# Fire dynamics in a room and in a multi-room compartment

The key role of ventilation factor

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Research interests:

- fire dynamics
- building fires
- fire safety engineering

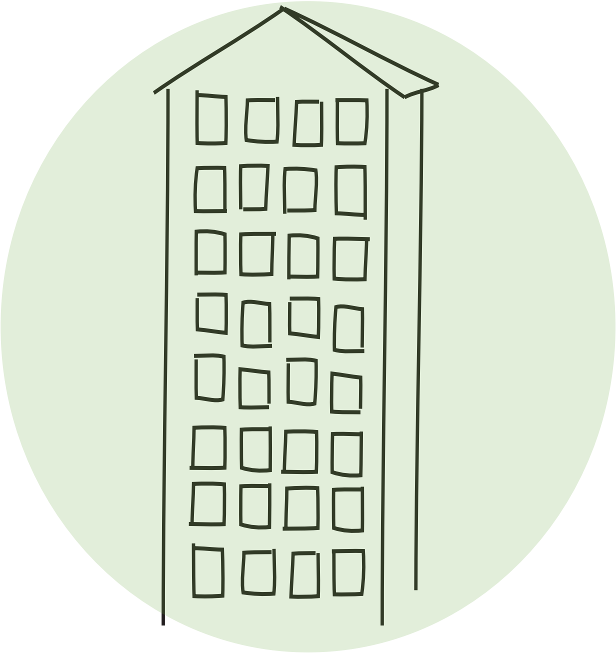
# Agenda

- Fires in buildings
- The compartment fire
- The design fire
- Gas temperatures

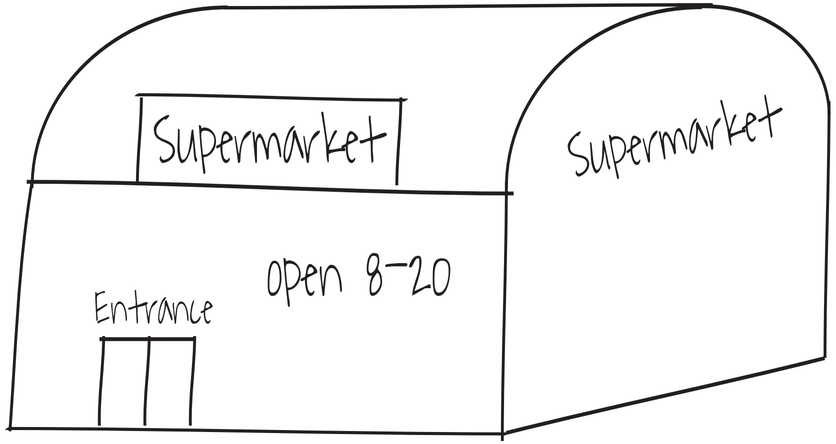
# Fires in enclosures

# Fires in enclosures

Compartment fires

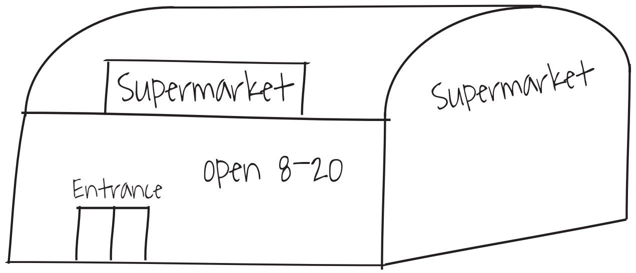


Fires in large enclosures



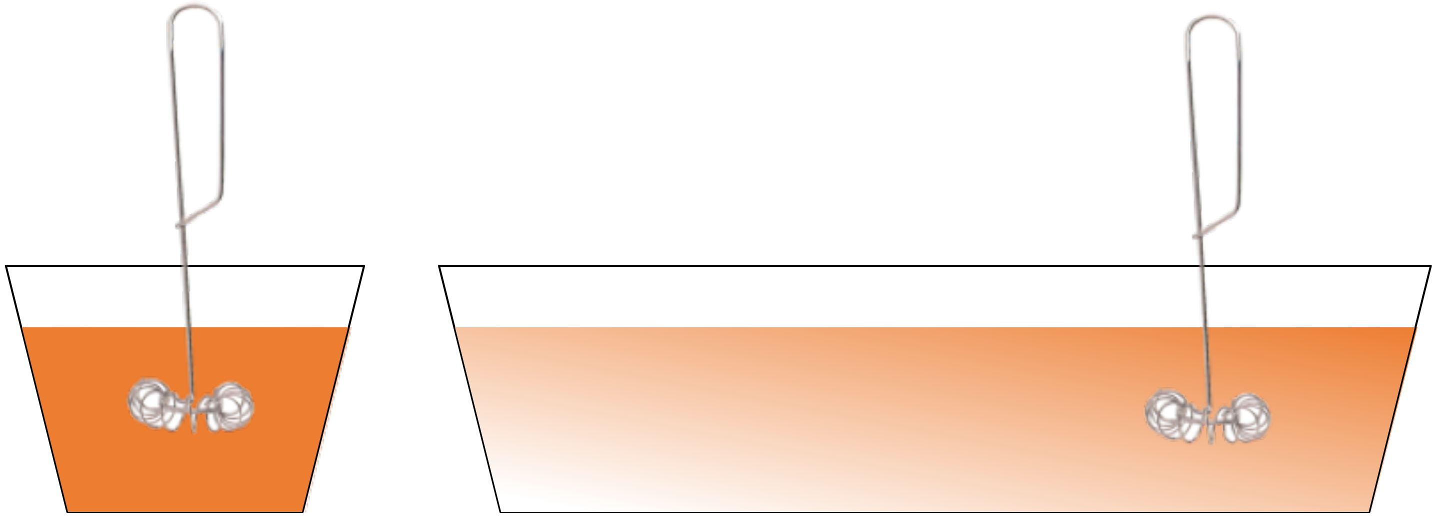
# Compartment fire vs. fire in large enclosure

- Homogenous gas mixture
- Flashover
- Under ventilated fire
- Fast fire development and pressure build up
- Perspective fire safety design




- Differences in temperature and concentration
- Local flashover, influence of layout
- Openings, leakage
- Slow fire growth
- Performance based design

