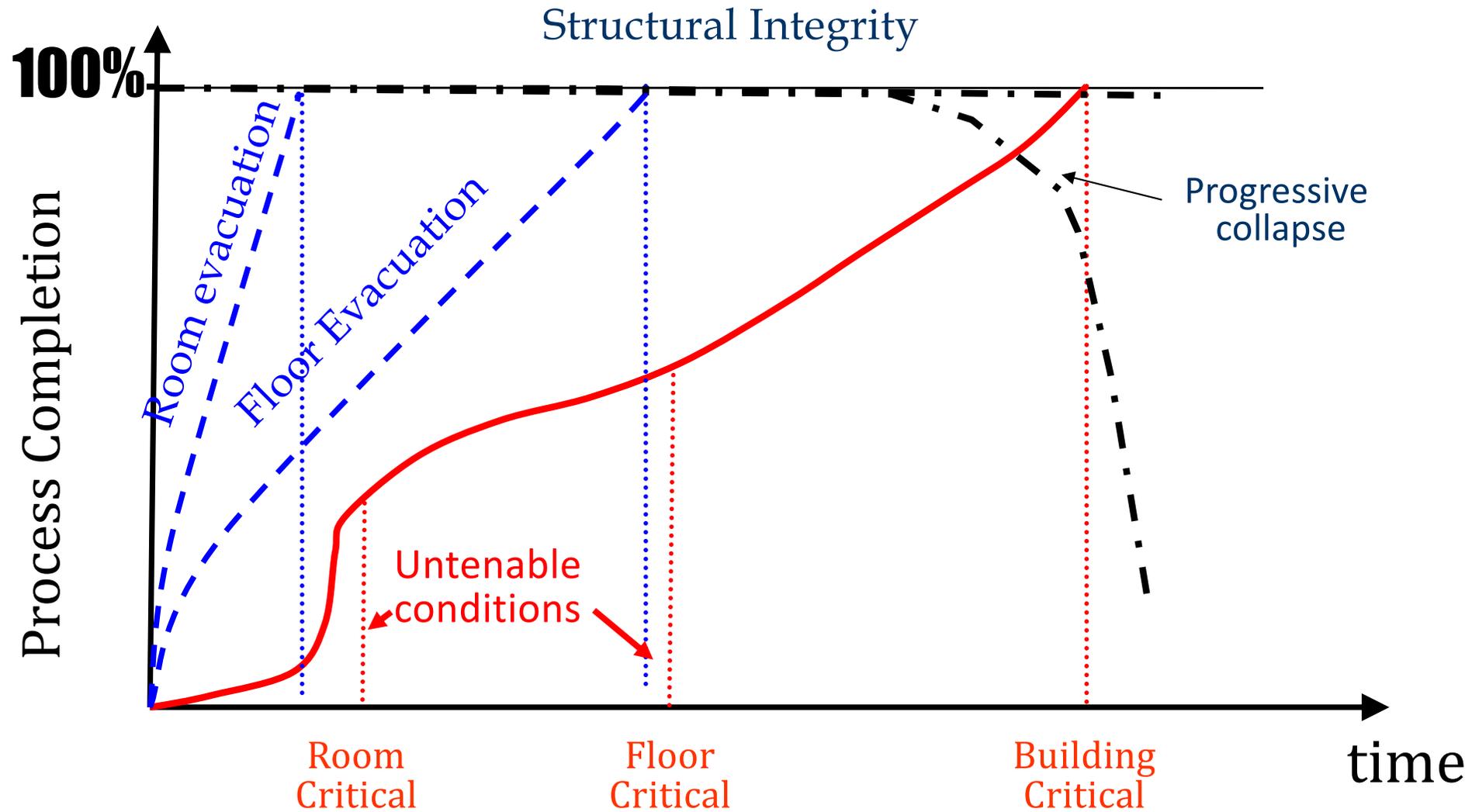
1. Prevention
2. Detection
3. Evacuation
4. Compartmentation
5. Suppression
6. Structural Resilience



*Not all layers must be present in a building, but all must be considered as least.

*Not all layers contribute equally or cost equal amounts.

Objective of Fire Safety Engineering: protect Lives, Property, Business and Environment



from Torero and Rein, Physical Parameters Affecting Fire Growth, Chapter 3 in: Fire Retardancy of Polymeric Materials, CRC Press 2009

Science and Engineering

“Medical doctors and engineers both welcome all the relevant science they can muster, but neither can wait for complete scientific understanding before acting to save life or create a new life-saving machine”

Henry Petroski (1942-)

in *The Essential Engineer: Why Science Alone Will Not Solve Our Global Problems*

Compartment fire

<https://www.youtube.com/watch?v=86zRGLZoTk8>



Initial stages ~ fire growth and free burning



Smoke filling and fire growth



Near flashover – secondary ignition



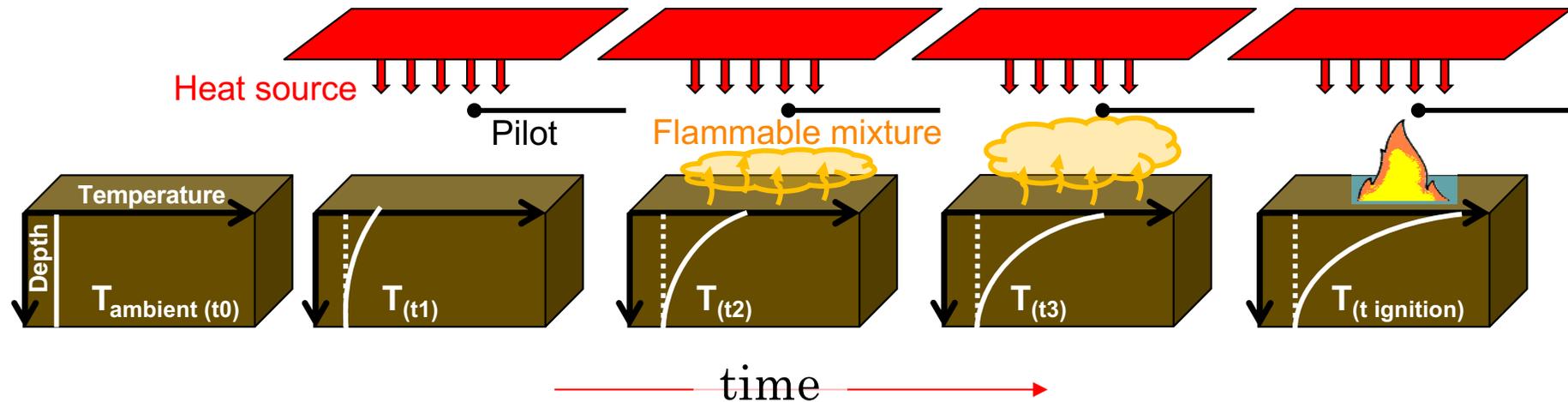
Flashover



Post-Flashover



Ignition of a condensed-phase fuel



Scenario: an external source heats the fuel in the presence of a pilot

- Ignition takes place when a flammable mixture of fuel vapours is formed over the fuel surface
- In simple liquids, it is driven by **evaporation**
- In complex liquids and solids, it is driven by **pyrolysis**
- If no pilot present, spontaneous ignition of the pyrolysate is possible (requires larger heat flux and longer times)

Ignition of a condensed-phase fuel

(Liquid or Solid)

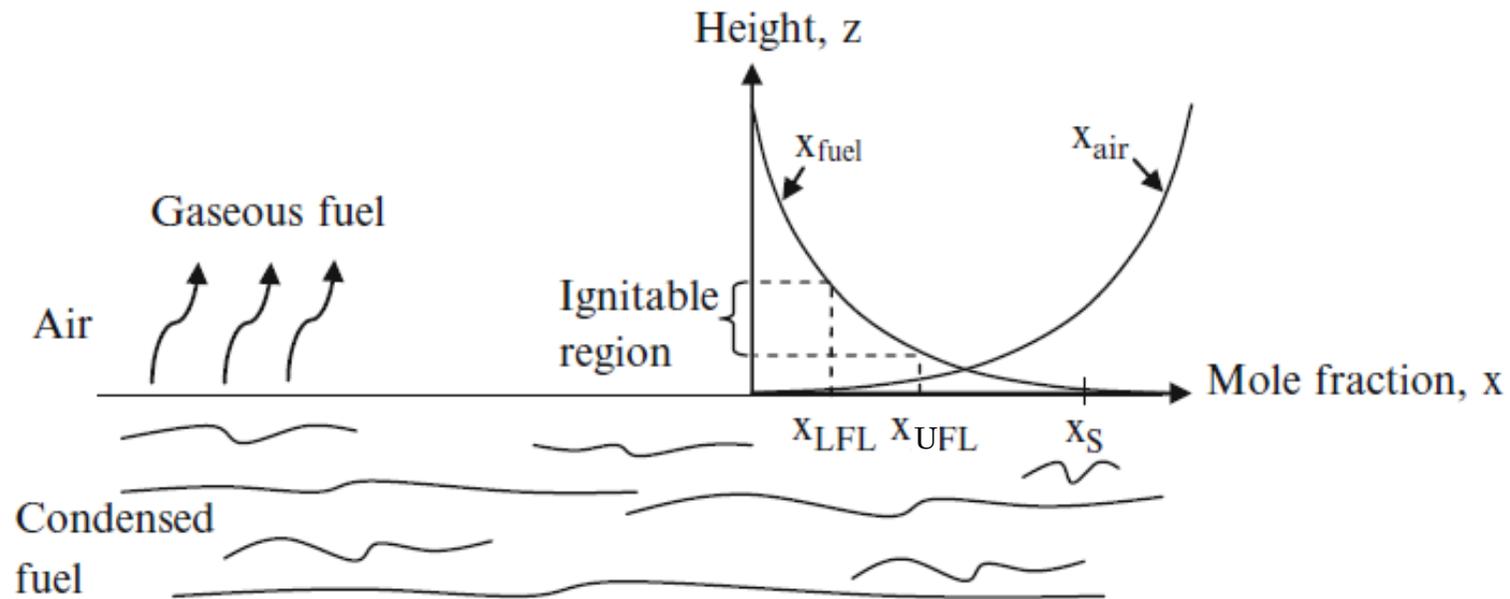
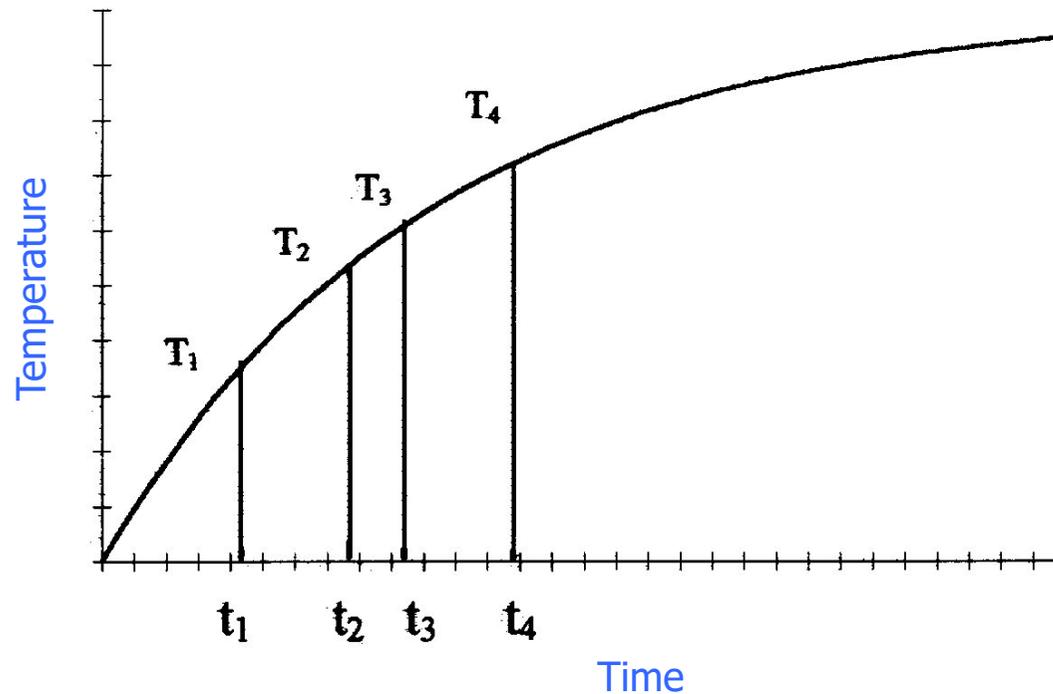


Fig. 5.6 Sketch of condensed fuel combustion

From phase-change to ignition



- $t=0$ Heating of fuel begins
- T_1 Onset of phase-change (evaporation or pyrolysis)
- T_2 Flashpoint (if piloted present)
- T_3 Firepoint (if piloted present)
- T_4 Spontaneous ignition (no need of pilot)

Ignition of a condensed-phase fuel

- **Flash point:** Lowest temperature of the fuel at which vapour/air mixture ignites producing a flash of light blue flame, characteristic of premixed burning. This is a single event not followed by sustained burning. Determined in a “closed cup” apparatus.
- **Fire point:** Lowest temperature of the fuel at which the ignition of the vapour/air mixture is followed by sustained burning. Determined in a “open cup” apparatus.

Fire point \geq Flash point

Table 2-8.2 *Flash and Fire Points of Some Hydrocarbon Liquids in Air*

Liquid	Flash Point (°C)	Fire Point (°C)
Fuel oil ^a	133	164
Crude ^a	125	155
Light fuel ^a	187	220
Black oil ^a	144	172
Refined oil ^a	122	135
Texas solar oil ^a	92	97
Shale oil ^a	130	150
Gas oil ^a	90	109
Neutral oils ^a	135	163
	216	252
Paraffin oils ^a	163	193
	216	254
Paraffin oil ^b	98	112
Naphthene base oil ^a	196	227
Diesel fuel ^b		
Russia	53–138	78–180
N. America	82–166	103–200
India	92–150	120–174
Tar oil for diesels ^b		
Coke oven	90–135	108–166
Water gas	34–91	50–155
Oil gas	18–69	20–89
Coal tar oil	66–121	84–160

