Factors Affecting Fire and Combustion Toxicity

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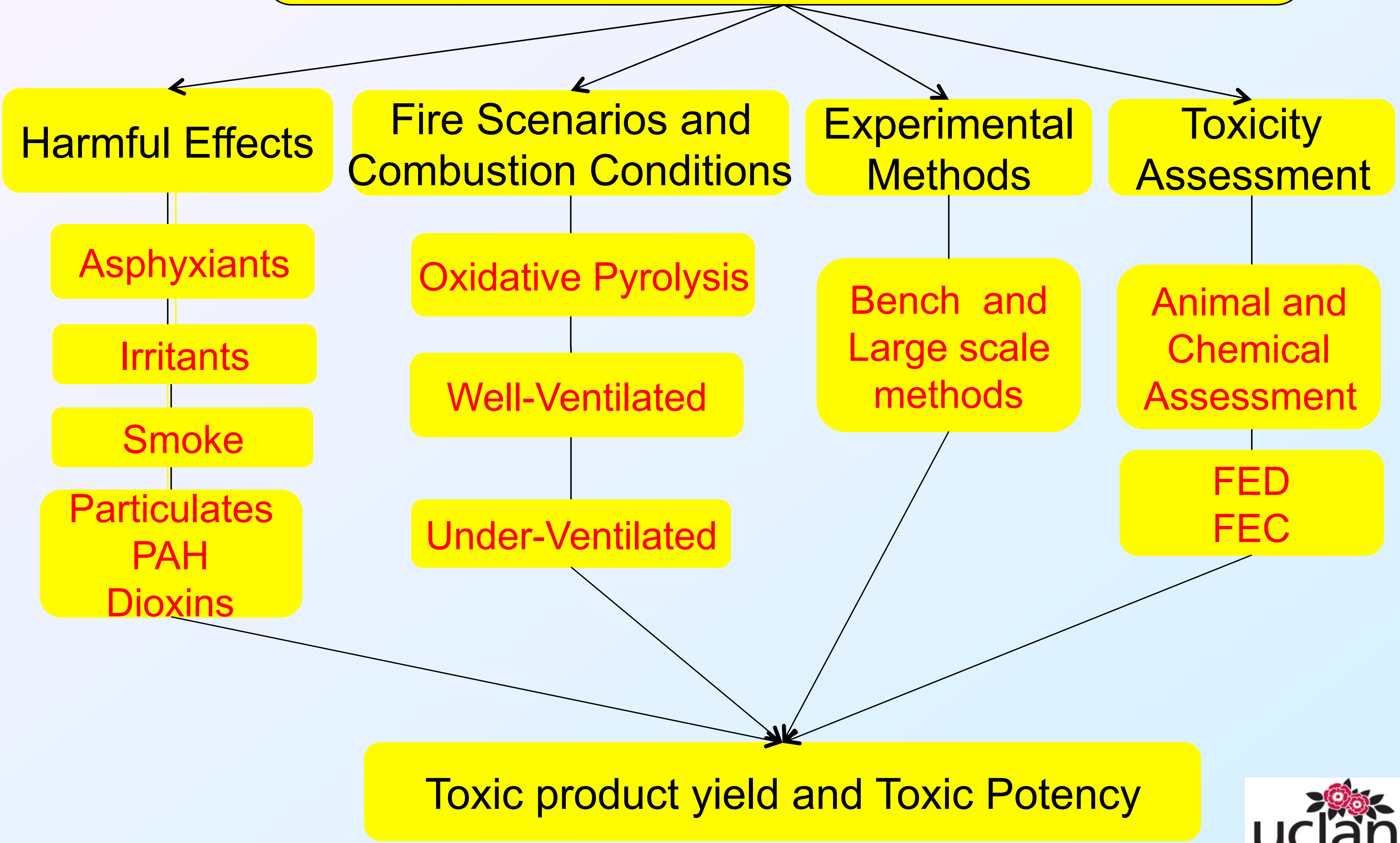
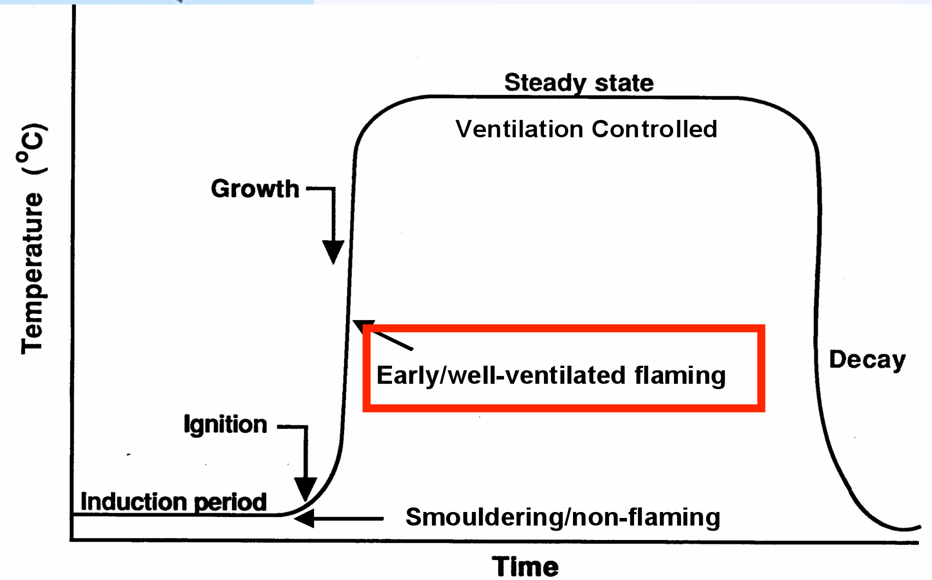
The need for toxicity assessment

- Synthetic polymers increased fire toxicity.
- Flame retardants can also increase fire toxicity.
- Research focus on preventing ignition and fire growth, and PHRR.
- Fire toxicity is more complicated, but not impossible!