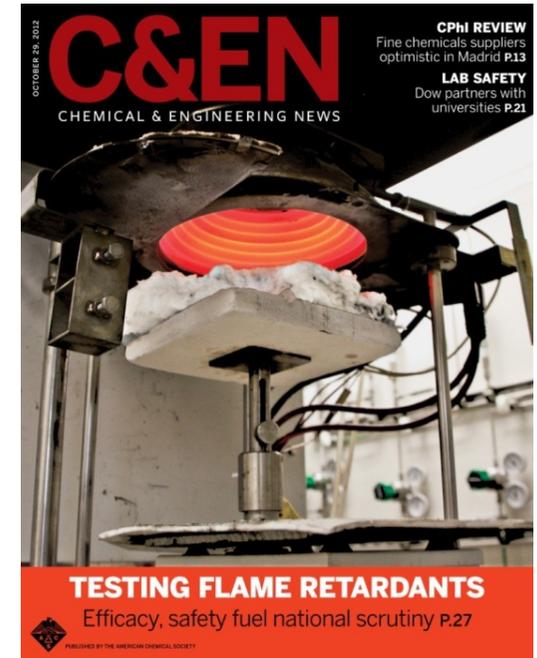
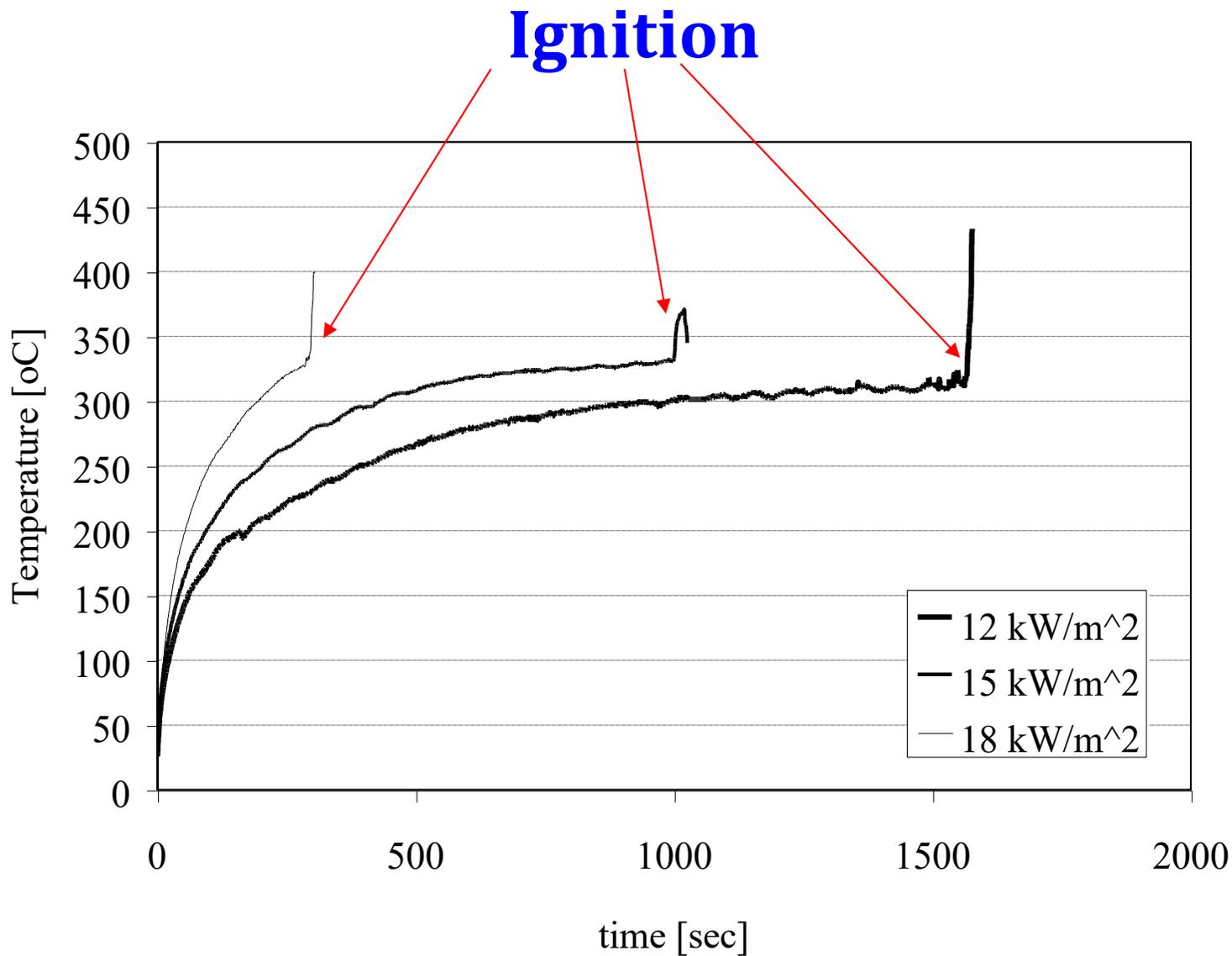
^a = Open cup

^b = Pensky closed cup

Source: Extracted from the *International Critical Tables*⁵



from SFPE handbook



Characteristic surface temperature histories for several heat fluxes. The material used is PMMA.

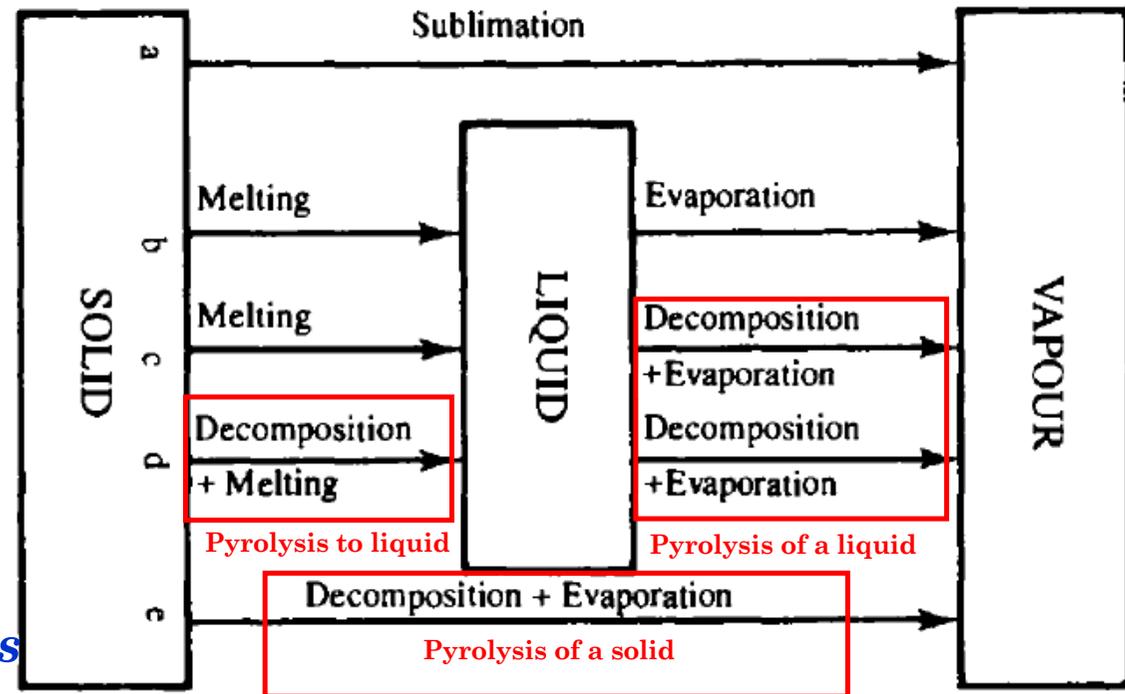
This process is called pyrolysis

When an organic solid material heats up, it eventually reaches a temperature threshold where it begins to break down: pyrolysis.

Pyrolysis is the chemical decomposition of a solid material solely by heating. It is endothermic and irreversible.

Material undergoes simultaneous change of chemical composition and physical phase.

G Rein, Smoldering Combustion, Chapter 19, SFPE Handbook of Fire Protection Engineering, 2016.
<http://hdl.handle.net/10044/1/41594>



- Chemical change from long hydrocarbon chains to shorter chains.
- Phase change from solid (or liquid) to vapour.
- *i.e.*, pyrolysis is similar to evaporation but also involves chemical change.

Note: when a solid is burning with a flame, it is actually the pyrolysis vapours (aka *pyrolyzate*) directly above it that are burning, not the solid itself.

Experimental Pyrolysis



The screenshot shows a YouTube video player. The video title is "Pyrolysis of PMMA.wmv". The video content shows a cross-section of a polymer sample being heated in a furnace. The sample is a light brown, fibrous material. The furnace is a dark, cylindrical chamber. The video is from the University of Edinburgh, BRE Centre for Fire Safety Engineering. The video player interface shows a progress bar at 1:24 / 3:17, a play button, a volume icon, and a settings icon. The YouTube logo is visible in the bottom right corner of the video player.

University of Edinburgh, BRE Centre for Fire Safety Engineering

Pyrolysis of PMMA.wmv

You Tube^{GB}

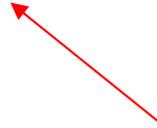
<http://www.youtube.com/watch?v=UusEwufhWaw>

Piloted Ignition of **solid fuels**

The concepts of flashpoint and fire point are also applicable to combustible solids but they cannot be differentiated easily, so fire point rules.

Ignition Data from ASTM E-1321 per Quintiere

Material	T_{ig} [°C]
Wood fiber board	355
Wood hardboard	365
Plywood	390
PMMA	380
Flexible foam plastic	390
Rigid foam plastic	435
Acrylic carpet	300
Wallpaper on plasterboard	412
Asphalt shingle	378
Glass-reinforced plastic	390



fire point

Source: Quintiere, J.G., *Principles of Fire Behavior*, Delmar Publishers, New York, 1998.

Thermally Thick Solid Fuels

If we assume a constant radiative heat flux (irradiation) at the exposed face ($x = 0$) and neglect convective losses, then the temperature T for $x > 0$ and $t > 0$ is:

$$T - T_o = \frac{2\dot{q}_e''}{k} \left[\left(\frac{\alpha t}{\pi} \right)^{1/2} \exp\left(-\frac{x^2}{4\alpha t}\right) - \frac{x}{2} \operatorname{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right) \right]$$

Surface temperature, T_s , i.e. $x = 0$, is then:

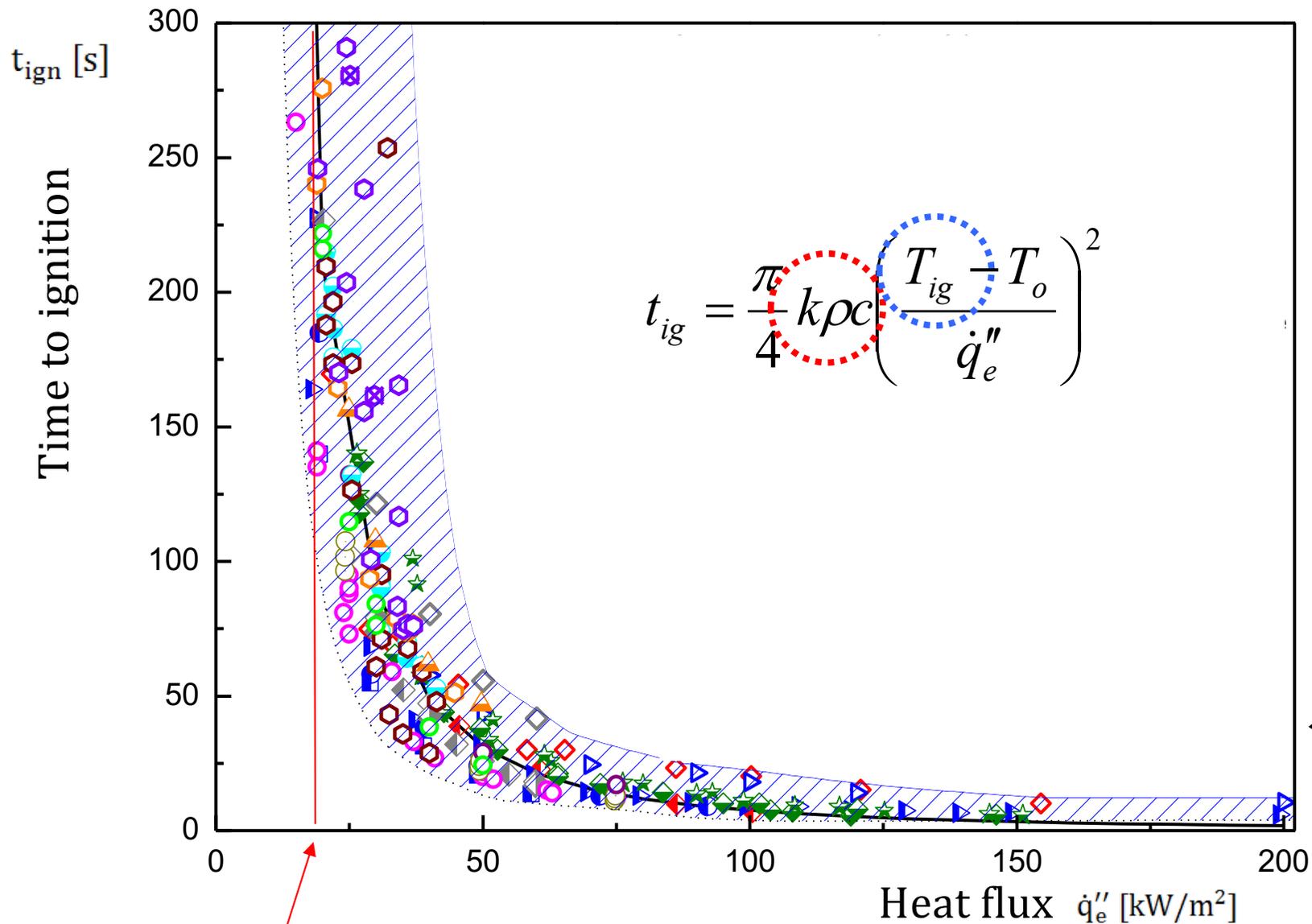
$$T_s - T_o = \frac{2\dot{q}_e''}{k} \left(\frac{\alpha t}{\pi} \right)^{1/2} \quad \text{note: } \frac{k^2}{\alpha} = k\rho c$$

This can be rearranged to give the time to ignition (t_{ig}) when $T_s = T_{ig}$

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

Time to ignition – Thick Samples

Experimental data for PMMA (polymer) from the literature. Thick samples



from Bal and Rein, Combustion and Flame 2011

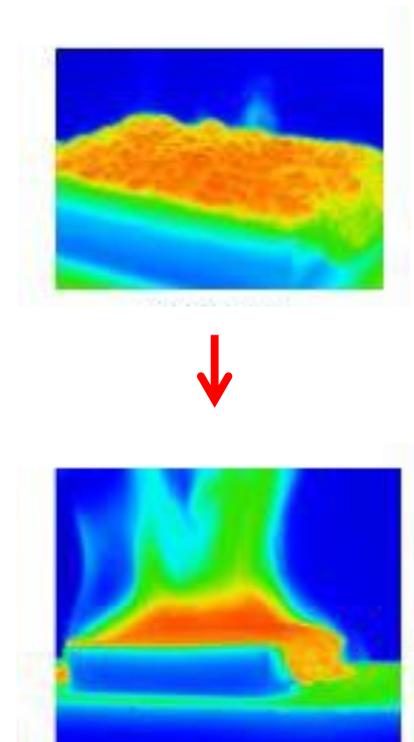
Critical heat flux ~10 kW/m² = heat level below which ignition is not ever possible due to heat losses (term not included in the expression above)

Flammability

~ material property

Ignition Data from ASTM E-1321 per Quintiere

Material	T_{ig} [°C]	$k\rho C$ [(kW/m ² K) ² s]
Wood fiber board	355	0.46
Wood hardboard	365	0.88
Plywood	390	0.54
PMMA	380	1.00
Flexible foam plastic	390	0.32
Rigid foam plastic	435	0.03
Acrylic carpet	300	0.42
Wallpaper on plasterboard	412	0.57
Asphalt shingle	378	0.70
Glass-reinforced plastic	390	0.32

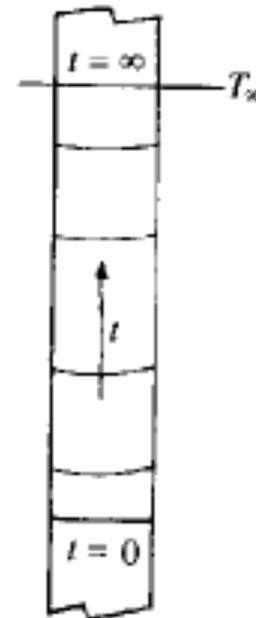


Source: Quintiere, J.G., *Principles of Fire Behavior*, Delmar Publishers, New York, 1998.

Time to ignition – Thin Samples

- If τ is thickness, ρ is density, c is specific heat:
- Thermally thin is when $Bi=h\tau/k<0.1$
- This means that one single temperature represents the whole slab
- No temperature gradients – lumped system
- For thin fuels exposed to high radiant heat fluxes, t_{ig} can be plotted against q''_e to give a straight line of gradient $\tau\rho c$.