FIRE COMBUSTION AND TOXICITY

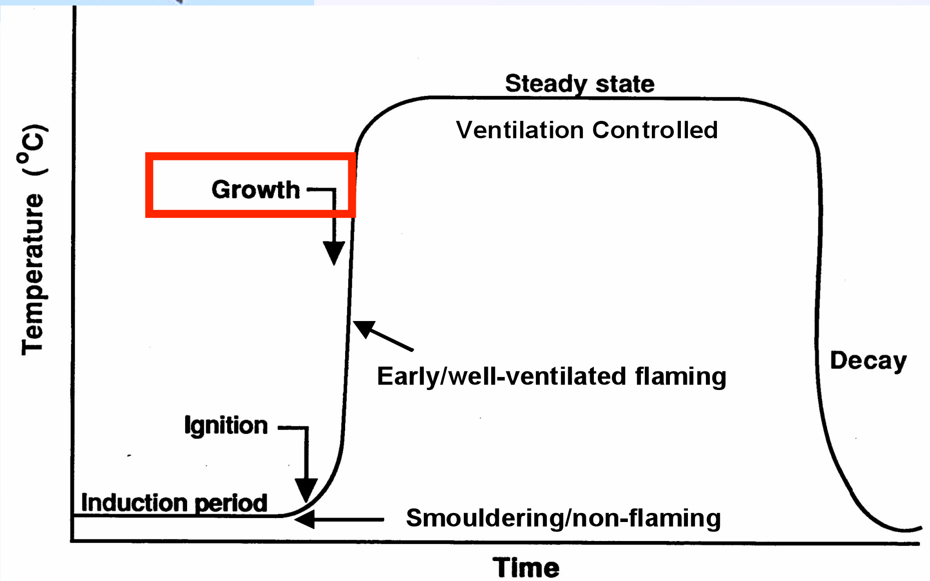


Early/well-ventilated flaming fires



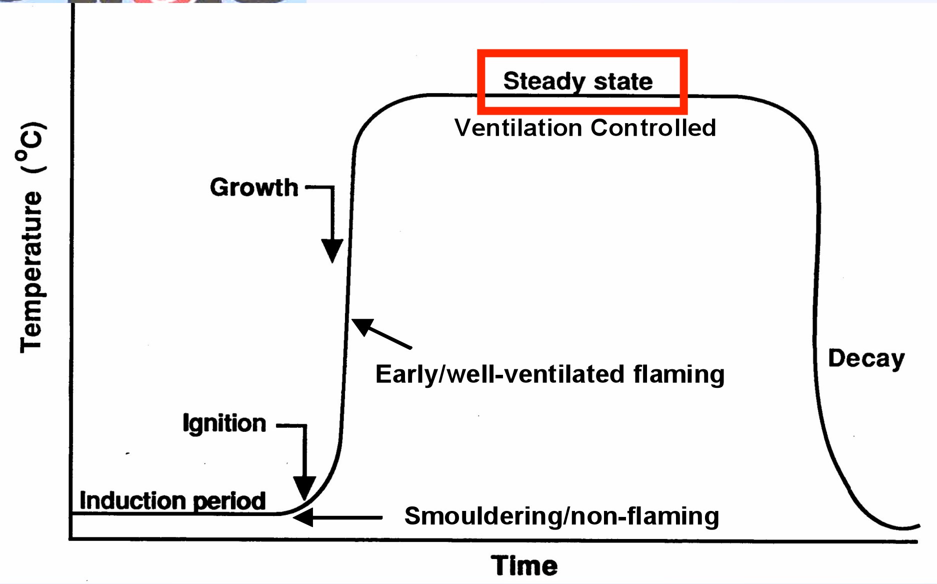
- Flaming fires begin by being well ventilated.
- Products are mainly heat, carbon dioxide (CO_2), water and small amounts of sooty smoke.
- Fire grows rapidly as long as fuel and fresh air are available.
- Smoke forms a layer under the ceiling.
- Main hazard: radiant heat - relatively low toxicity smoke.

Fire Growth



- Smoke fills rapidly down from the ceiling.
- Heat becomes hazardous to occupants,
- Either:
  - Oxygen concentration decreases as air is recirculated, and combustion inefficient.
  - Main Hazard - rapid increase in smoke and toxic gases.
- Or:
  - Fire may continue to grow as a well-ventilated fire.
  - Main hazard is from heat, and from smoke at the upper levels.
  - Danger that the fire will grow large enough for flashover to occur - producing very large amounts of hot, toxic fire effluent.

Early ventilation-controlled (vitiated) flaming fires



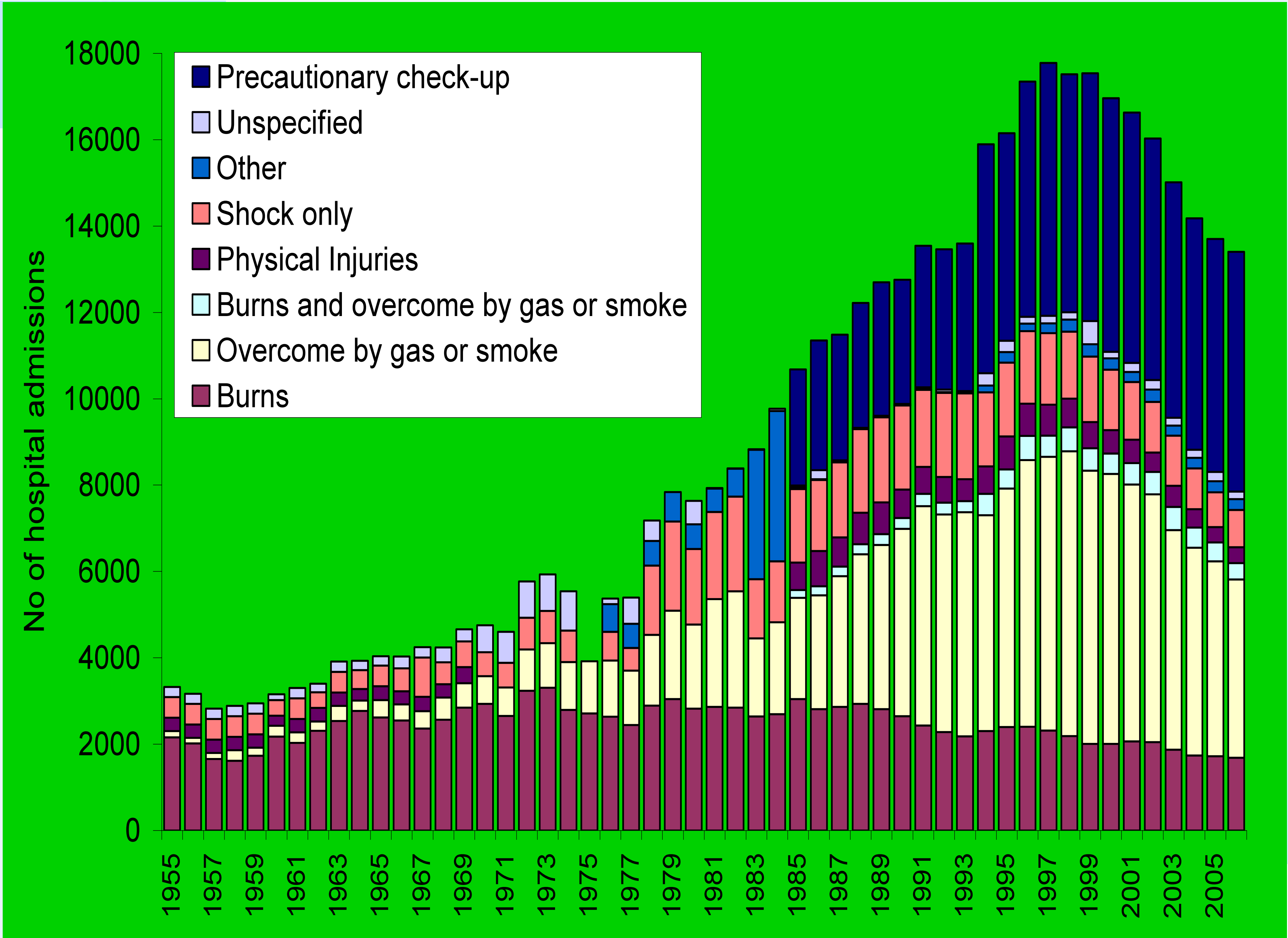
- Combustion occurs
  - between the fuel and the base of the flame,
  - in the lower part of the flame zone,
  - in the hot layer - in an oxygen depleted atmosphere - high yields of toxic products.
- Main hazard is high yields of irritant smoke and asphyxiant gases (the temperatures not particularly high).
- In the UK and Europe, (less open layouts), most fire deaths (55% in 2009 in the UK) result from small fires when the victim is in the room of fire origin.
- In the US only 21% of fire deaths occur in the room of origin of the fire, and 67% occur on another floor.
- UK flashover fires are not the major cause of fire fatalities, in the US it is believed that 80% of fire deaths are post flashover.

Fire Conditions

$$\phi = \frac{\text{Actual fuel / Air ratio}}{\text{Stoichiometric fuel / Air ratio}}$$

Combustion condition	Temperature (°C)	Equivalence ratio	Oxygen from fire %	CO_2/CO ratio
Smouldering	350	not applicable	>21	1-5
Well-ventilated flaming	650 or 700	$\phi < 0.75$	5 to 21	2-20
Under ventilated flaming:				
small vitiated fires	650	$\phi > 1.5$	0 to 12	2-20
post-flashover fires	825	$\phi > 1.5$	0 to 12	2-20



18000
16000
14000
12000
10000
8000
6000
4000
2000
0
No of hospital admissions
Precautionary check-up
Unspecified
Other
Shock only
Physical Injuries
Burns and overcome by gas or smoke
Overcome by gas or smoke
Burns
1955
1957
1959
1961
1963
1965
1967
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1971
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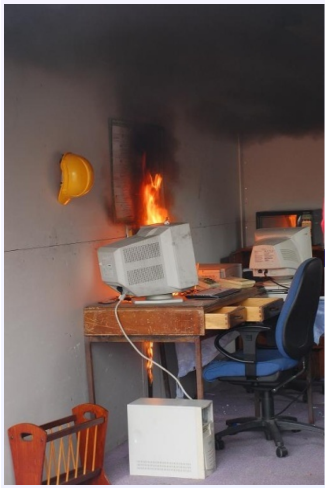
Fire Conditions and Harmful Effects

Fire toxicity involves a set of different physiological effects occurring over different time scales

a few seconds

a few minutes



Impaired vision from smoke obscuration

Impaired vision, pain and breathing difficulties from effects of smoke irritants on eyes and respiratory tract

Asphyxiation from toxic gases leading to confusion and loss consciousness

Pain to exposed skin and respiratory tract followed by burns from exposure to radiant and convected heat leading to collapse