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



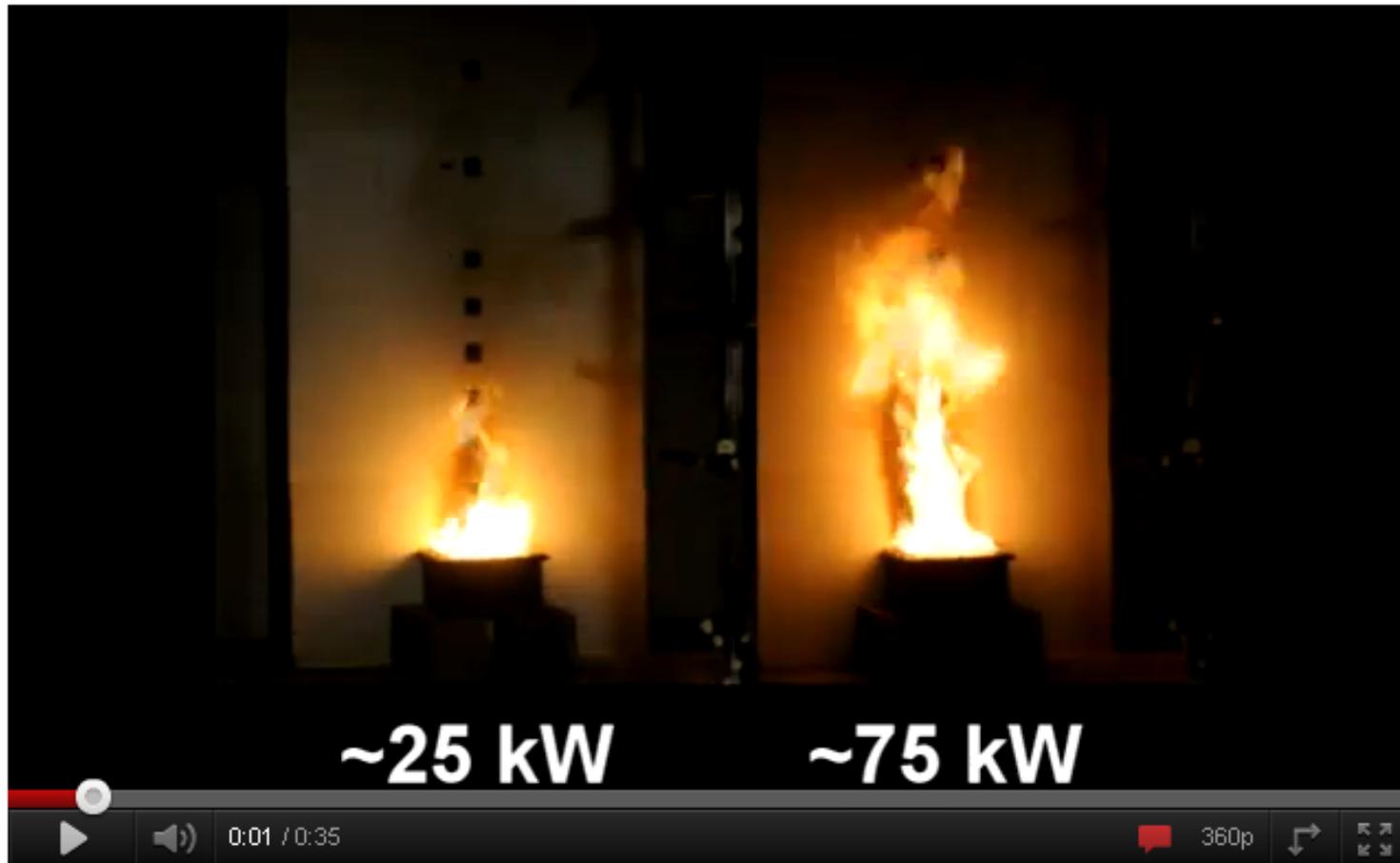
Initial stages ~ fire growth and free burning



Flame and Fire Power

Effect of heat Release Rate on Flame height (video WPI)

http://www.youtube.com/watch?v=7B9-bZCCUxU&feature=player_embedded



 Like   Add to  Share 

370 views 

Uploaded by [SRcombexp](#) on 14 Apr 2011

More information at: <http://firesciencetools.com/>

2 likes, 0 dislikes



Order of fire power

(*average HRR*):

Match ~10 W

Sofa ~1 MW

Room ~3-10 MW

Car ~3-7 MW

Heavy Goods Vehicle

~50 MW

Oil tank

(*Buncefield*) >300 MW

Fire Power – Heat Release Rate

- Heat release rate (HRR) is the power of the fire (energy release per unit time)

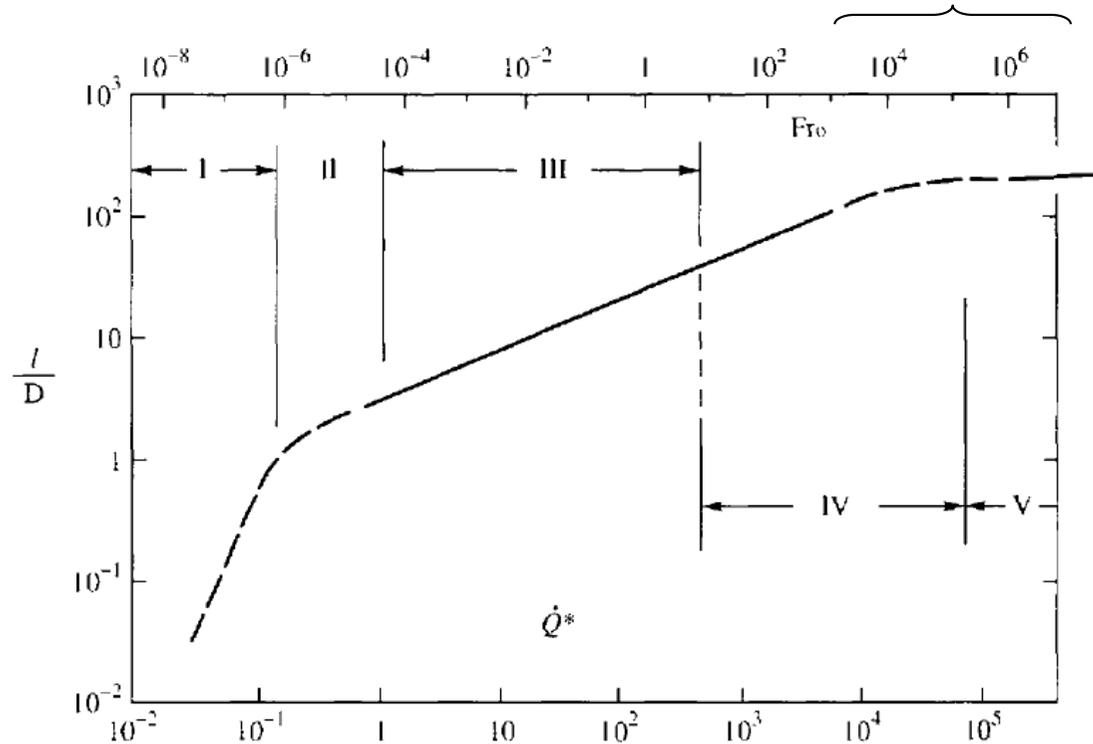
$$\dot{Q} = \Delta h_c \dot{m} = \Delta h_c \dot{m}'' A$$

\dot{Q}	Heat Release Rate (kW) - evolves with time
Δh_c	Heat of combustion (kJ/kg-fuel) ~ constant
\dot{m}	Burning rate (kg/s) - evolves with time
\dot{m}''	Burning rate per unit area (kg/s/m ²) ~ constant
A	Burning area (m ²) - evolves with time

Note: the heat of reaction is negative for exothermic reaction, but in combustion this is always the case, so we will drop the sign from the heat of combustion for the sake of simplicity

Flame Height

momentum-driven flow: jet flames



Buoyancy-driven flows:
compartment fires

Flame height
(dimensionless) is given
by heat release rate
(dimensionless)

Expressions:

$$\frac{l}{D} = 3.7(\dot{Q}^*)^{2/5} - 1.02$$

$$l = 0.235\dot{Q}^{2/5} - 1.02D$$

this expression is dimensional, in kW and m.

Burning rate (per unit area)



Table 9.3 Asymptotic burning rates (from various sources)

	g/m ² s
Polyvinyl chloride (granular)	16
Methanol	21
Flexible polyurethane (foams)	21–27
Polymethymethacrylate	28
Polystyrene (granular)	38
Acetone	40
Gasolene	48–62
JP-4	52–70
Heptane	66
Hexane	70–80
Butane	80
Benzene	98
Liquid natural gas	80–100
Liquid propane	100–130



from Quintiere, Principles of Fire Behaviour

It is a material and scenario dependant.
 Values in table above are for free burning conditions. Values inside a small compartment are larger

$$\dot{m}'' = \frac{\dot{q}''}{\Delta h_p}$$

Heat flux from the flame ← \dot{q}''
 Latent Heat of pyrolysis ← Δh_p

Heat of Combustion

Table 1.13 Heats of combustion^a of selected fuels at 25°C (298 K)

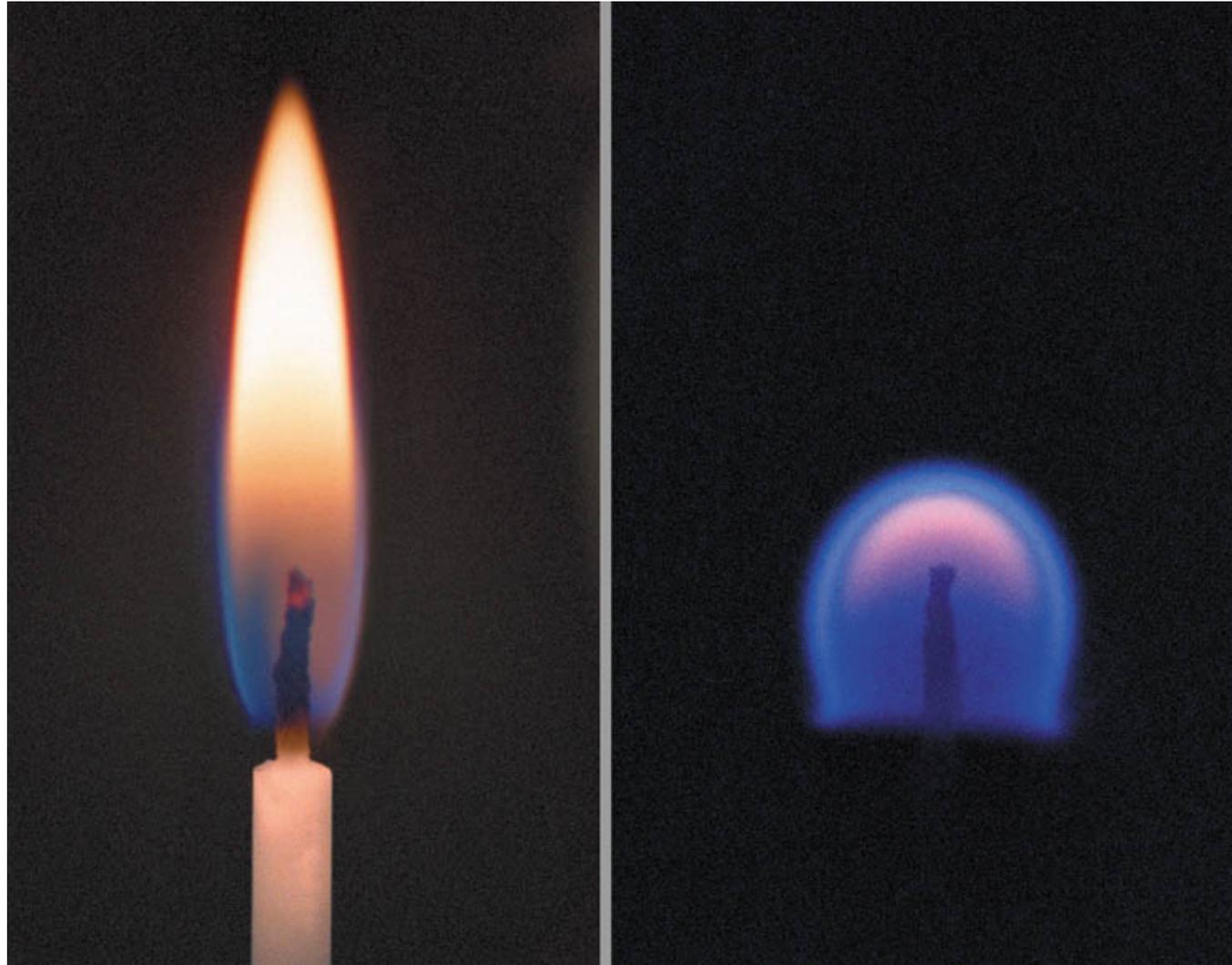
		$-\Delta H_c$ (kJ/mol)	$-\Delta H_c$ (kJ/g)	$-\Delta H_{c,air}$ (kJ/g(air))	$-\Delta H_{c,ox}$ (kJ/g(O ₂))
Carbon monoxide	CO	283	10.10	4.10	17.69
Methane	CH ₄	800	50.00	2.91	12.54
Ethane	C ₂ H ₆	1423	47.45	2.96	11.21
Ethene	C ₂ H ₄	1411	50.35	3.42	14.74
Ethyne	C ₂ H ₂	1253	48.20	3.65	15.73
Propane	C ₃ H ₈	2044	46.45	2.97	12.80
<i>n</i> -Butane	<i>n</i> -C ₄ H ₁₀	2650	45.69	2.97	12.80
<i>n</i> -Pentane	<i>n</i> -C ₅ H ₁₂	3259	45.27	2.97	12.80
<i>n</i> -Octane	<i>n</i> -C ₈ H ₁₈	5104	44.77	2.97	12.80
<i>c</i> -Hexane	<i>c</i> -C ₆ H ₁₂	3680	43.81	2.97	12.80
Benzene	C ₆ H ₆	3120	40.00	3.03	13.06
Methanol	CH ₃ OH	635	19.83	3.07	13.22
Ethanol	C ₂ H ₅ OH	1232	26.78	2.99	12.88
Acetone	(CH ₃) ₂ CO	1786	30.79	3.25	14.00
D-Glucose	C ₆ H ₁₂ O ₆	2772	15.4	3.08	13.27
Cellulose	—	—	16.09	3.15	13.59
Polyethylene	—	—	43.28	2.93	12.65
Polypropylene	—	—	43.31	2.94	12.66
Polystyrene	—	—	39.85	3.01	12.97
Polyvinylchloride	—	—	16.43	2.98	12.84
Polymethylmethacrylate	—	—	24.89	3.01	12.98
Polyacrylonitrile	—	—	30.80	3.16	13.61
Polyoxymethylene	—	—	15.46	3.36	14.50
Polyethyleneterephthalate	—	—	22.00	3.06	13.21
Polycarbonate	—	—	29.72	3.04	13.12
Nylon 6,6	—	—	29.58	2.94	12.67

^a The initial states of the fuels correspond to their natural states at normal temperature and pressure (298°C and 1 atm pressure). All products are taken to be in their gaseous state—thus these are the net heats of combustion.

It is a material property only if the combustion efficiently is also taken into account. Efficiency is scenario dependant.



Buoyancy



Candle burning on Earth (1g) and
in microgravity inside the ISS ($\sim 0g$)

Buoyancy vs. Momentum

The relative importance of the inertia and gravity in a flow is given by:

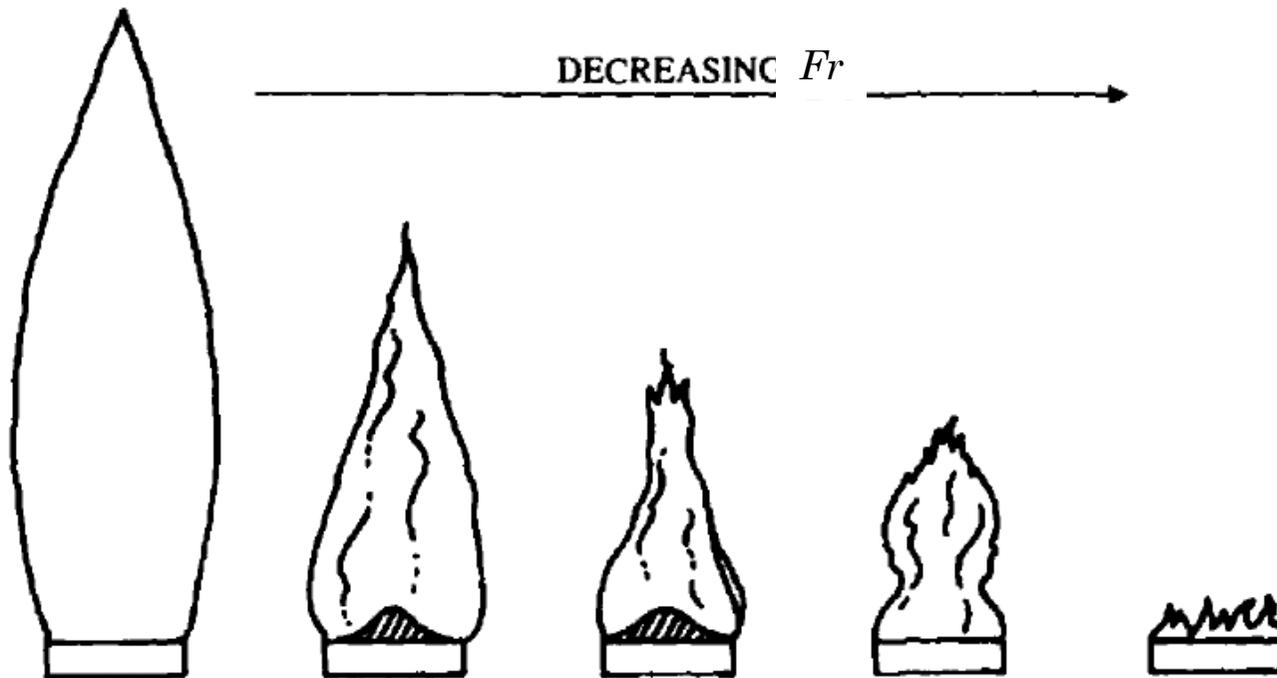
$$Fr = \frac{u^2}{gD}$$

Fr Froude number

u Velocity of gases

D Dimension (diameter of source)

g Gravity acceleration



Momentum-driven flow: jet flames

Buoyancy-driven flows: natural fires

Buoyancy vs. Momentum

The relative importance of the inertia and gravity in a flow is given by:

$$Fr = \frac{u^2}{gD}$$

- Fr** Froude number
- u** Velocity of gases
- D** Dimension (diameter of source)
- g** Gravity acceleration

The Fr number in fire becomes the dimensionless heat release rate:

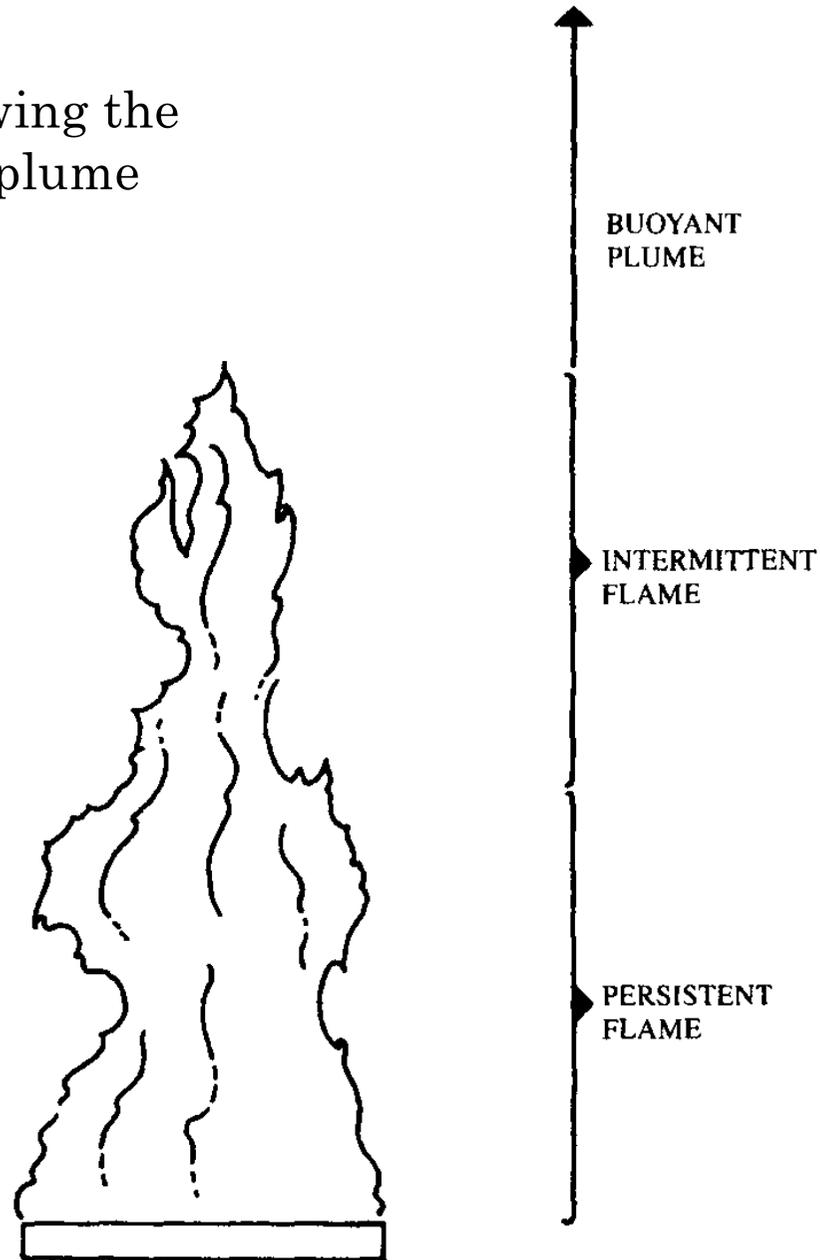
$$\dot{Q}^* = \frac{\dot{Q}}{\rho_{\infty} c_p T_{\infty} D^2 \sqrt{gD}}$$

- \dot{Q}** Heat release rate
- T_{∞}** Ambient temperature (in K)
- ρ** Ambient air density
- c_p** Specific heat of ambient air

this suggest fire scales with size as $\dot{Q} \propto D^{2/5}$

Turbulent Flame Regions

Schematic diagram showing the three regions of the fire plume



Temperature of the plume

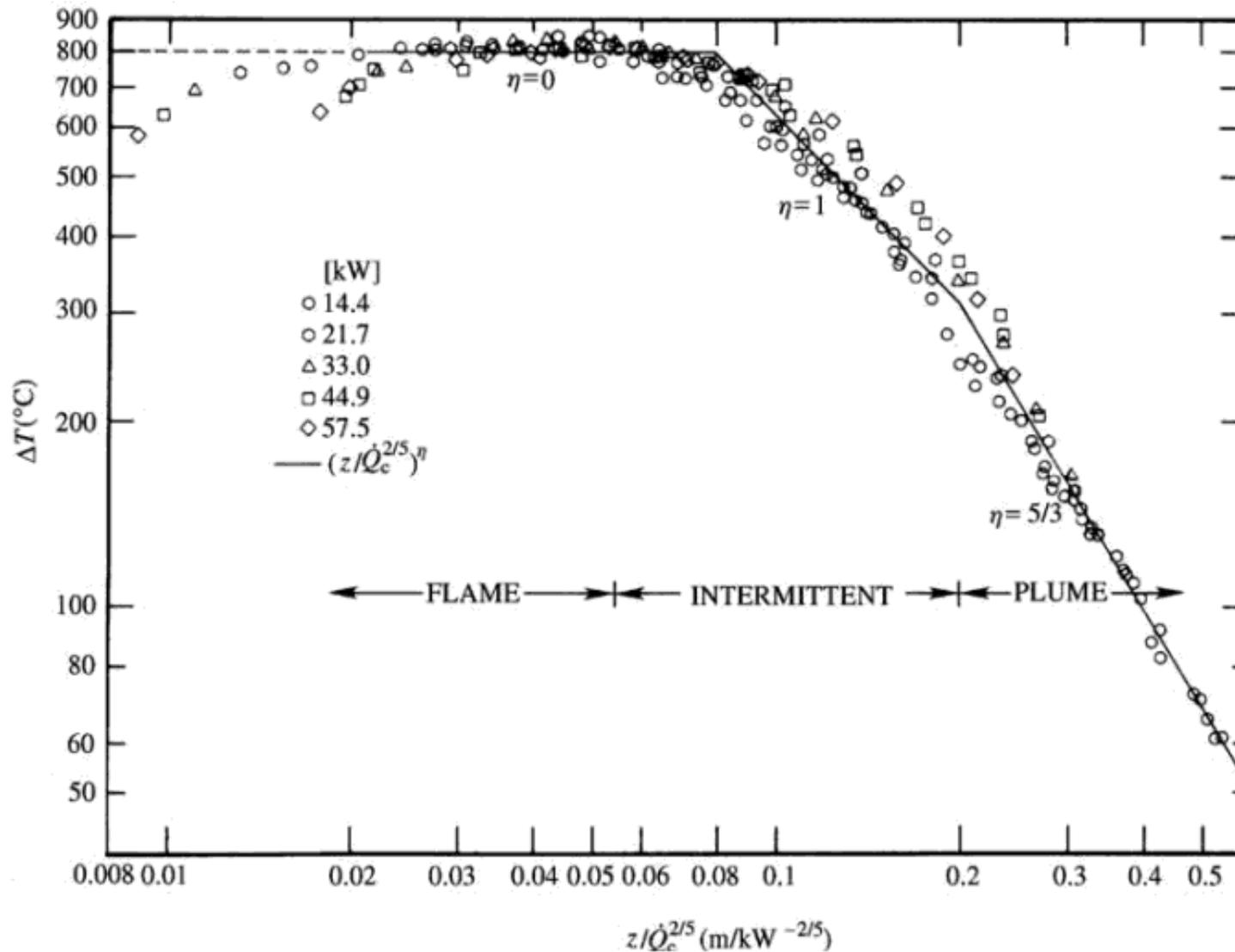


Figure 4.22 Variation of centreline temperature rise with height in a buoyant methane diffusion flame. Scales as $z/\dot{Q}_c^{2/5}$ (Table 4.2) (McCaffrey (1979), by permission). A similar correlation has been demonstrated for a range of hydrocarbon pool fires by Kung and Stavrianides (1982)

Flame Temperatures vs. Measurements of Flame Temperature

- We saw in class that the adiabatic flame temperature T_{ad} is ~ 2000 °C (eg, methane in air).
- Laminar diffusion flames reach peak ~ 1600 °C (experiment of Smyth *et al.* as seen today) lower than T_{ad} because of heat losses, mainly radiation.
- The flame is a thin region 2 mm thick, so as turbulence increases and because of intermittency, temperature in a fix location in space is the time average of the flame and nearby regions, thus resulting in measurements of substantially lower values (~ 900 °C) at the sensor location.

Entrainment & Fire Plumes

Because hot gases rise up in a colder environment,

a point source of heat at ground level creates an axisymmetric buoyant plume.

Cooling of the plume gases occurs as a result of dilution with ambient air which is entrained through the plume boundary

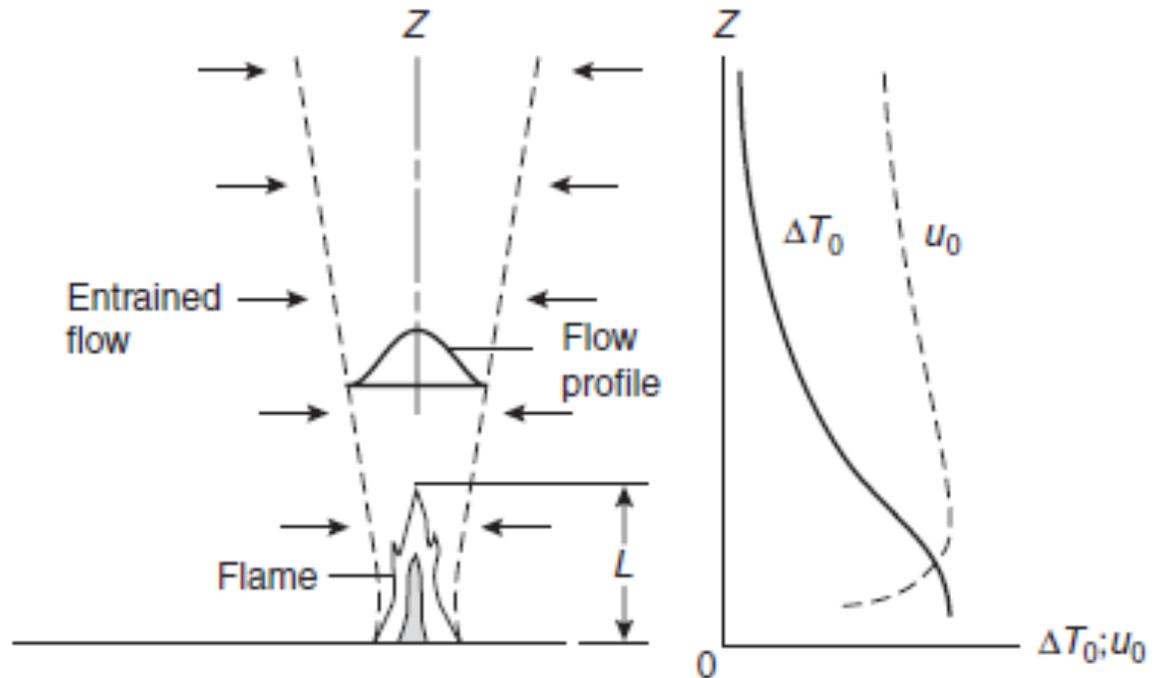


Figure 2-1.1. Features of a turbulent fire plume, including axial variations on the centerline of mean excess temperature, ΔT_0 , and mean velocity, u_0 .³⁴

NOTE: Much more air is entrained to the flame than is required for stoichiometric burning (10 ± 5 times more) \Rightarrow free burning flames are naturally over ventilated

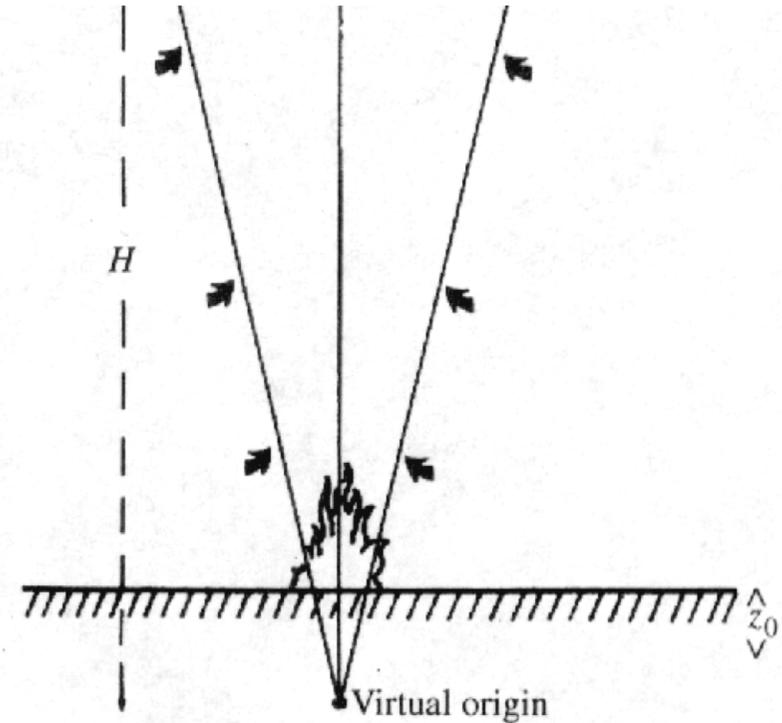
Fire Plumes

$$u_0 = 3.4 \left(\frac{g}{c_p \rho_\infty T_\infty} \right)^{1/3} \dot{Q}_c^{1/3} (z - z_0)^{-1/3}$$

$$\dot{m}_{\text{ent}} = E \left(\frac{g \rho_\infty^2}{c_p T_\infty} \right)^{1/3} \dot{Q}_c^{1/3} (z - z_0)^{5/3}$$

$$E = 0.153.$$

$$\frac{z_0}{D} = -1.02 + 0.083 \frac{\dot{Q}_c^{2/5}}{D} \quad (\dot{Q}_c \text{ in kW, } D \text{ in m})$$