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Sequence of fire hazard

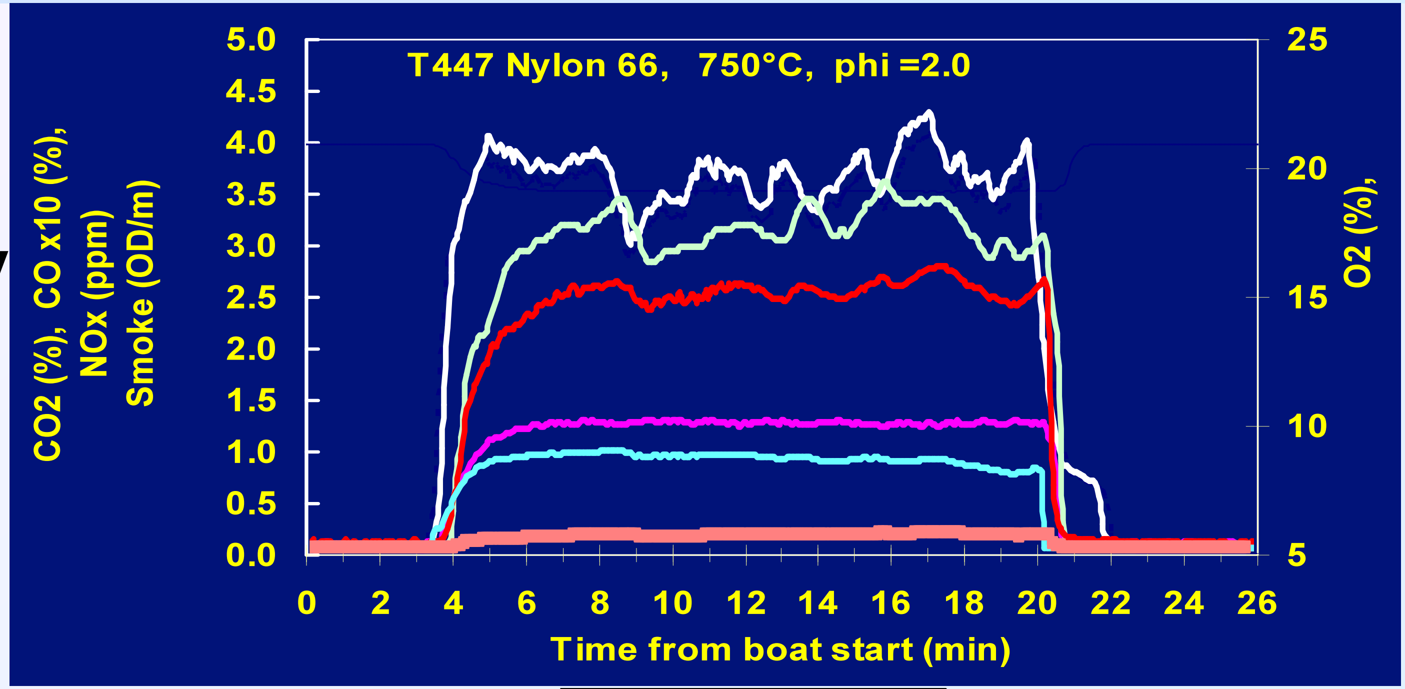
ASPHYXIANTS : CO, HCN, CO_2, Low Oxygen

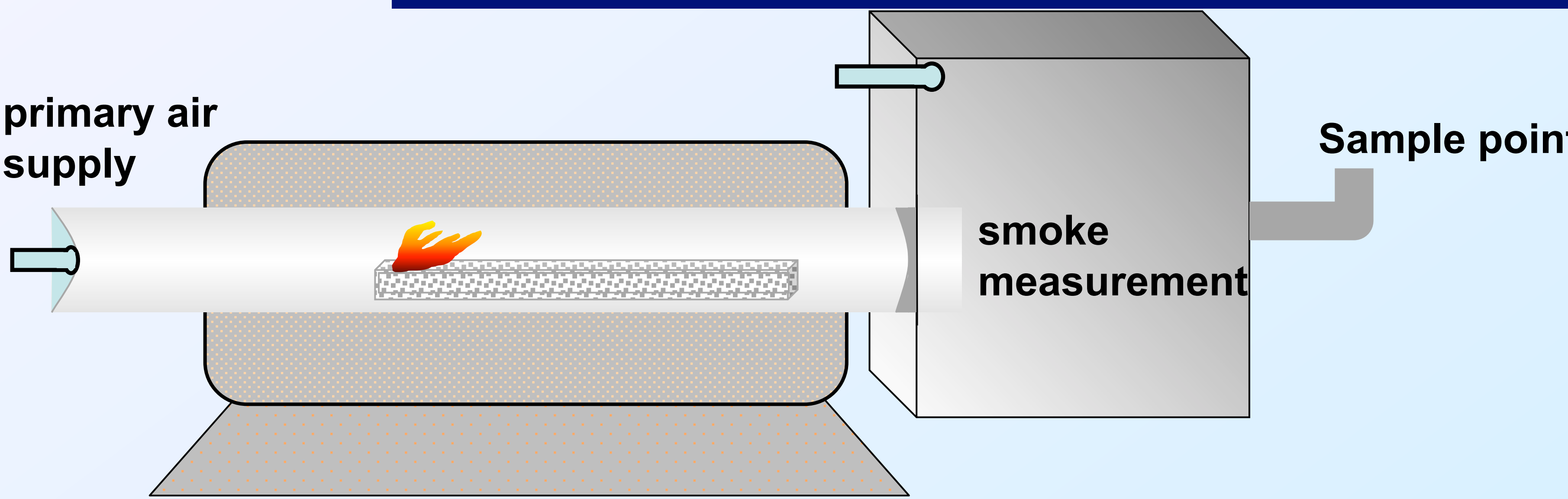
- Cause confusion and loss of consciousness followed by death from asphyxia when a sufficient dose has been inhaled
- For asphyxiants effects depend upon an exposure dose. There is little effect until a threshold dose is inhaled after which confusion occurs rapidly followed by collapse

IRRITANTS : HCl, HBr, HF, NOx, organoirritants, particulates etc.

- Depending upon the concentration cause painful stimulation of the eyes, nose, mouth, throat and lungs with some hypoxia due to breathing difficulties which impedes escape and can be fatal
- Depending upon dose inhaled cause lung inflammation and oedema which may be fatal usually some hours after exposure