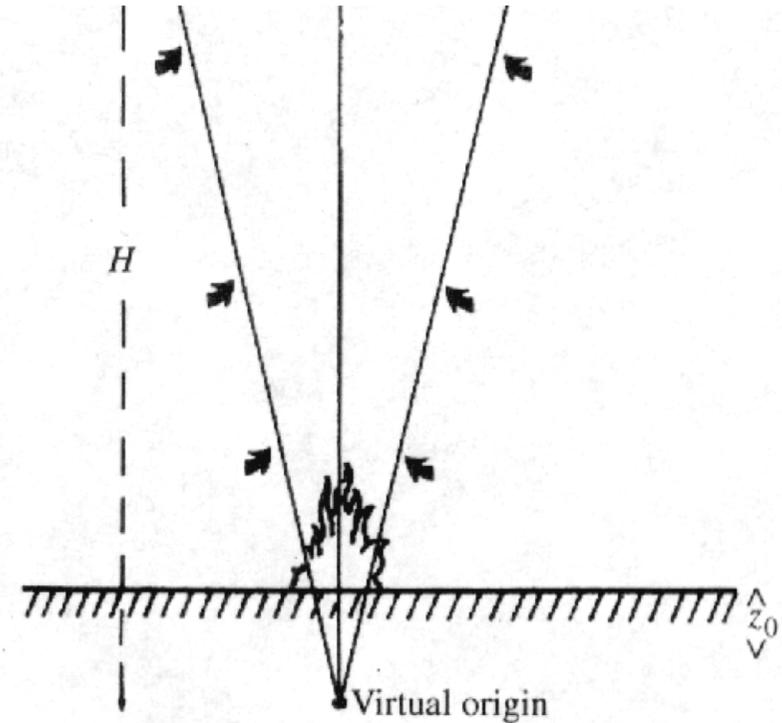


A buoyant plume from a “real” source has a virtual origin – i.e. location of a point source that would produce the same buoyant plume

Fire Plumes

$$\Delta T_0 = 9.1 \left(\frac{T_\infty}{g c_p \rho_\infty^2} \right)^{1/3} \dot{Q}_c^{2/3} (z - z_0)^{-5/3}$$

$$\frac{z_0}{D} = -1.02 + 0.083 \frac{\dot{Q}_c^{2/5}}{D} \quad (\dot{Q} \text{ in kW, } D \text{ in m})$$



Alternative forms and semiempirical correlations:

$$\Delta T_0 = 25 (\dot{Q}_c^{2/5} / (z - z_0))^{5/3}$$

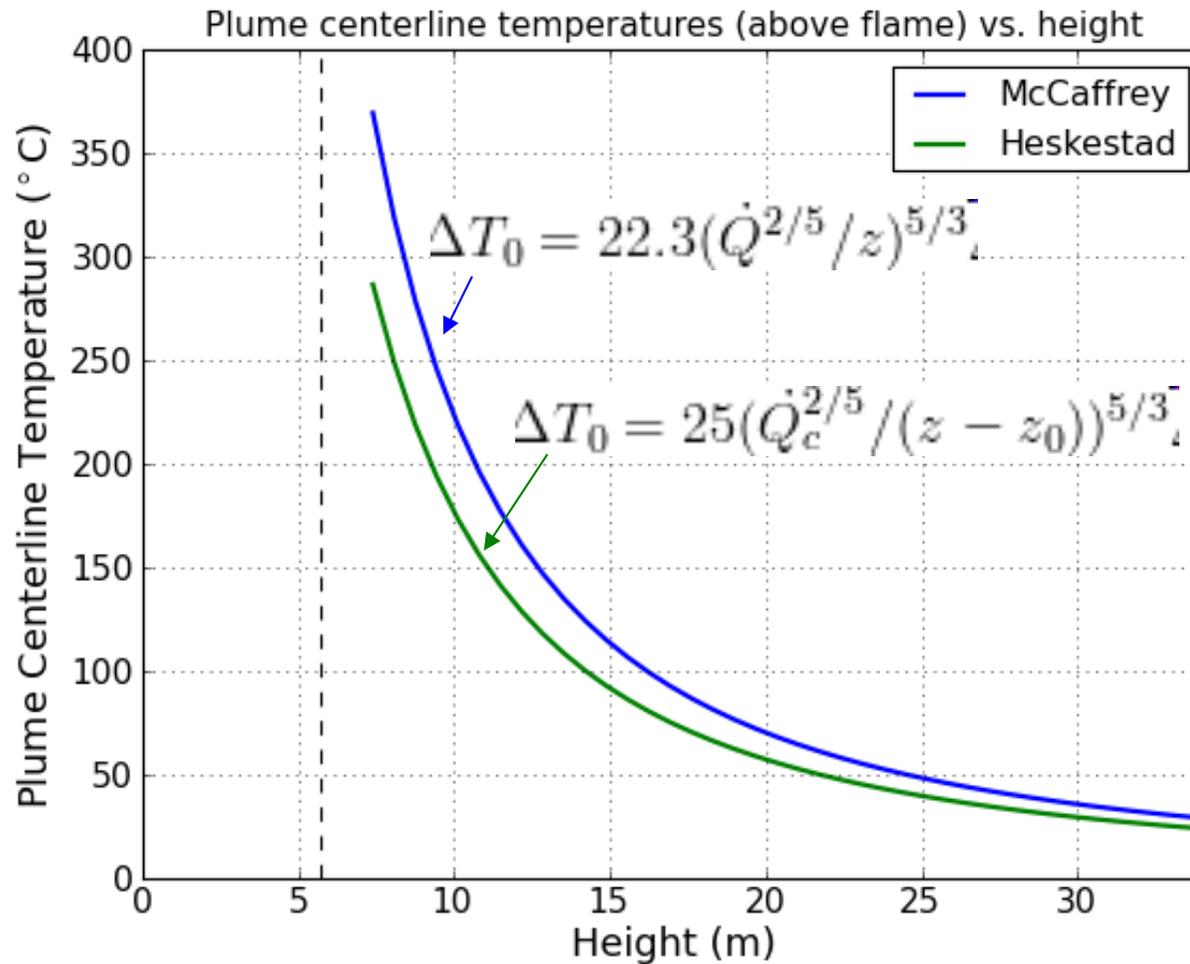
$$\Delta T_0 = 22.3 (\dot{Q}_c^{2/5} / z)^{5/3}$$

$$\Delta T_0 = 26 \frac{\dot{Q}_c^{2/3}}{z^{5/3}}$$

A buoyant plume from a “real” source has a virtual origin – i.e. location of a point source that would produce the same buoyant plume

Example of Fire Plume

For a 10 MW fire with a diameter of 3.6 m, and a radiative fraction 0.35
the flame height l (or L)
is 5.68 m



$$L = -1.02D + 0.235(\dot{Q}^{2/5})$$

NOTE: Q_c is the convective part of the heat release rate



from <http://www.koverholt.com>, by Kristopher Overholt

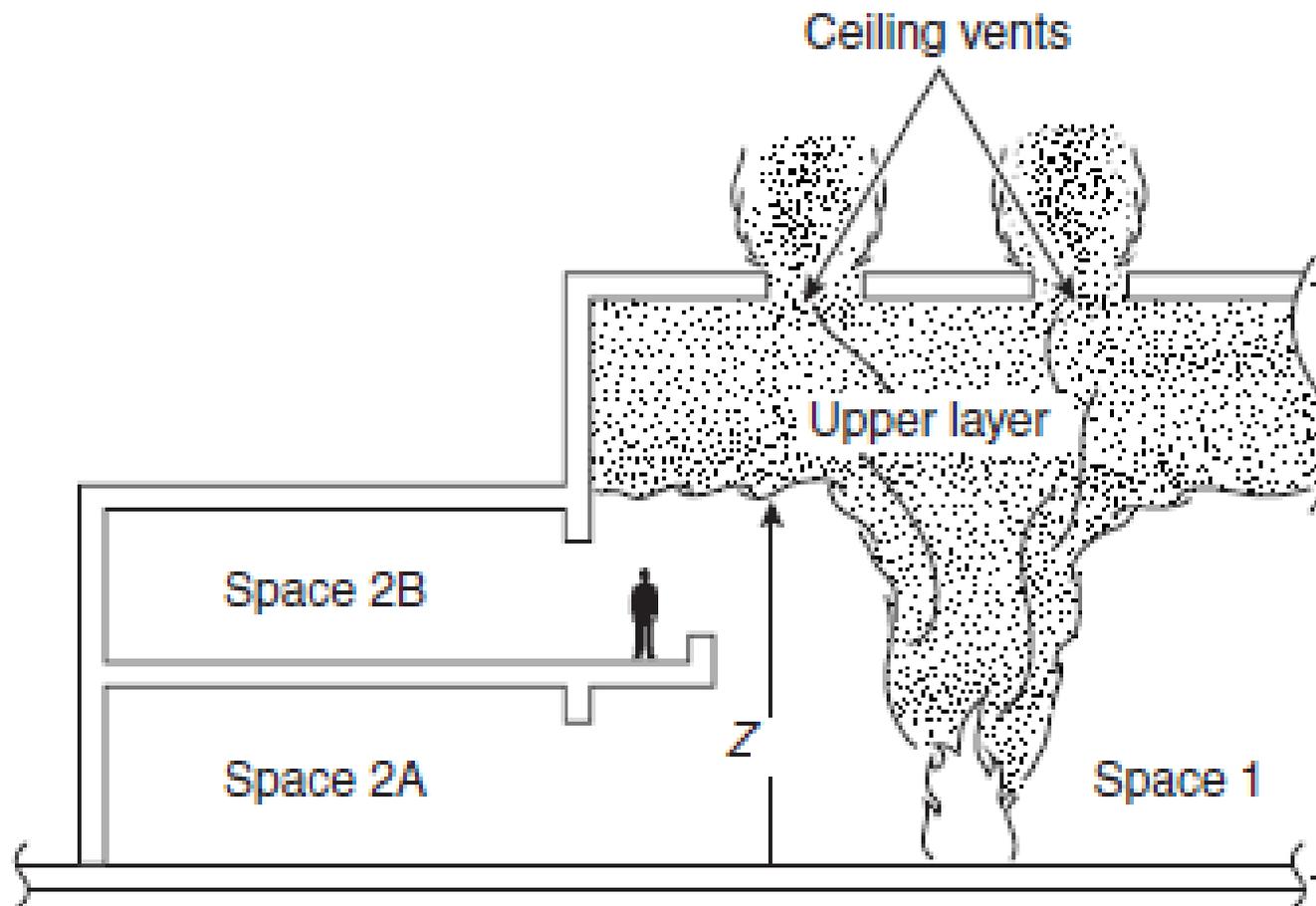
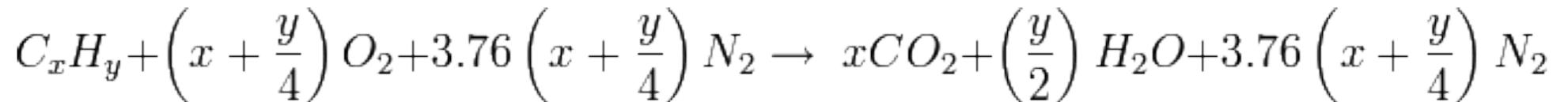


Figure 3-9.2. Fire near the floor of a ceiling-vented atrium with ground- and mezzanine-level shops.

Products of Combustion

Mass flow of combustion products at the flame:

(Atmospheric air is 21% Oxygen, $MW_{air}=29$ g/mol)



Flow of products
of combustion

$$\dot{m}_{pc} = \dot{m} + \dot{m}_{st,air} = \dot{m} \left(1 + \frac{MW_{air}}{MW_{fuel}} \frac{x + y/4}{0.21} \right) \sim \dot{m}(1 + 16)$$

fuel flow
rate
by pyrolysis

flow of
stoichiometric air

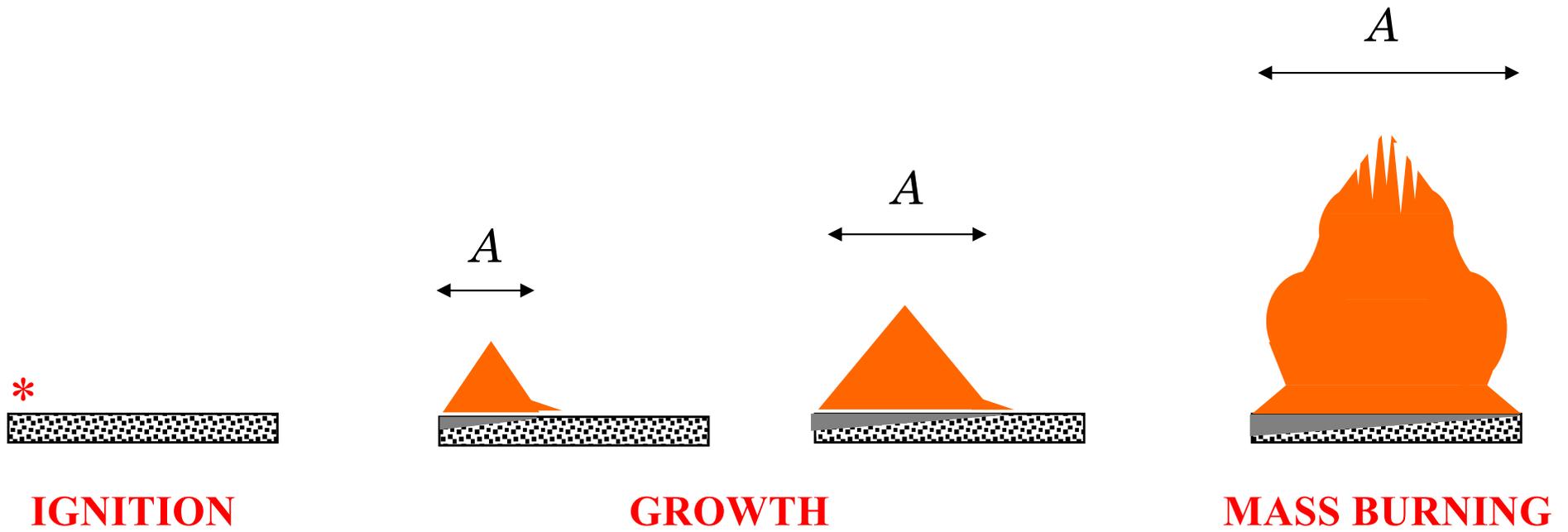
eg, value for propane

$$\dot{m}_{ent} \gg \dot{m}_{pc} \Rightarrow \dot{m}_{smoke} = \dot{m}_{pc} + \dot{m}_{ent} \approx \dot{m}_{ent}$$

- Smoke is mostly made of entrained air
- Most of the smoke is N_2 !