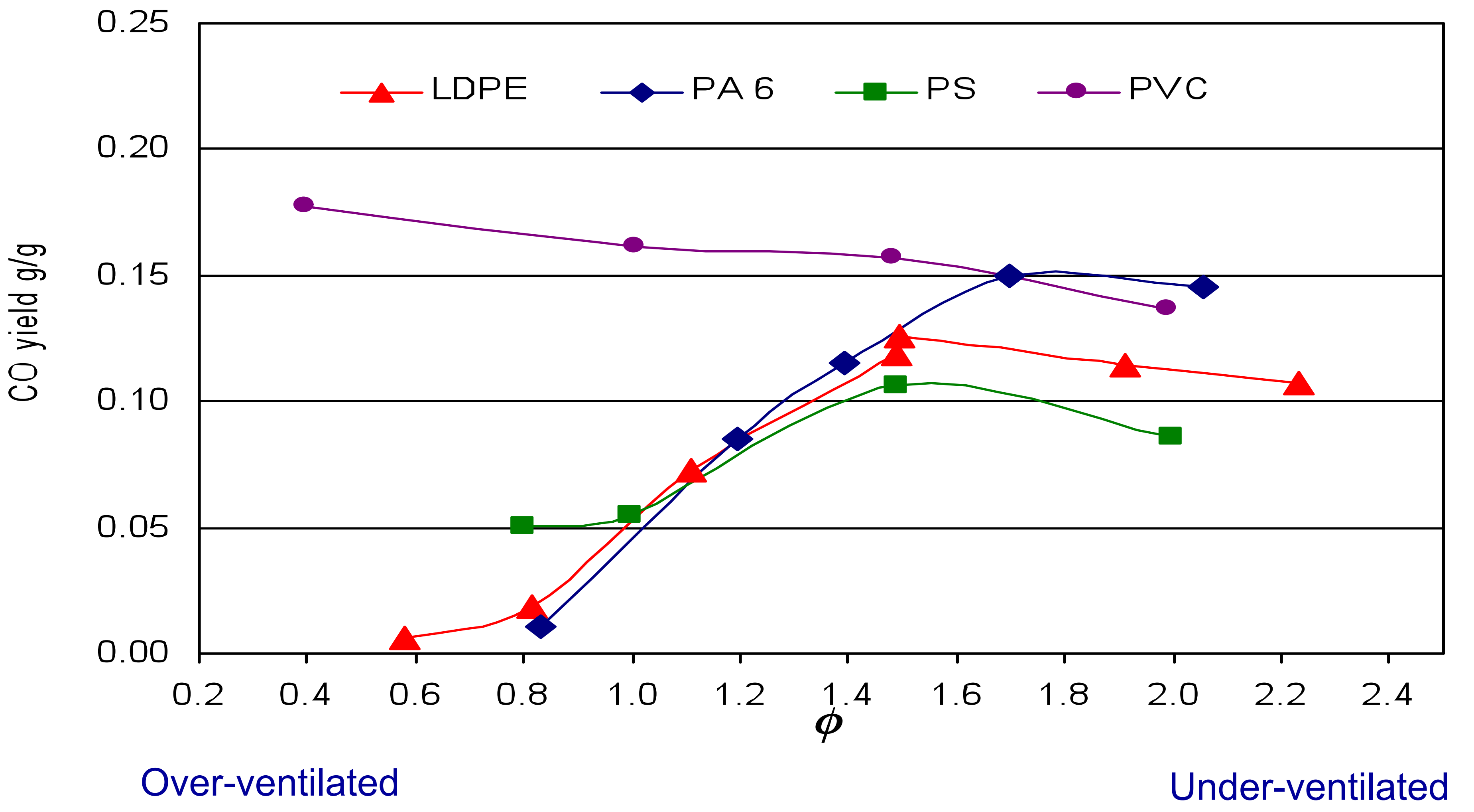
The steady state tube furnace method





A.A. Stec, T.R. Hull, K. Lebek, and, *Characterisation of the Steady State Tube Furnace*, Polymer Degradation and Stability, Vol. 93, pp. 2058–2065, 2008.

CO Yield from Steady State Tube Furnace

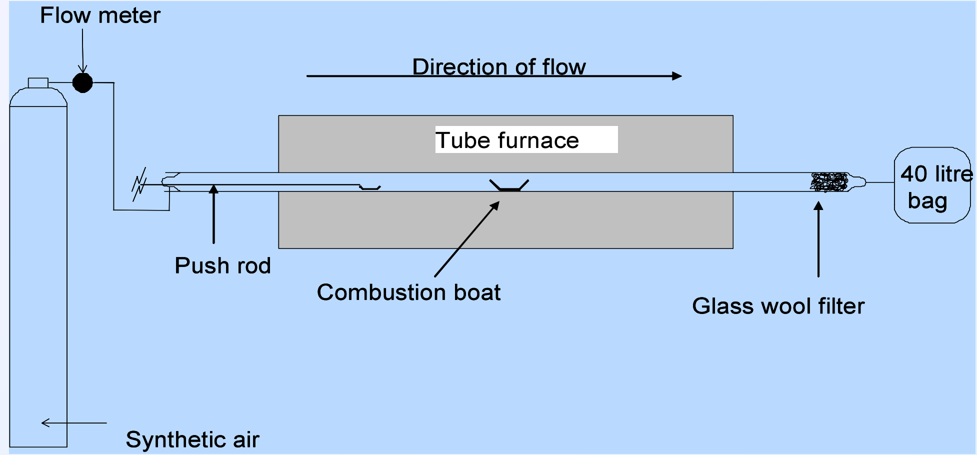


A.A. Stec, T.R. Hull, K. Lebek, J.A. Purser, D.A. Purser The effect of ventilation condition on the toxic product yields from burning polymers, Fire and Materials, Vol. 32, Issue 1, pp.49-60, January/February 2008.

How is Fire Toxicity Measured?

3 general approaches:

Well-ventilated (e.g. Cone calorimeter)
Closed box tests (e.g. NBS Smoke Box, ASTM E1678, NES 713)
Tube furnaces (e.g. NFX 70-100, DIN 53436, IEC 60695-7-50, Fire Propagation Apparatus)



T R Hull and K T Paul, *Bench-Scale Assessment of Combustion Toxicity – A Critical Analysis of Current Protocols* Fire Safety Journal, 42, 340-365 (2007).

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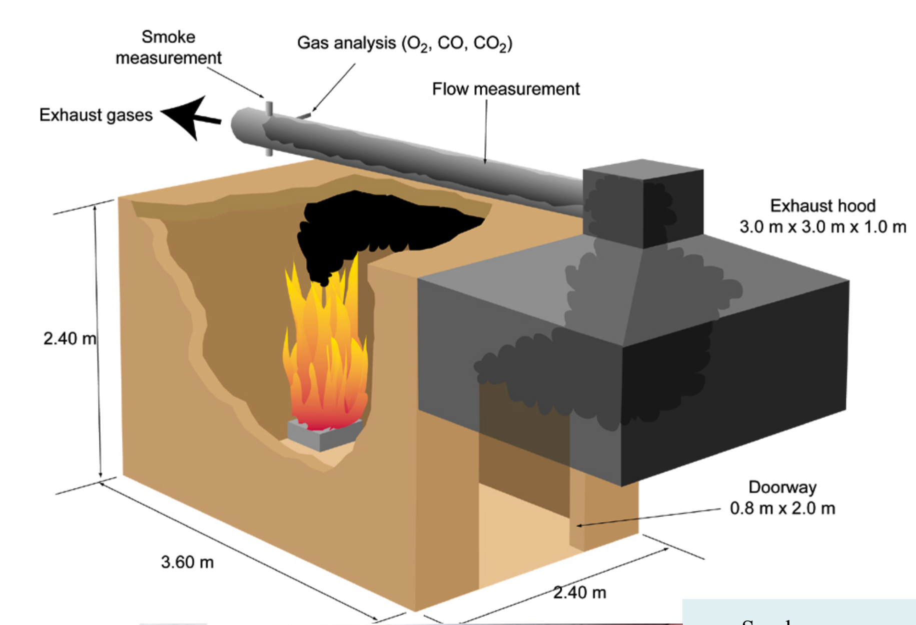
Smoke measurement
Gas analysis (O_2, CO, CO_2)
Flow measurement
Exhaust gases
Exhaust hood
3.0 m x 3.0 m x 1.0 m
2.40 m
Doorway
0.8 m x 2.0 m
3.60 m
2.40 m