Initial stages ~ fire growth and free burning

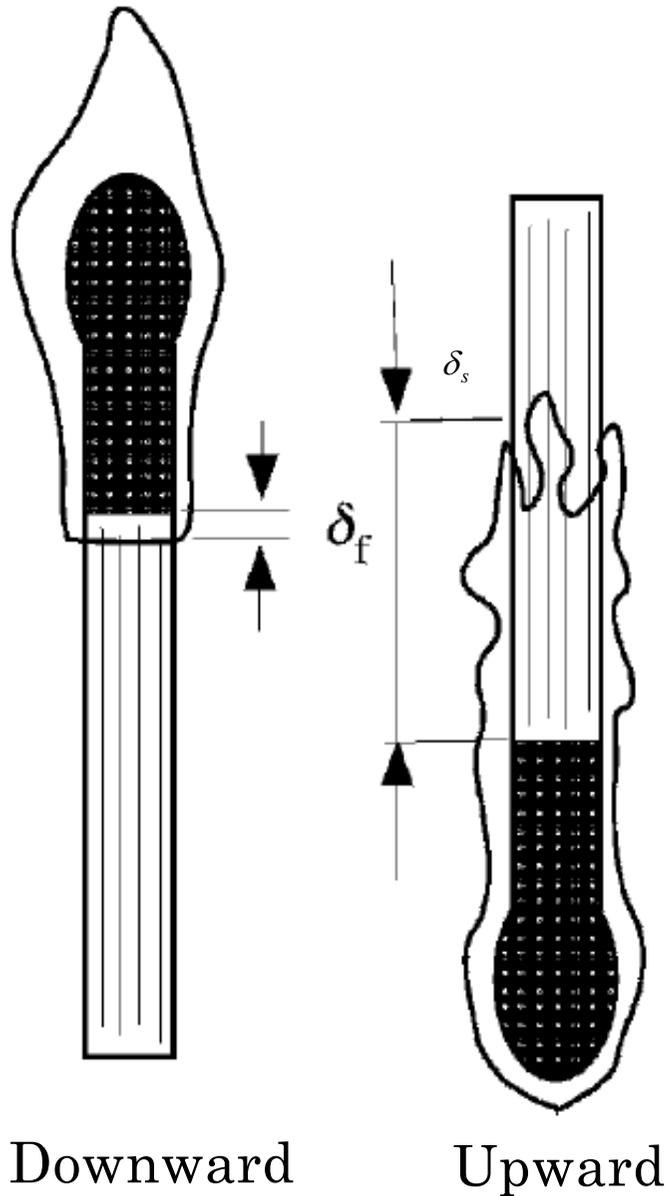




area of the fire A increasing with time



Flame Spread Rate



$$S \propto \frac{\delta_s}{t_{ig}}$$

Flame spread is inversely proportional to the time to ignition

Thick fuel

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

Thin fuel

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

Flame Spread vs. Angle



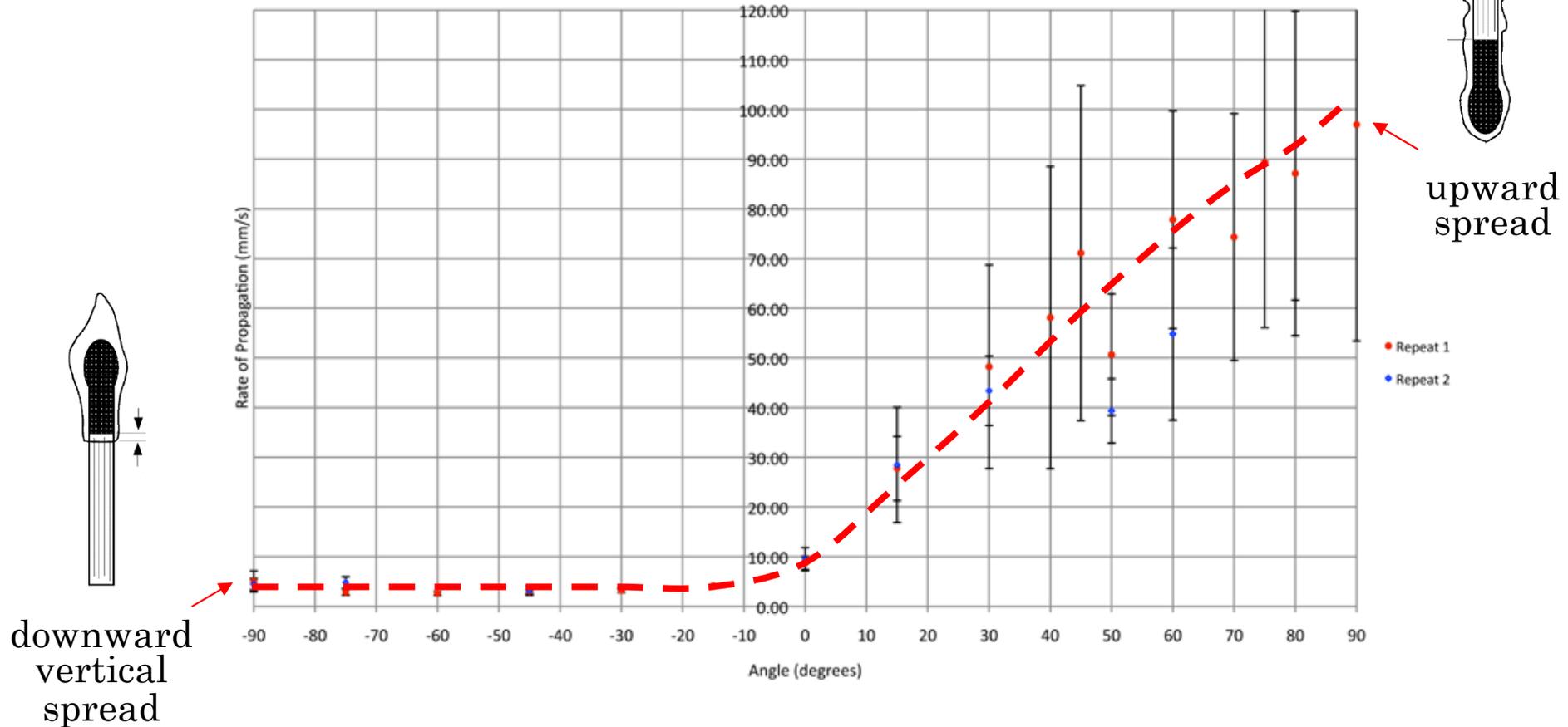
Rate of flame spread over strips of thin samples of balsa wood at different angles of 15, 90, -15 and 0°.

Test conducted by Aled Beswick BEng 2009

<http://www.youtube.com/watch?v=V8gcFX9jLGc>

Flame Spread vs. Angle

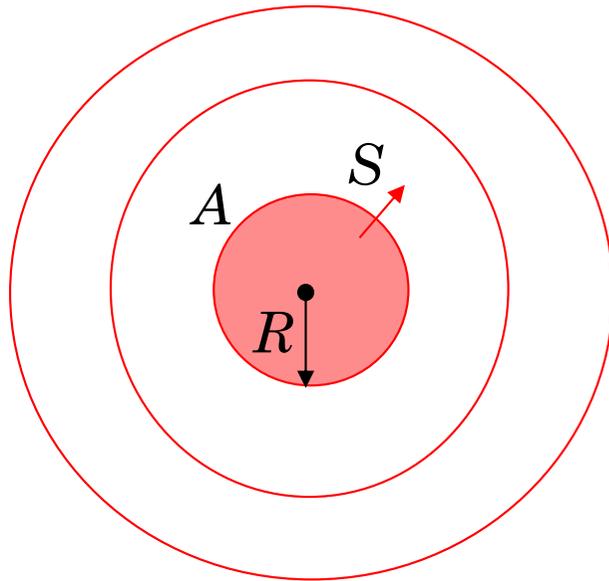
A graph to show the rate of flame spread over balsa at angles between -90 and 90 degrees



Upward spread is 20 times faster than downward spread

Flame spread

On a uniform layer of fuel, isotropic spread gives a circular pattern



$$\frac{dR}{dt} = S = \text{flame spread rate}$$

$$\text{if } S = \text{constant} \Rightarrow R = St$$

$$A = \pi R^2 = \pi (St)^2$$

$$\dot{Q} = \Delta h_c \dot{m}'' A = \pi \Delta h_c \dot{m}'' S^2 t^2$$

~ constant for a given fuel and scenario

$$\dot{Q} = \boxed{\pi \Delta h_c \dot{m}'' S^2} t^2 = \alpha t^2$$

when flame spread is ~constant, the fire grows as t^2

t-square growth fires

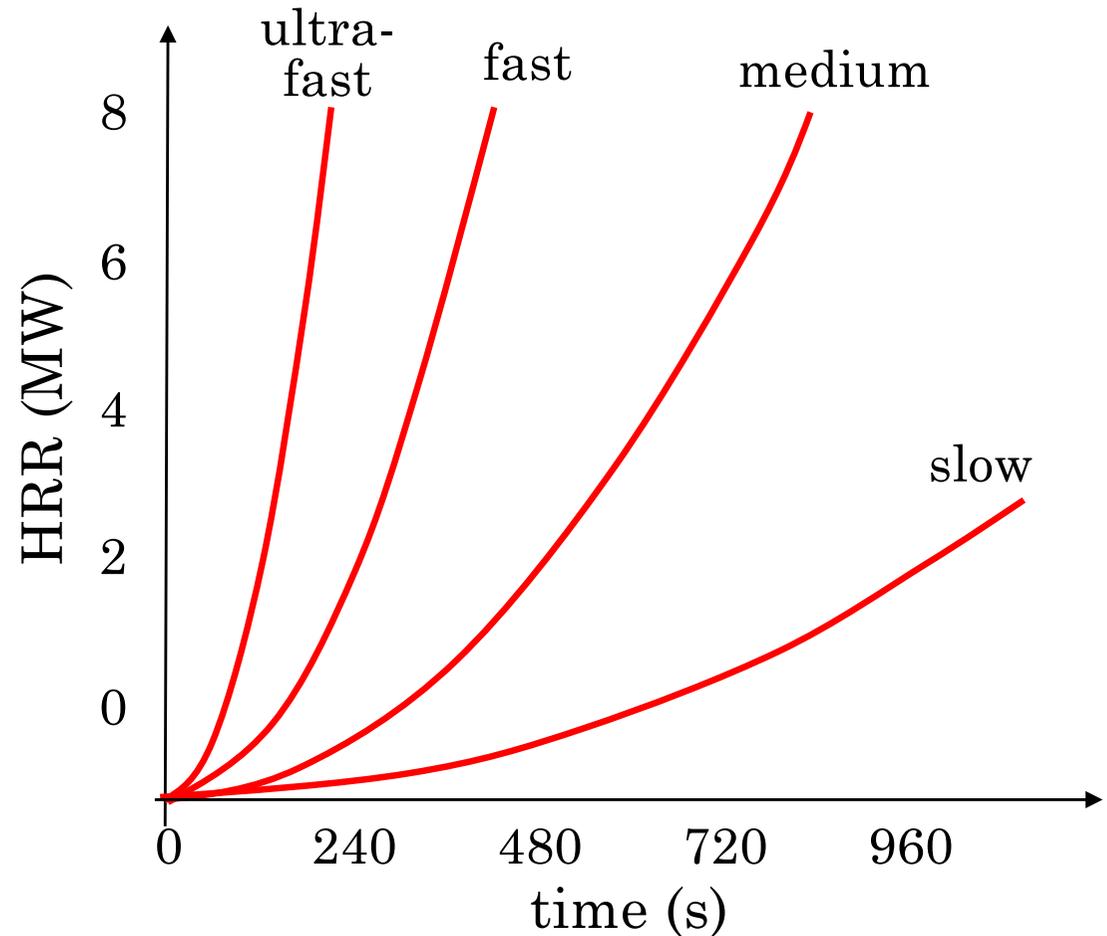
Tabulated fire-growths of different fire types

$$\dot{Q} = \alpha t^2$$

Table 9.6 Parameters used for 't-squared fires' (Evans, 1995)

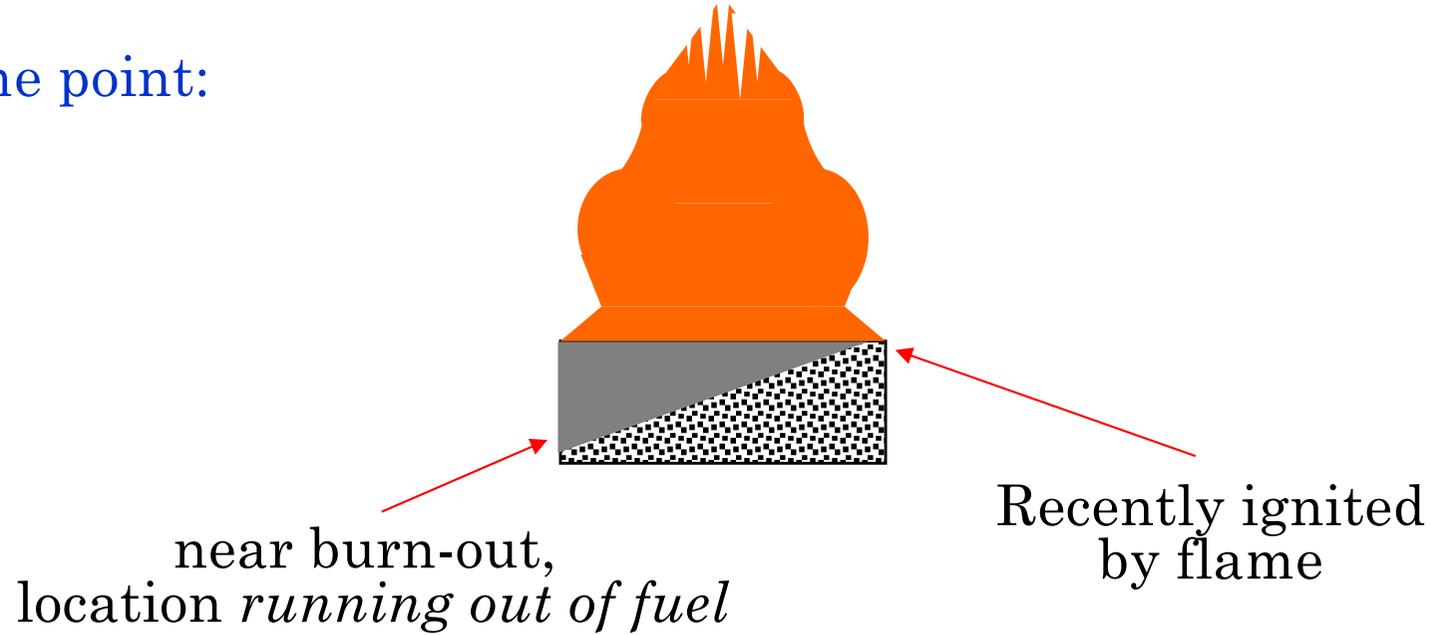
Description	Typical scenario	α_f kW/s ²
Slow	Densely packed paper products ^a	0.00293
Medium	Traditional mattress/boxspring ^a Traditional armchair	0.01172
Fast	PU mattress (horizontal) ^a PE pallets, stacked 1 m high	0.0469
Ultrafast	High-rack storage PE rigid foam stacked 5 m high	0.1876

^a National Fire Protection Association (1993a).