Fire Toxicity
Research
Facility
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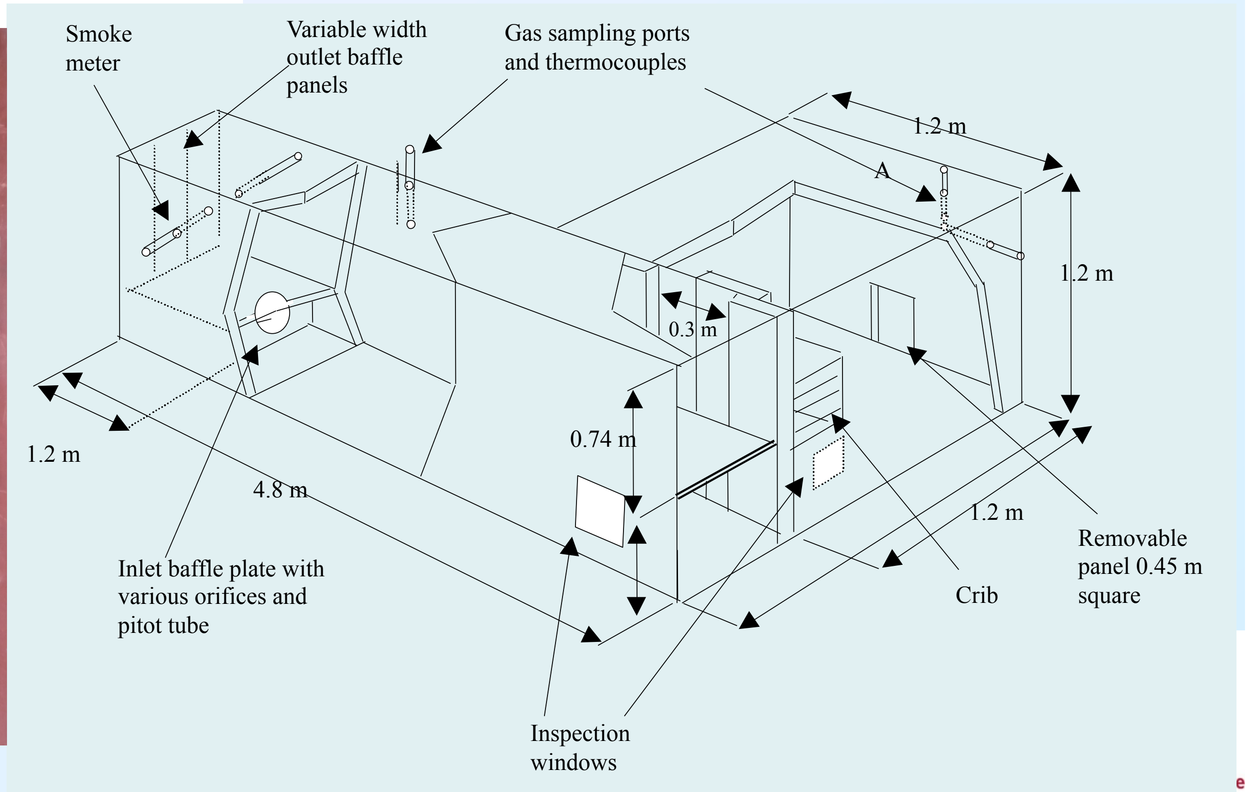
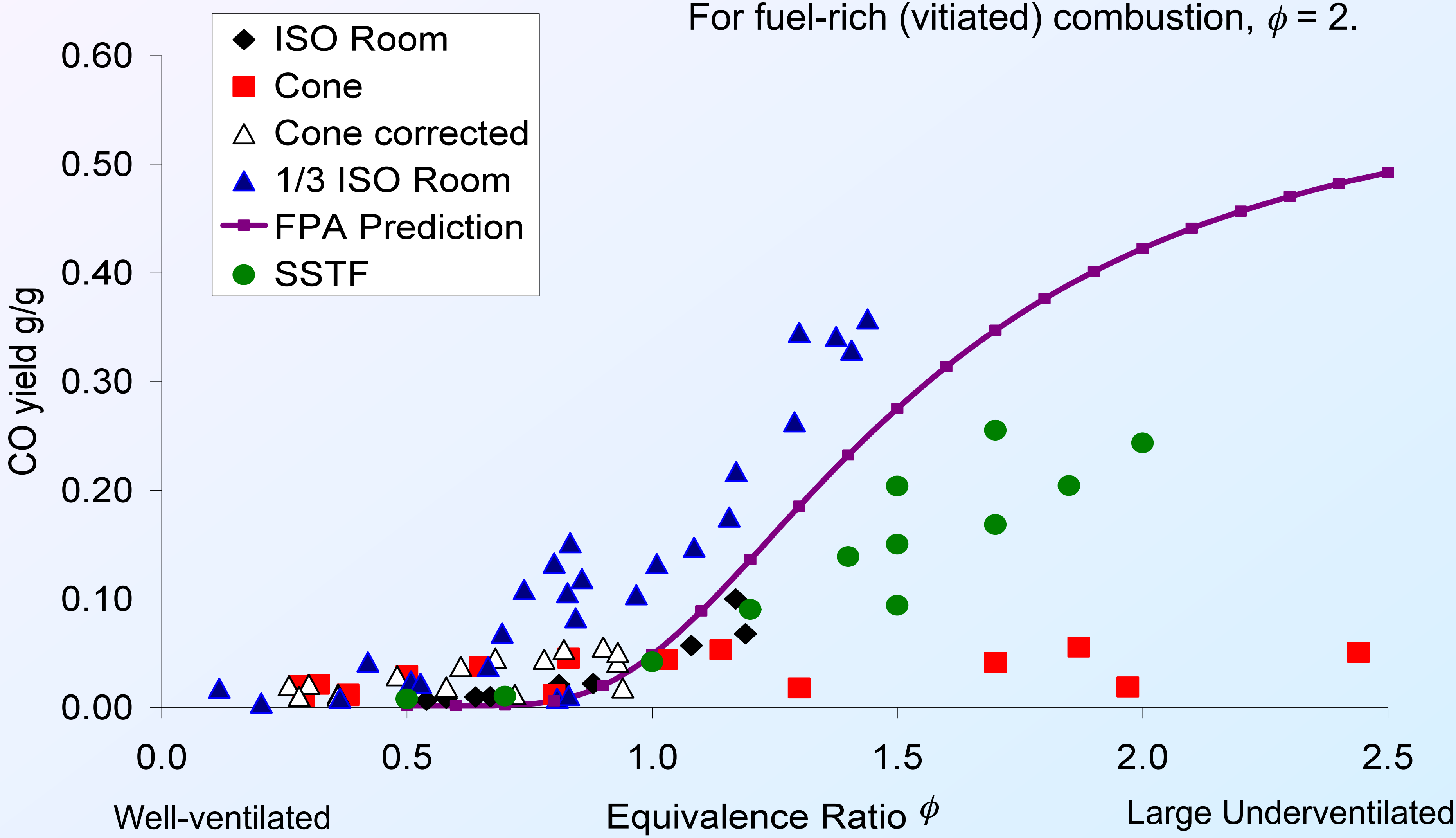

Smoke meter
Variable width outlet baffle panels
Gas sampling ports and thermocouples
1.2 m
A
1.2 m
0.3 m
0.74 m
1.2 m
4.8 m
1.2 m
Removable panel 0.45 m square
Inlet baffle plate with various orifices and pitot tube
Crib
Inspection windows

$$\phi = \frac{\text{Actual Fuel/Air Ratio}}{\text{Stoichiometric Fuel/Air Ratio}}$$

For "stoichiometric" combustion to CO_2 and water, ϕ = 1.
For well-ventilated fires, ϕ = 0.5
For fuel-rich (vitiated) combustion, ϕ = 2.

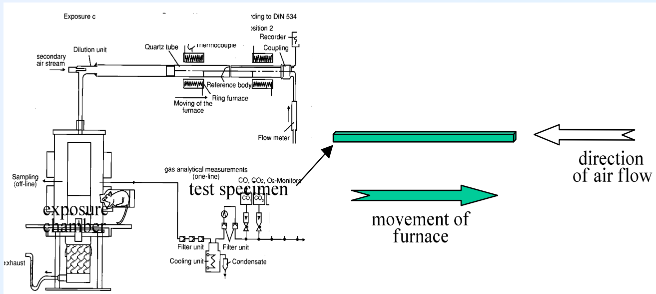


A.A. Stec, T.R. Hull, J.A. Purser, D.A. Purser, *Comparison of Toxic Product Yields from Bench-Scale to ISO Room*, Fire Safety Journal, Mar 2008 (Available online 7 May 2008)

Estimation of fire toxicity

Animals integrate all the smoke components, providing a true assessment of the toxic potency, BUT:

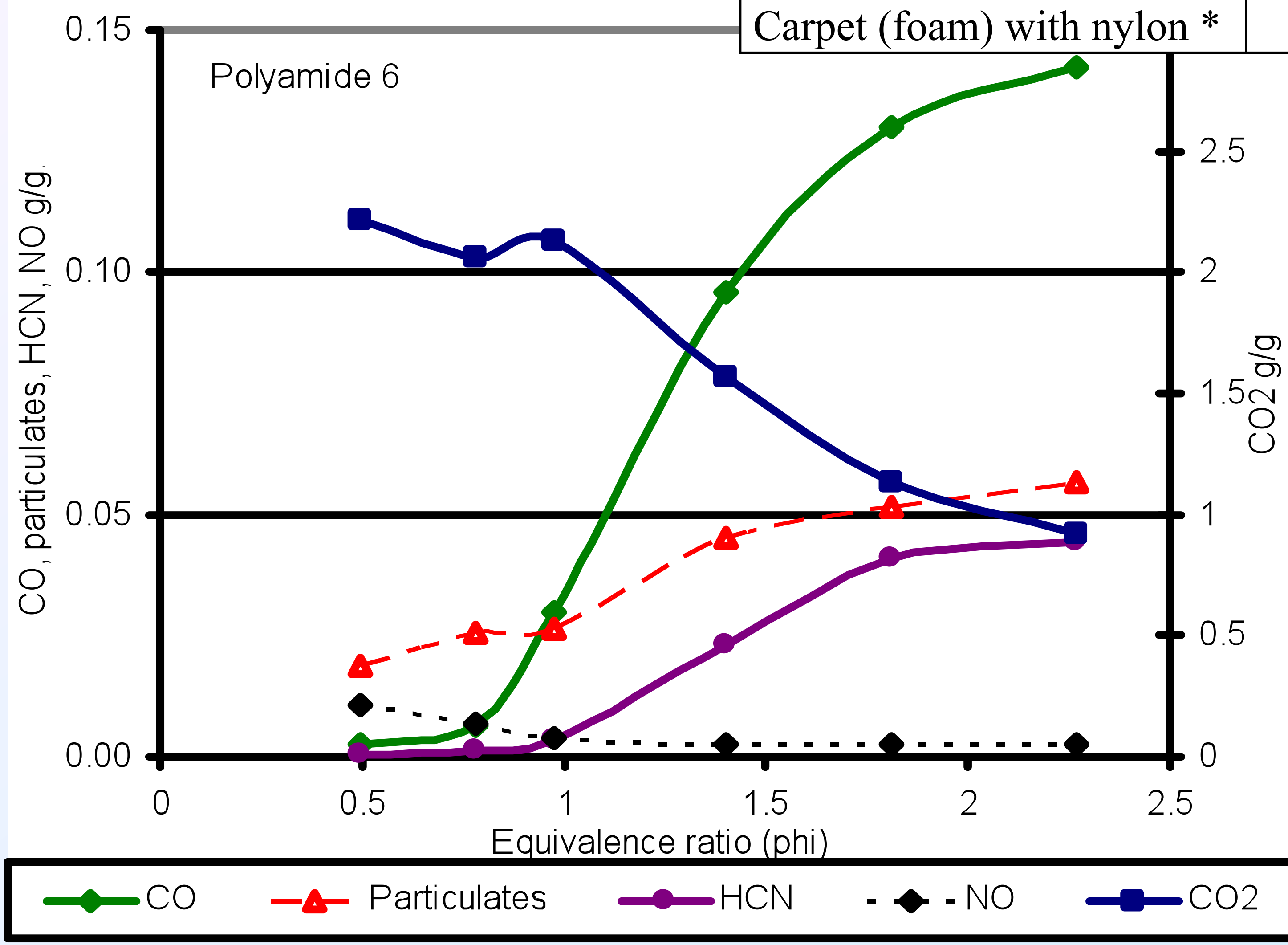
- Animal methods estimate total toxicity
- Few product data have been published
- The only publicly available toxicity data for smoke from burning commercial products is for rodents



- Use of animals for routine testing is not permitted in Europe (Council Directive 86/609 EEC Article 3)
- Chemical methods contribution of each toxicant
- Ultimately, both rely on the same assumption that animal toxicity data can be applied to humans

Fire Toxicity

Material	*Fire Conditions*	
	Oxidative pyrolysis	*Well ventilated*
Plasticised PVC *	22.9	26.2
Carpet (foam) with nylon *	68.0	108



Estimation of fire toxicity

ISO 13344

$$\mathrm{FED} = \frac{m[\mathrm{CO}]}{[\mathrm{CO_2}]-b} + \frac{21-[\mathrm{O_2}]}{21-\mathrm{LC}_{50,\mathrm{O_2}}} + \frac{[\mathrm{HCN}]}{\mathrm{LC}_{50,\mathrm{HCN}}} + \frac{[\mathrm{HCl}]}{\mathrm{LC}_{50,\mathrm{HCl}}} + \frac{[\mathrm{HBr}]}{\mathrm{LC}_{50,\mathrm{HBr}}} + \frac{[\mathrm{SO_2}]}{\mathrm{LC}_{50,\mathrm{SO_2}}} \ldots.$$

All the values are in ppm except O_2.

The values of *m* and *b* depend on the concentration of CO_2.

If $[CO_2] < 5$ %, $m = -18$ and $b = 122\,000$.

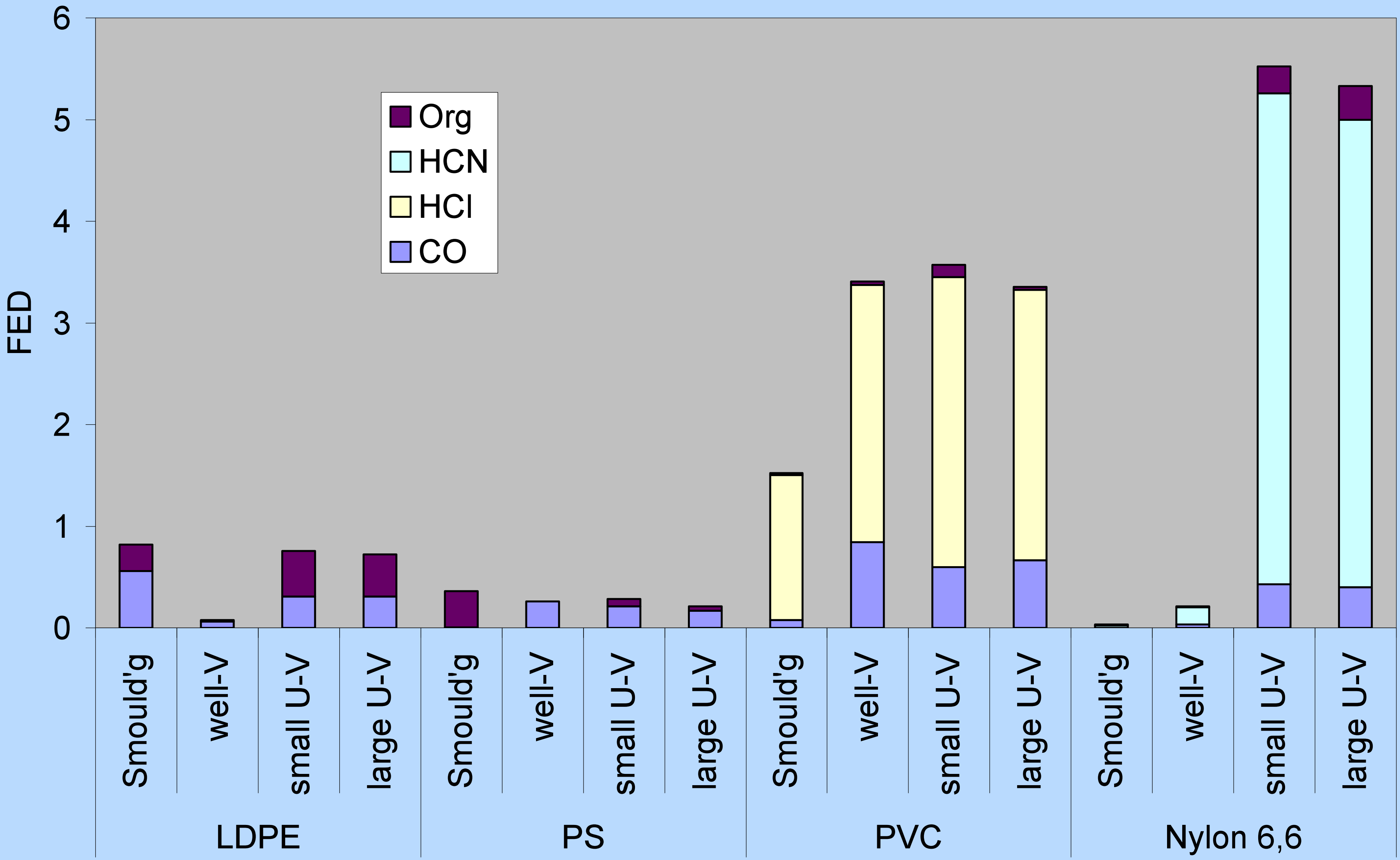
If [CO2] > 5 %, $m = 23$ and $b = -38\,600$.

ISO 13571

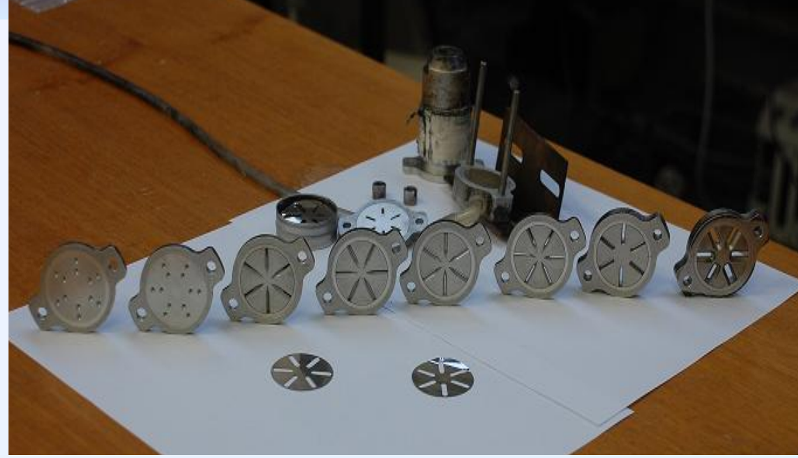
$$\mathrm{FED} = \sum_{t_1}^{t_2} \frac{[\mathrm{CO}]}{35000}\Delta t + \sum_{t_1}^{t_2} \frac{\exp([\mathrm{HCN}]/43)}{220}\Delta t$$

$$\mathrm{FEC} = \frac{[\mathrm{HCl}]}{\mathrm{IC}_{50,\mathrm{HCl}}} + \frac{[\mathrm{HBr}]}{\mathrm{IC}_{50,\mathrm{HBr}}} + \frac{[\mathrm{HF}]}{\mathrm{IC}_{50,\mathrm{HF}}} + \frac{[\mathrm{SO_2}]}{\mathrm{IC}_{50,\mathrm{SO_2}}} + \frac{[\mathrm{NO_2}]}{\mathrm{IC}_{50,\mathrm{NO_2}}} + \frac{[\mathrm{acrolein}]}{\mathrm{IC}_{50,\mathrm{acrolein}}} + \frac{[\mathrm{fomaldehyde}]}{\mathrm{IC}_{50,\mathrm{fomaldehyde}}} + \sum \frac{[\mathrm{irritant}]}{\mathrm{IC}_{50,\mathrm{irritant}}}$$

How toxicity changes with fire condition for different polymers



Particulates



Smoke particles: small, less than one micron in diameter; behave like a gas

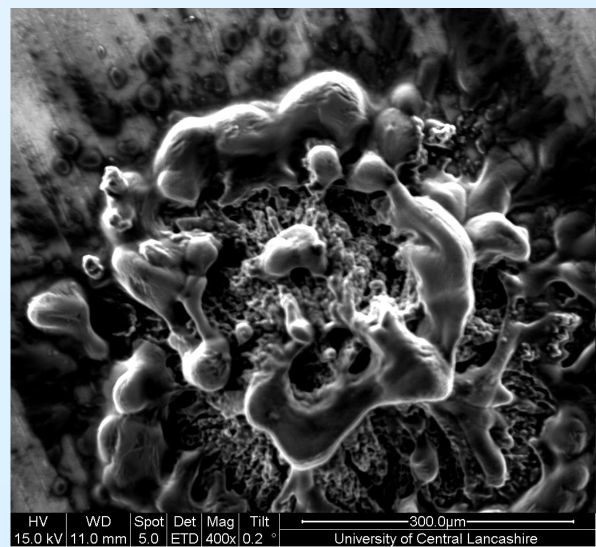
Penetrate indoors and deep into the lung

Have high surface area: adsorb other combustion products, catalytic surface

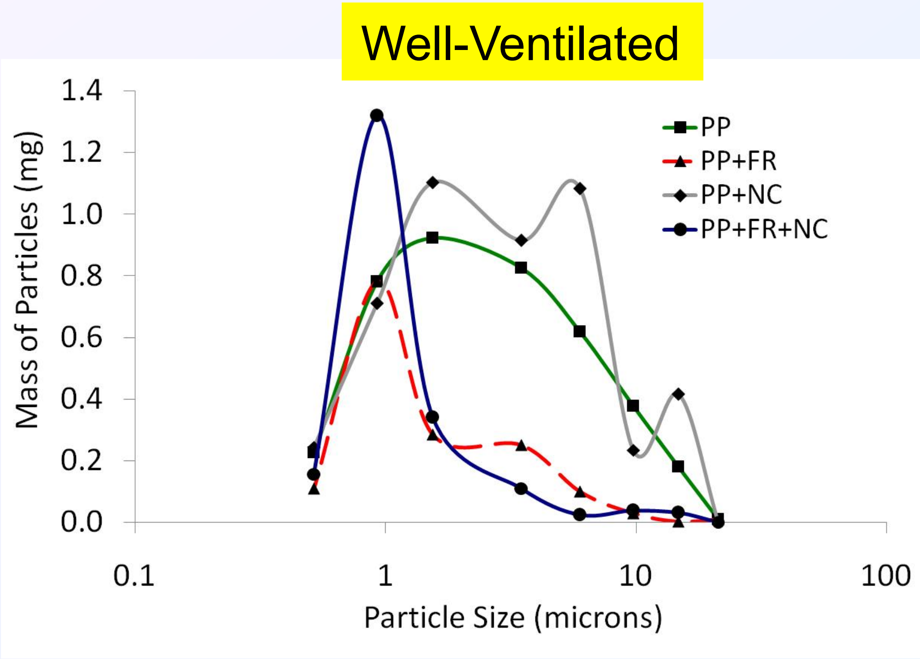
Soot is the major source of radiation from flames, resulting in flame spread and fire growth

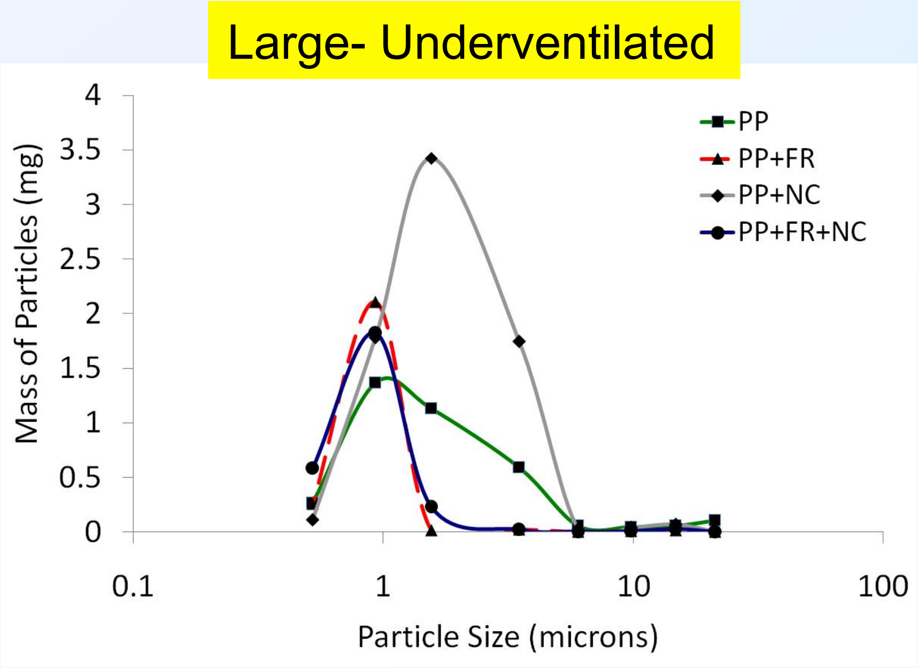
Solid and liquid aerosols are characterized by:

- Concentration,
- Particles size distribution,
- Chemical nature (depending on aerosol size),
- Morphology (depending on aerosol chemical nature).