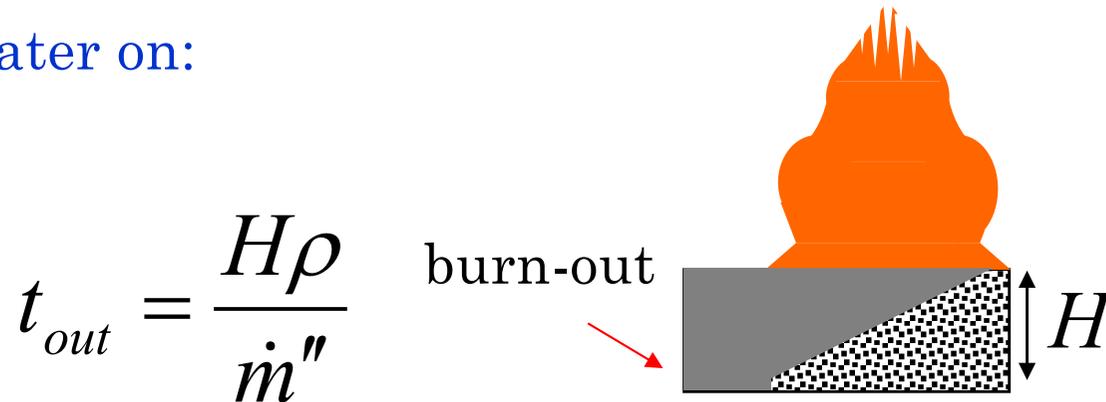


Burn-out

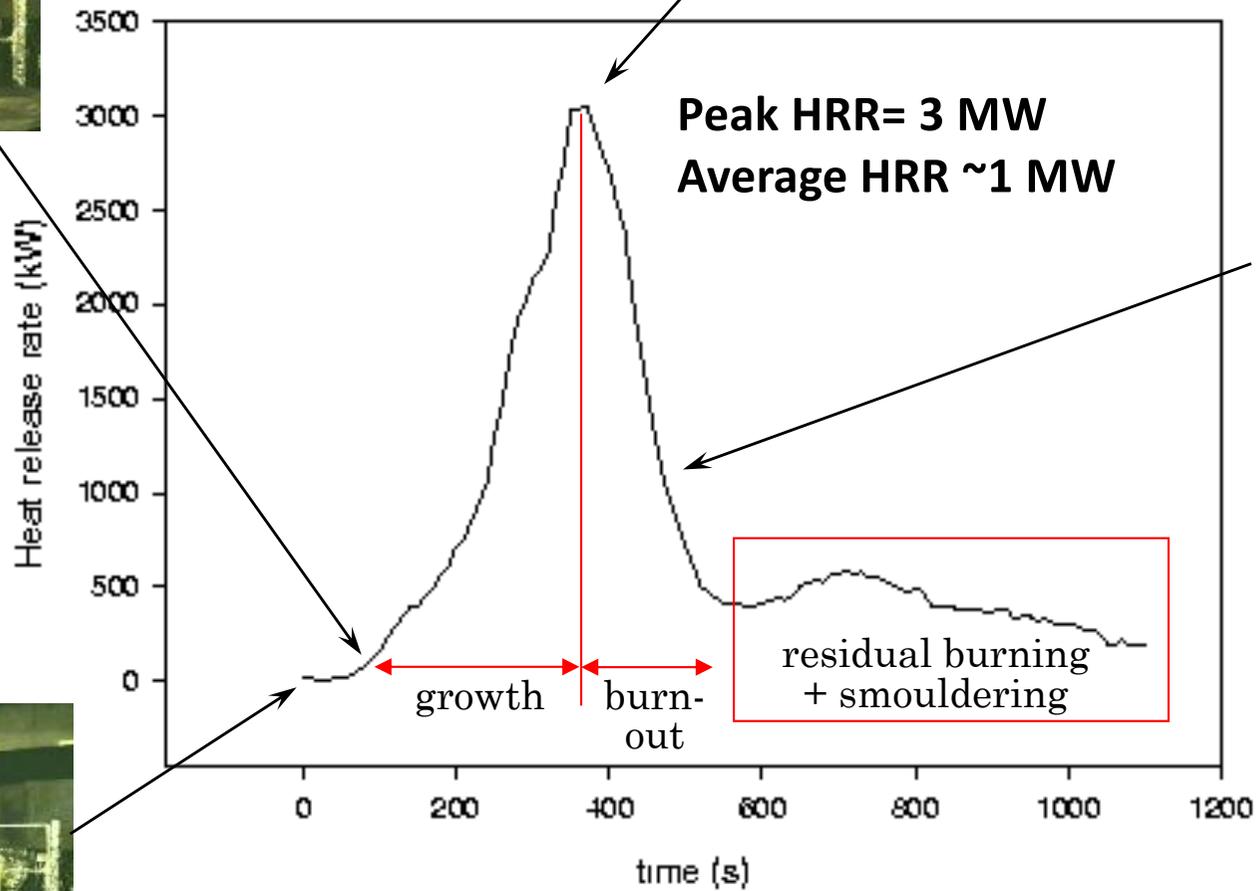
At some point:



Later on:

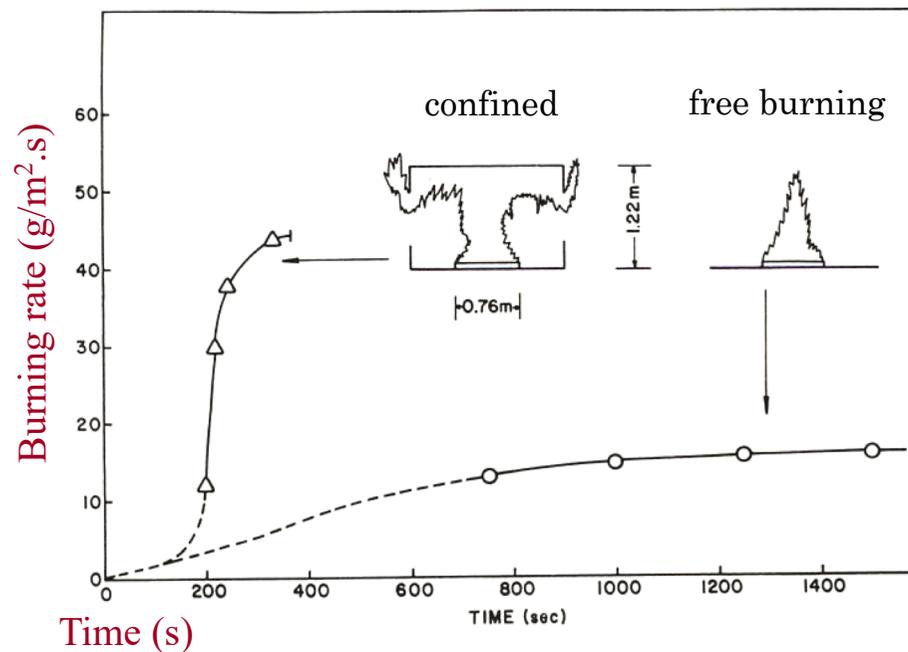


Sofa fire



from NIST <http://fire.nist.gov/fire/fires>

Free burning vs. Confined burning



Additional irradiation from deflected flames, hot walls and hot smoke layer

Experimental data from slab of PMMA (0.76m x 0.76m) at unconfined and confined conditions

This illustrates the key difference between a fire in the open and one in a confined space

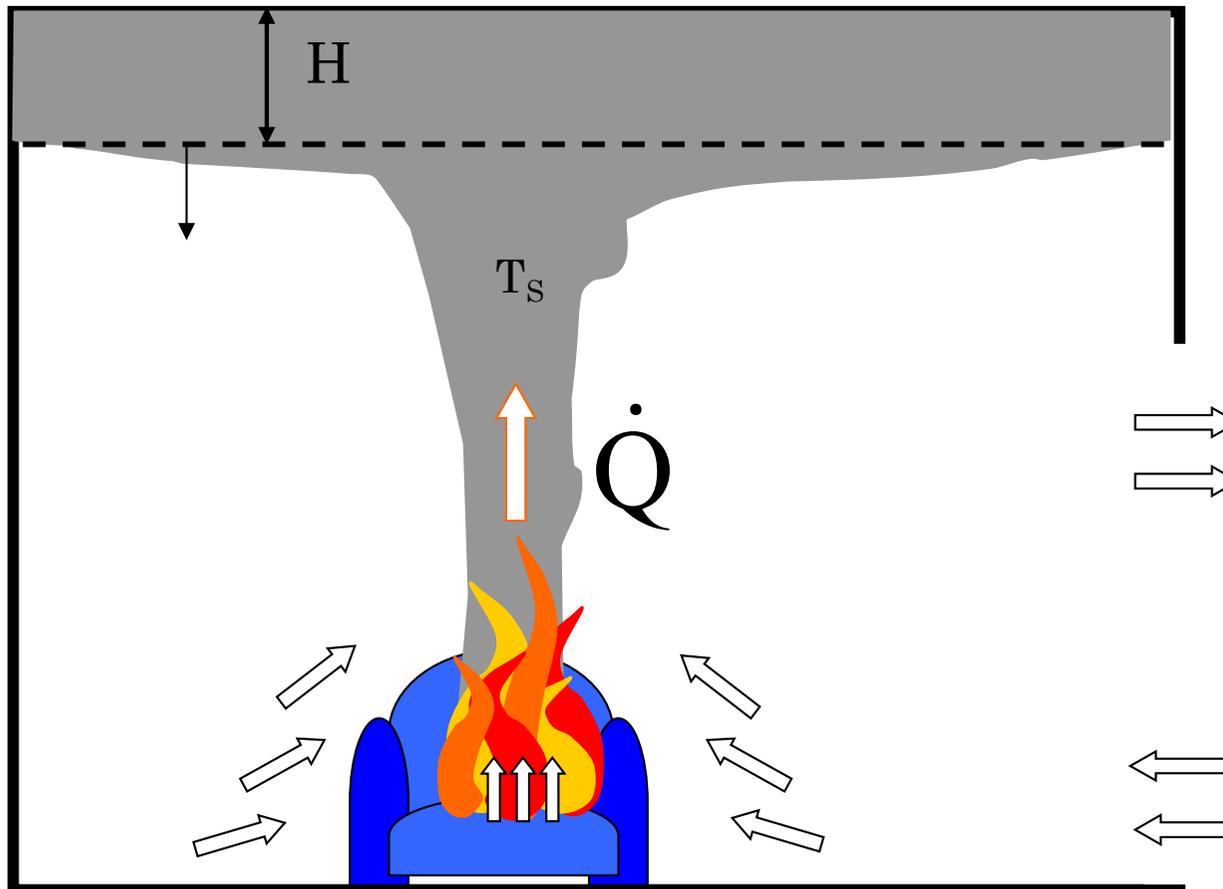


Smoke filling and fire growth



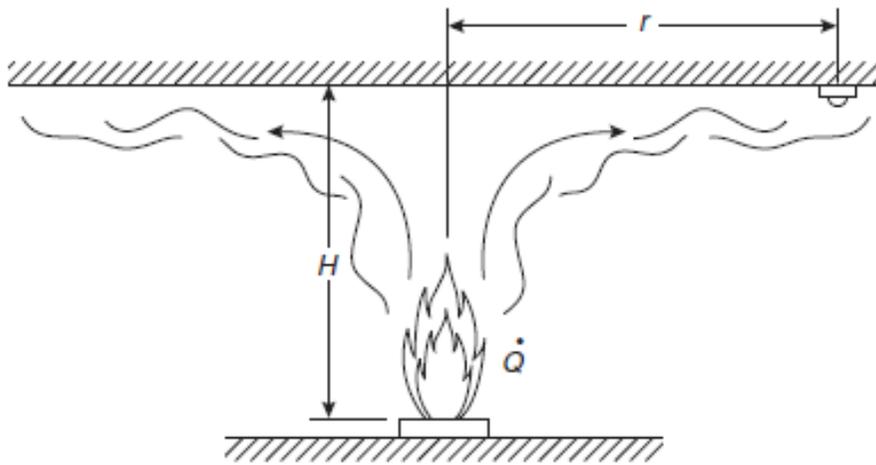
The Compartment Fire

- The influence of a compartment on a fire
 - ⌘ Retaining heat
 - ⌘ Restricting airflow in
 - ⌘ Two zones: smoke layer vs. air layer.



Ceiling Jet

Alpert developed correlations which gave the (maximum) temperatures and velocities in the flow near the ceiling – aka “the ceiling jet”



$$T - T_{\infty} = 16.9 \frac{\dot{Q}^{2/3}}{H^{5/3}} \quad \text{for } r/H \leq 0.18$$

$$T - T_{\infty} = 5.38 \frac{\dot{Q}^{2/3} / H^{5/3}}{(r/H)^{2/3}} \quad \text{for } r/H > 0.18$$

$$U = 0.96 \left(\frac{\dot{Q}}{H} \right)^{1/3} \quad \text{for } r/H \leq 0.15$$

$$U = 0.195 \frac{(\dot{Q}/H)^{1/3}}{(r/H)^{5/6}} \quad \text{for } r/H > 0.15$$

Figure 2-2.1. Ceiling jet flow beneath an unconfined ceiling.

NOTE: U is the velocity of the flow along the ceiling

Flashover



Sudden and generalized ignition (*flashover*)

What is flashover?

Sudden event of very rapid growth caused by generalized ignition of all fuel items in the room

Some indicators:

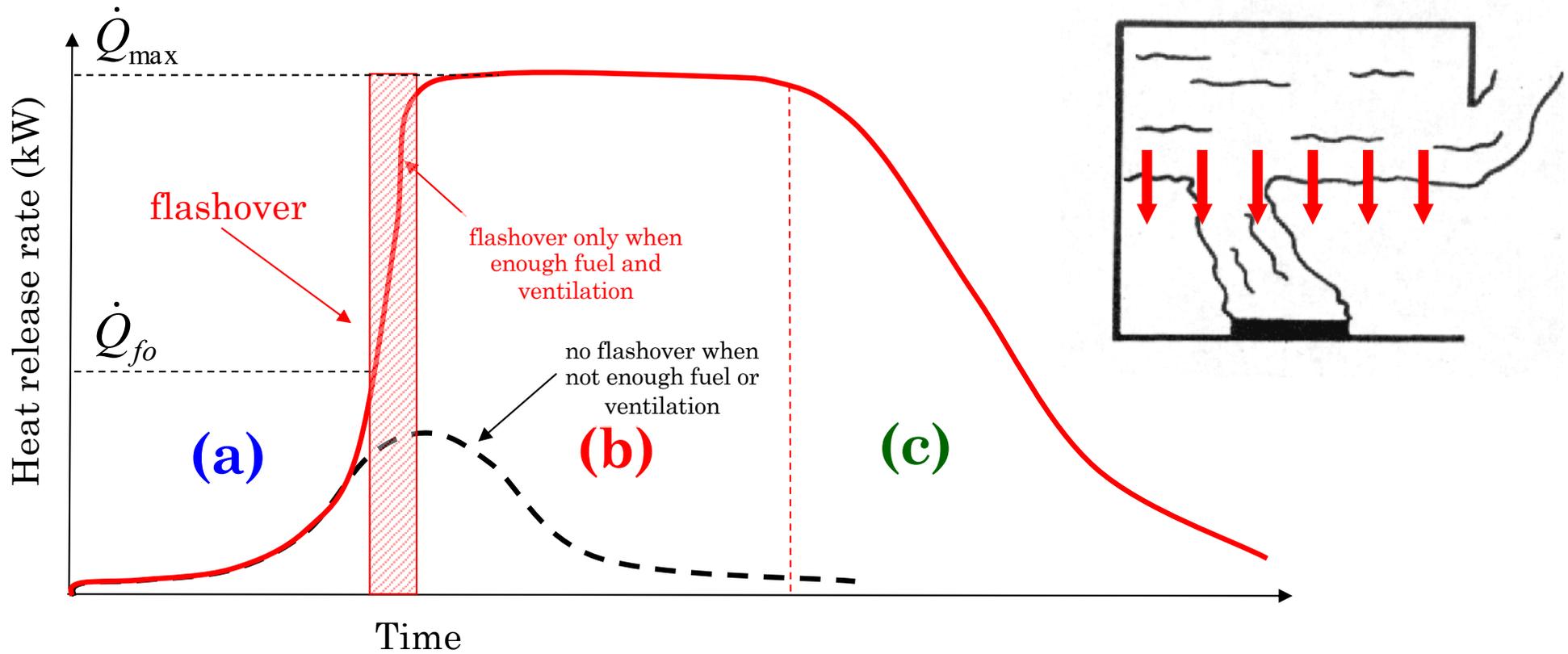
- Average smoke temperature of $\sim 500-600$ °C
- Heat flux ~ 20 kW/m² at floor level
- External flaming, out of openings (ventilation controlled)

NOTE: These three are *not* definitions but indicators only

NOTE 2: Average temperature of 600°C implies that the room space is occupied mostly by interment flames. Therefore, this can only happen in *small* compartments (TBC).