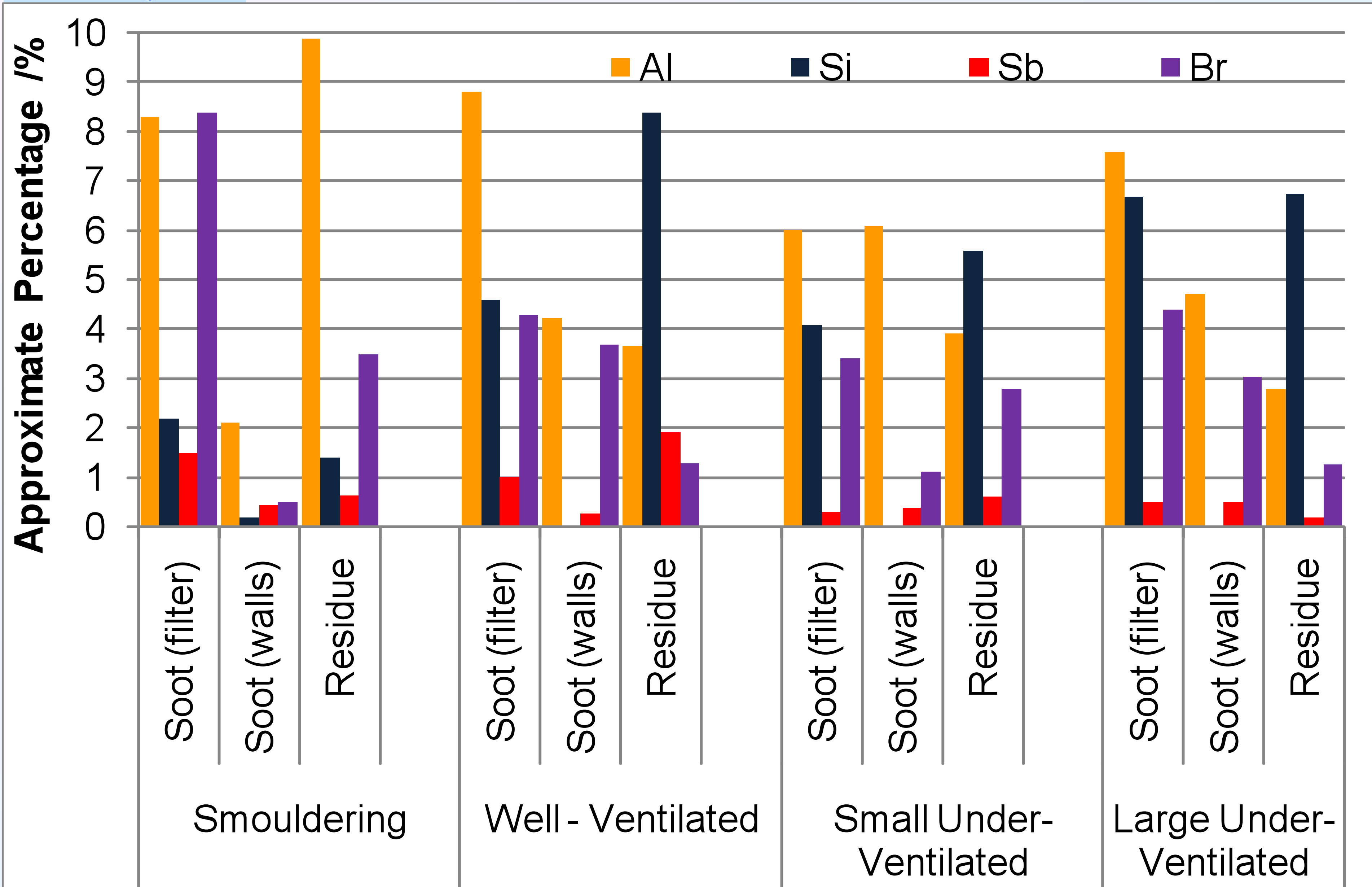


Particulate Size Distributions





Soot and Residue Analysis by SEM-EDAX



Conclusions

- Fire toxicity is essential component of fire hazard analysis and is dependent on both material and fire conditions
- Toxic product yields vary considerably with combustion conditions, and underventilated fires are the most toxic.
- Toxic hazards in fires depend upon exposure to smoke, irritants (concentration related), asphyxiant gases (dose related) and heat
- CO is a good indicator of incomplete combustion however, it is not always the major toxicant. The asphyxiants, CO and HCN are much more prevalent in developed flaming
- Irritants (e.g. organics and smoke particles) are also more prevalent in developed flaming, while HCl is independent of fire condition and NOx is favoured by well-ventilated conditions.
- Bench-scale methods rarely distinguish particular fire conditions

FIRE TOXICITY
THE NEW GOAL IN FIRE SAFETY

Fire effluent toxicity creates a multidisciplinary area and it requires understanding of :

- relationships between decomposition conditions and product yields
- the behaviour of the aerosol particulates;
- the response of living organisms to the components present;
- the chemical quantification of those fire effluents;
- the behaviour of fire on different scales;
- prediction of toxic product yields for application to FSE calculations:
  - Numerical simulation of fires and their hazards,
  - Modelling fire growth and toxic gas formation,
  - Computer simulation of fire hazards and evacuation

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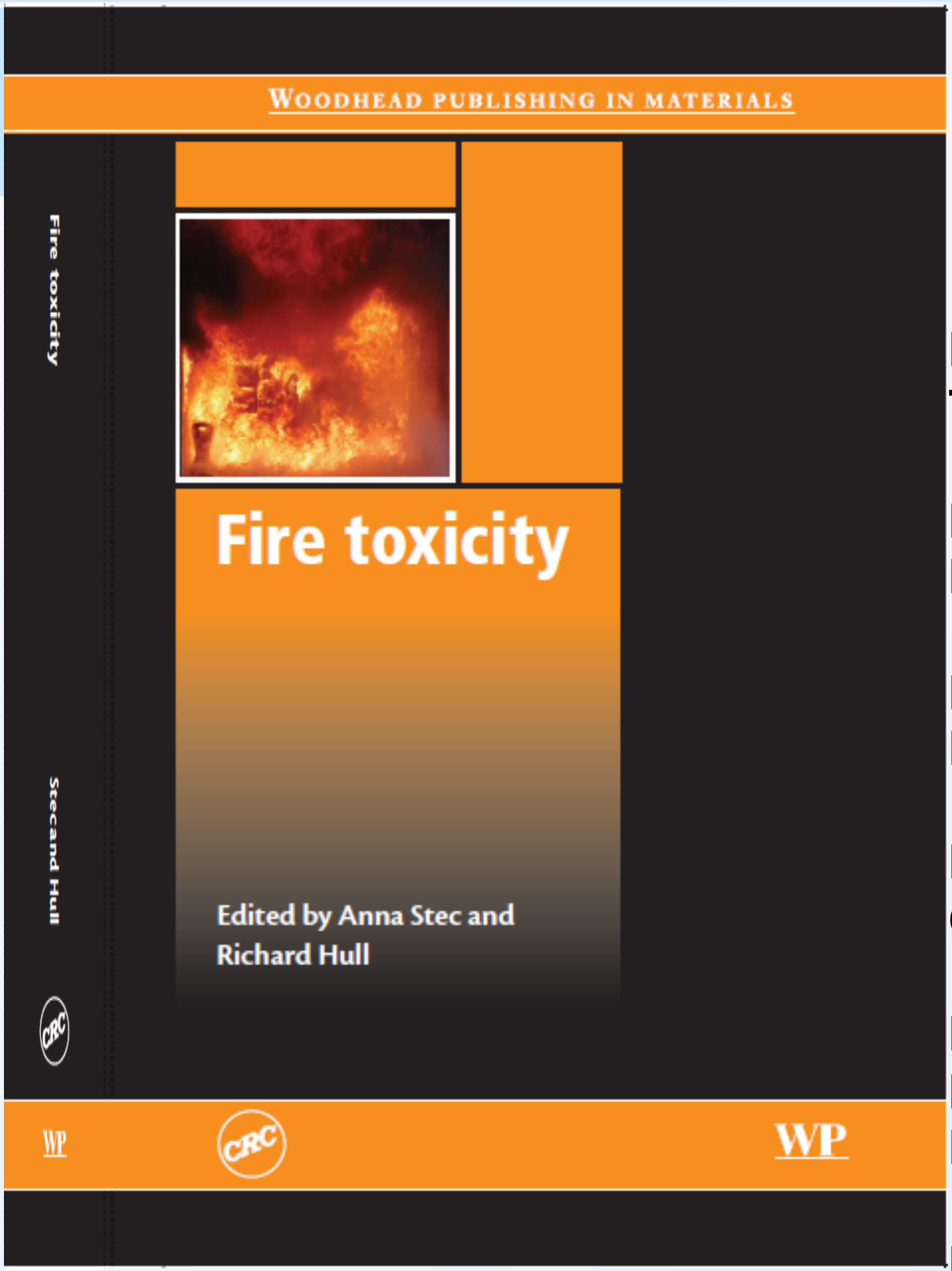

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PART 1 INTRODUCTION TO FIRE TOXICITY,

PART 2 HARMFUL EFFECTS OF FIRE EFFLUENTS

PART 3 BIOLOGICAL ASSESSMENT OF FIRE TOXICITY

PART 4 TOXICITY ASSESSMENT USING CHEMICAL ANALYSIS

PART 5 NATIONAL AND INTERNATIONAL FIRE SAFETY REGULATIONS

PART 6 NUMERICAL SIMULATION OF FIRES AND THEIR HAZARDS

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Thank you for your attention !

ANY QUESTIONS???