Compartment fires

Fire development in a compartment - rate of heat release as a function of time



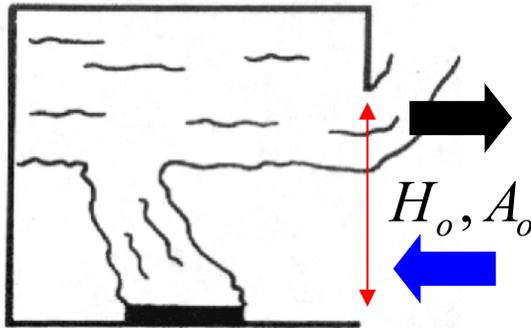
- (a) growth period
- (b) fully developed fire
- (c) decay period

pre-flashover fire

post-flashover fire

(shortly after flashover, a fire usually reaches ventilation limited conditions)

Fully Developed fire



When the maximum flow rate of air entering the compartment is reached, the fire becomes limited by the amount of oxygen not the amount of fuel. This gives the **maximum possible HRR** in the compartment given its ventilation factor.

$$\dot{m}_{a,\max} = 0.5 A_o \sqrt{H_o}$$

$$\dot{Q}_{\max} = \dot{m}_{a,\max} y_{O_2} \Delta h_c = 1.5 A_o \sqrt{H_o} \text{ (in MW)}$$

\dot{m}_a Mass flow of air into compartment (kg/s)

A_o Opening area (m²)

H_o Height of opening (m)

Δh_c Heat of combustion per unit O₂ consumed (kJ/g-O₂)

y_{O_2} Oxygen mass fraction in air (0.23)

Under Ventilated fires and External flaming



0:00 min

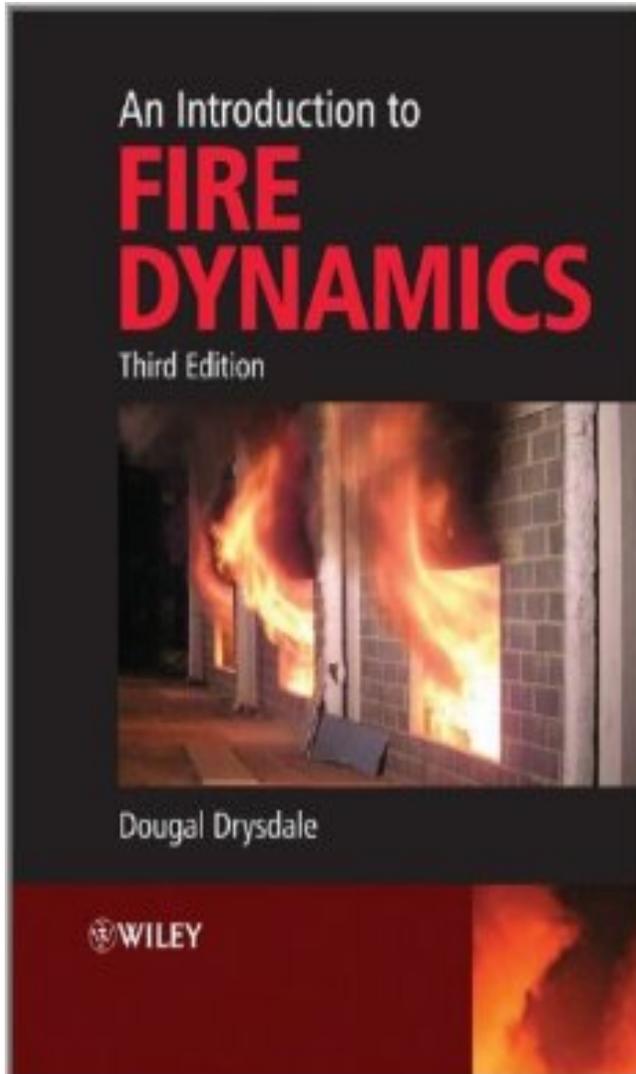


4:15 min

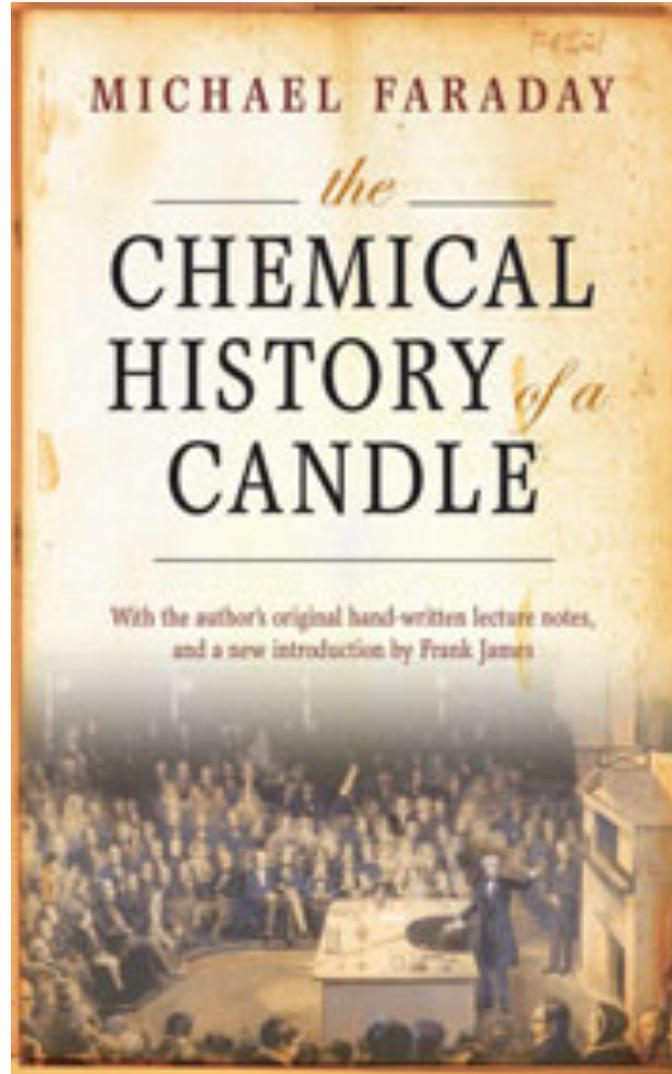


5:00 min

Polypropylene: burning inside a small compartment (0.4m cube)

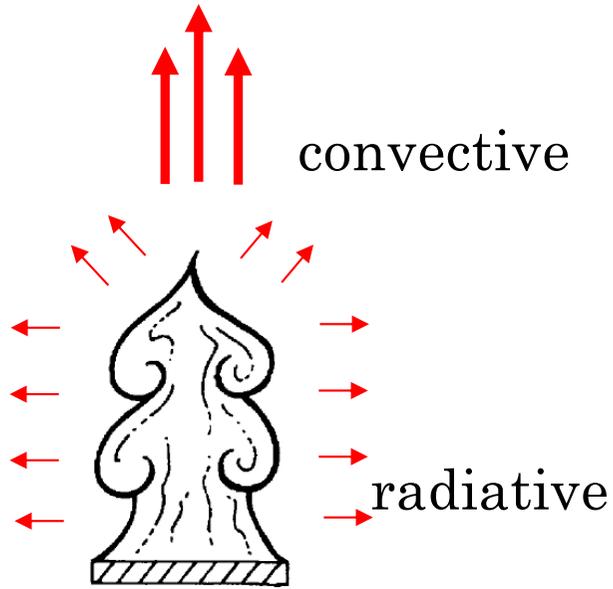


The authoritative scientific text
on fire science



SFPE Handbook
of Fire Protection
Engineering,
5th Edition,
Springer, 2016.

Radiative fraction



$$\dot{Q}_{conv} = (1 - \chi)\dot{Q}$$

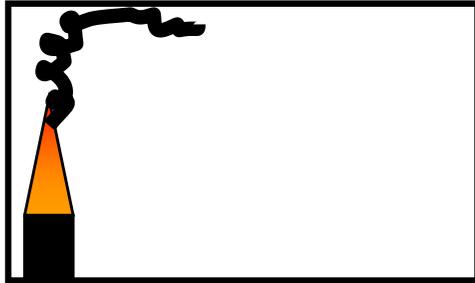
$$\dot{Q}_{rad} = \chi\dot{Q}$$

\dot{Q} Total heat release rate (convective + radiative)

\dot{Q}_{conv} Convective heat release rate

χ Radiative fraction (typically ~ 0.35 for most fuels). Its value is strongly correlated to soot yield

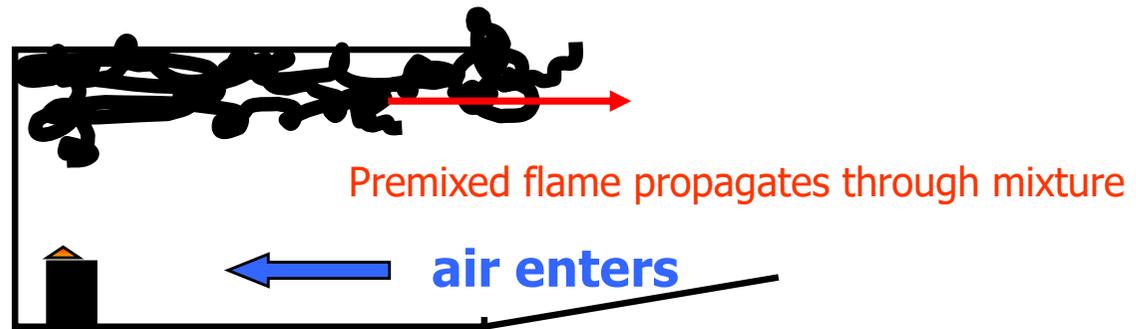
Smoke Composition and Backdraught



Fire in sealed compartment



Flame self-extinguishes after some time due to O_2 depletion. It leaves smoke with high content of unburnt fuel (poor combustion)



When the compartment is suddenly opened (fire-fighting or breakage) air enters and forms a mixture which fuel concentration might be below the rich flammability limit. Then, if an ignition source is found (glowing hot spots, nearby fire), a large deflagration takes place as the premixed flame propagates out of the compartment

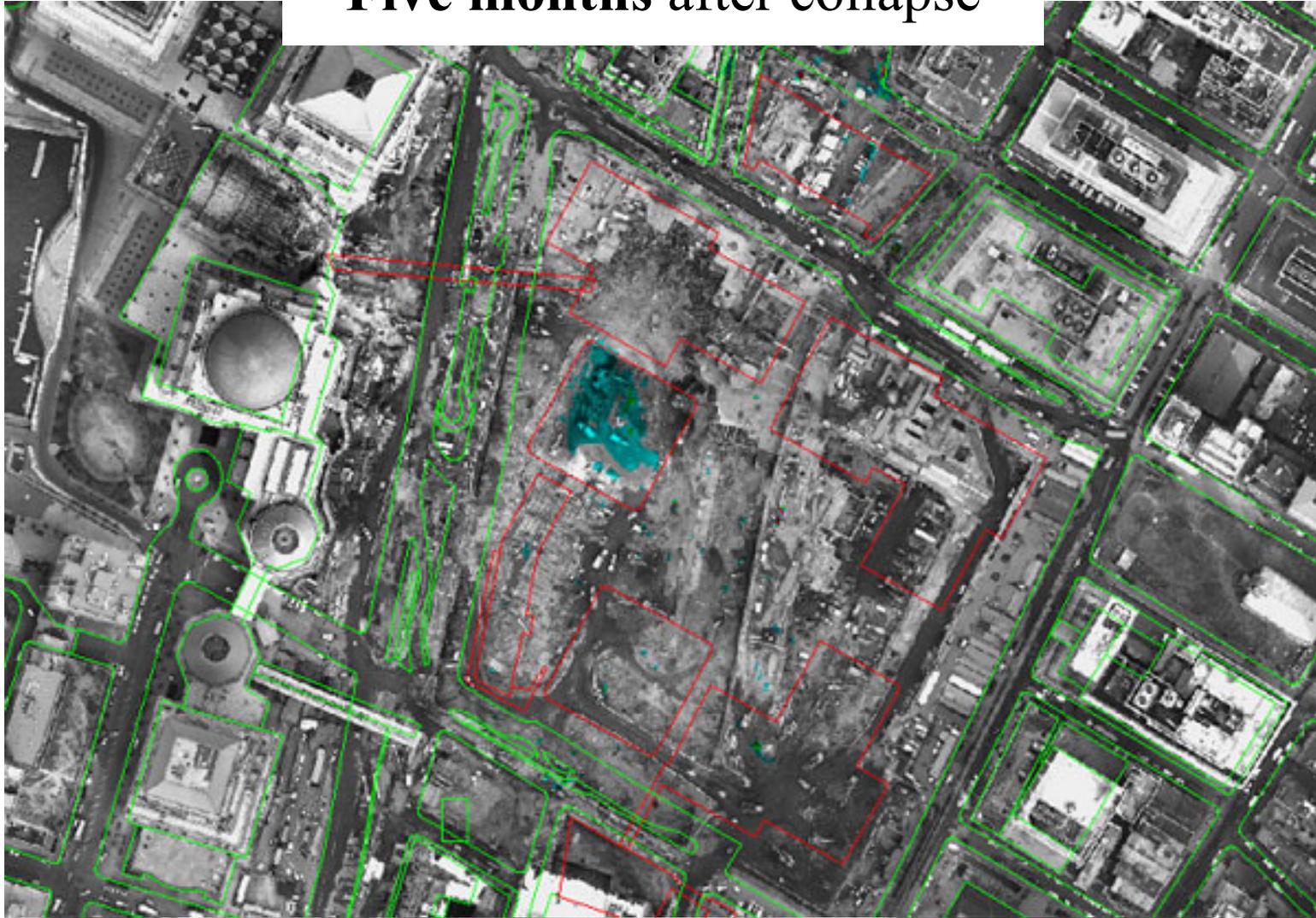
after 2001 WTC collapse...

“the longest-burning structural fire in history” (New Scientist, Dec. 2001)



Longest-burning building fire: 5 months

Five months after collapse



Photographs from the Office for Technology, New York State, 2001

Smouldering vs. Flaming

- Global combustion reaction of solid fuel, in its simplest form, can be approximated by two steps: **pyrolysis** followed by **oxidation**.



or



2. **Two possible oxidation paths:**

- If oxidation of pyrolyzate (gas-phase) → **flaming**
- If oxidation of char (solid-phase) → **smouldering**

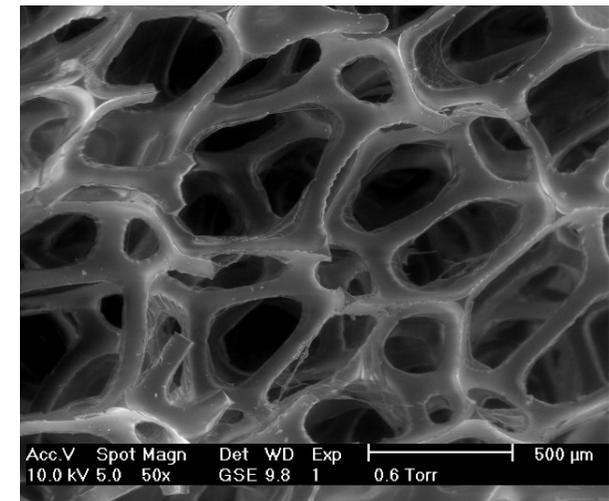
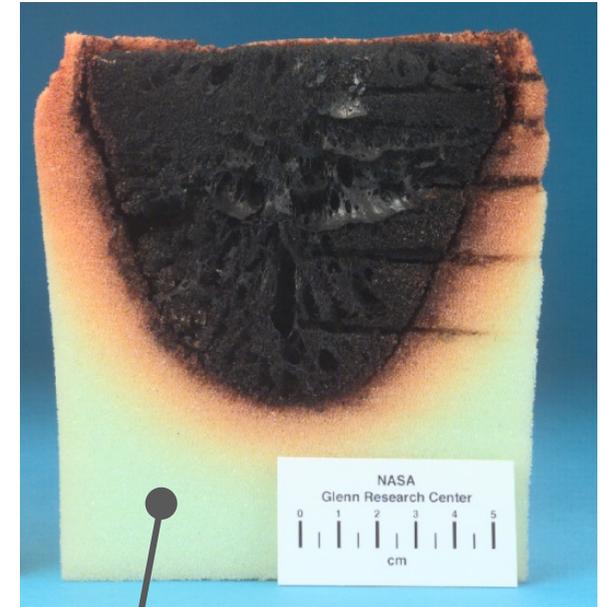
What is it?

- **Smoldering combustion** is the slow, low temperature, flameless burning of porous fuels.
- **Heterogeneous combustion:** Heat is released when oxygen directly attacks the surface of a solid fuel.
- It is especially common in:
 - ⌘ **Natural fuels:** biomass, peat, duff, litter, wood, coal.
 - ⌘ **Synthetic fuels:** cellulose, polyurethane foam.



Smouldering Nature

- *In chemical terms:* fuels **form a char** on heating.
- *In physical terms:* fuels consist of a permeable medium formed by grains, fibers or some other **porous matrix**.
- This porous nature provides large surface area per unit volume, which facilitates **heterogeneous reaction** with oxygen while permits **transport of oxygen** through the fuel bed.



Smouldering and Safety

➤ Smoldering combustion is among the **leading causes** of residential fires and fire deaths (~25%) due to:

- Difficult to detect
- Higher yield of toxic gases
- Sudden transition to flaming



➤ It is a source of safety concerns in industrial premises (eg, **biomass and waste storage**) as well as in commercial and space flights.