# Analogy: baking a cake ...



Small cake /
Compartment fire

Big cake /
Fire in large enclosure

# The compartment fire

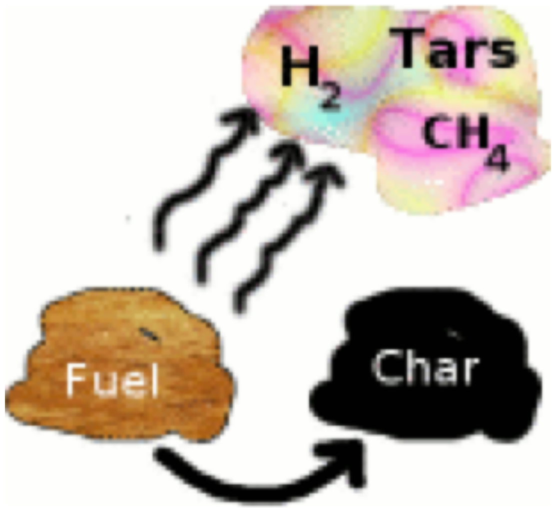
# Combustion

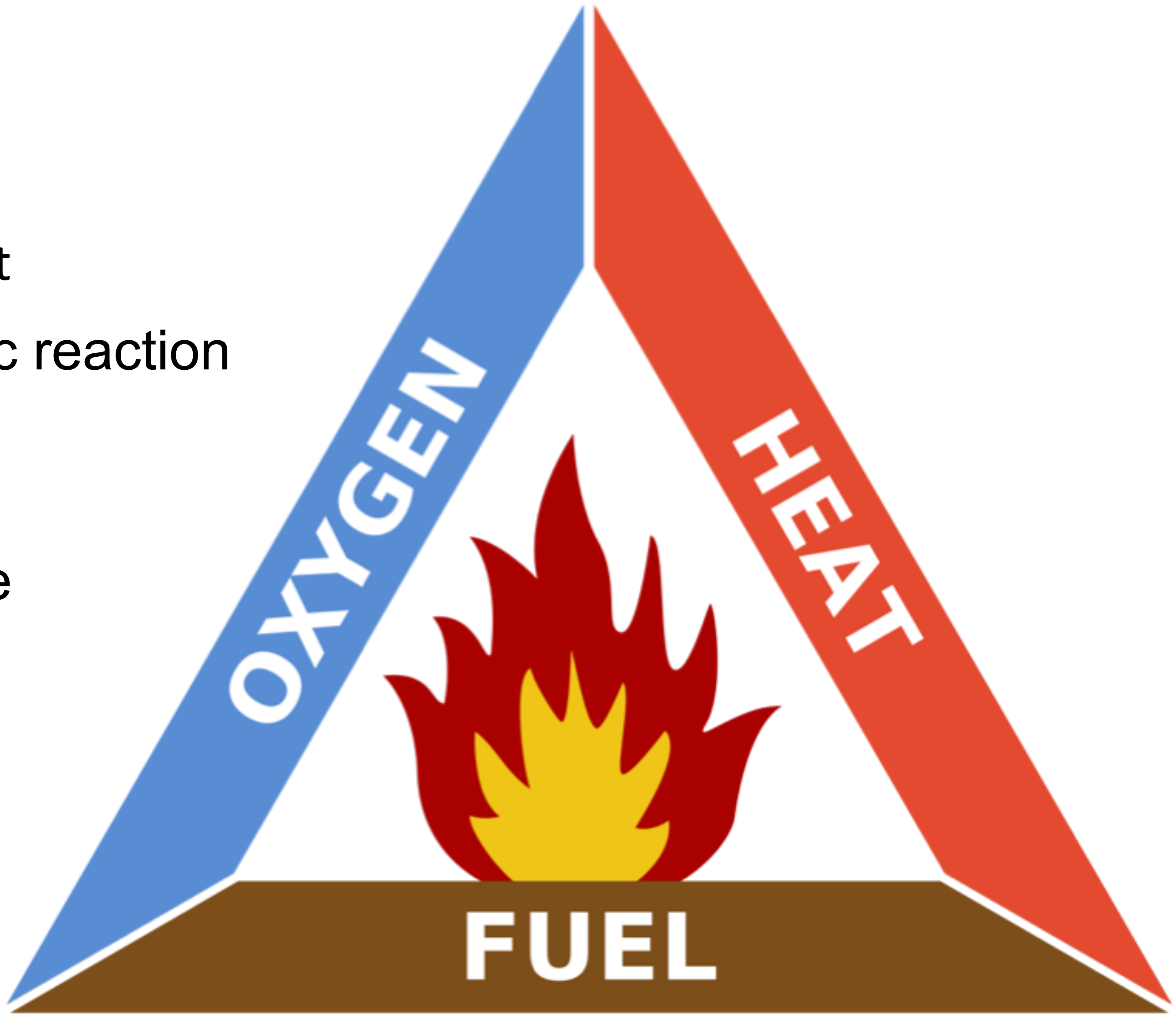
fuel + oxygen → water + $CO_2$ + heat

exothermic reaction

Fuels are in:

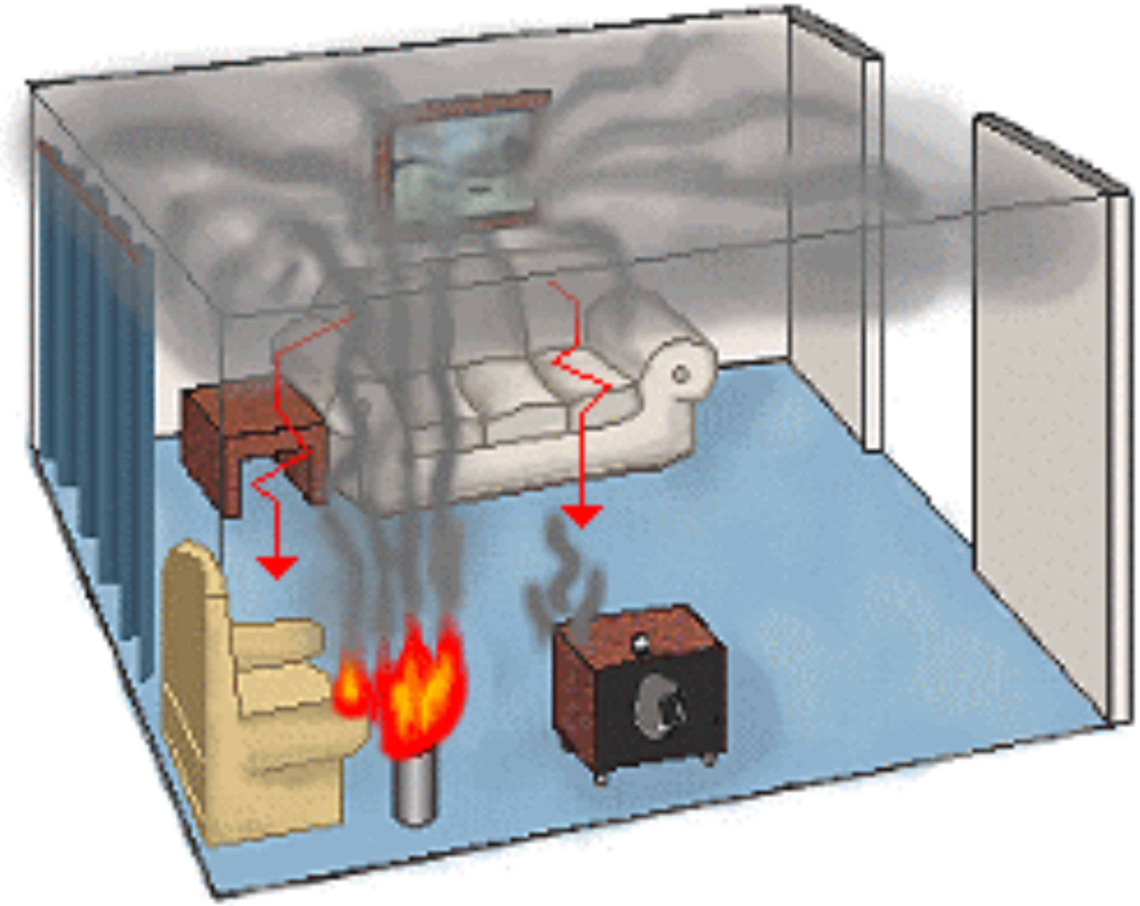
- Solid, liquid or gaseous phase



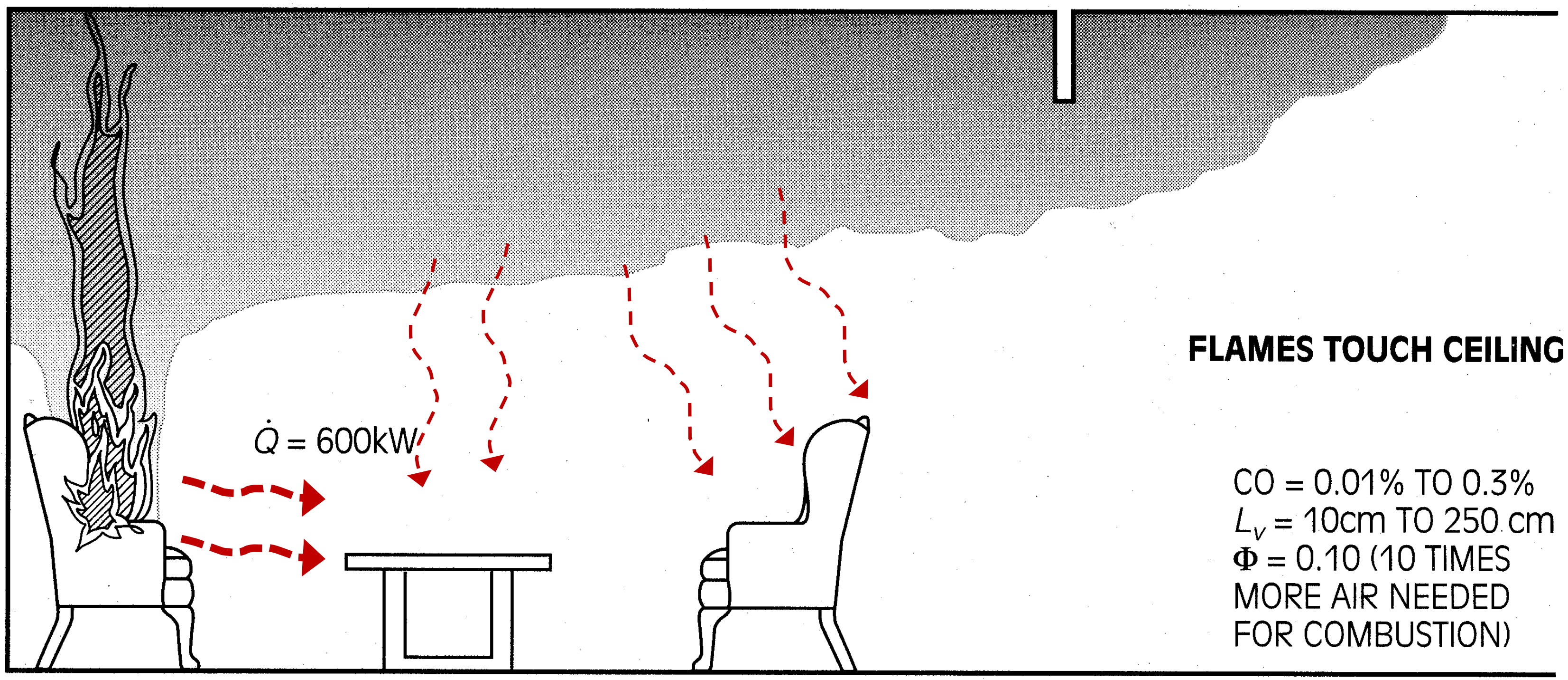
# Factors influencing fire development in a compartment

- Ignition source
- Fuel
- Geometry
- Openings
- Bounding surface



# Ignition

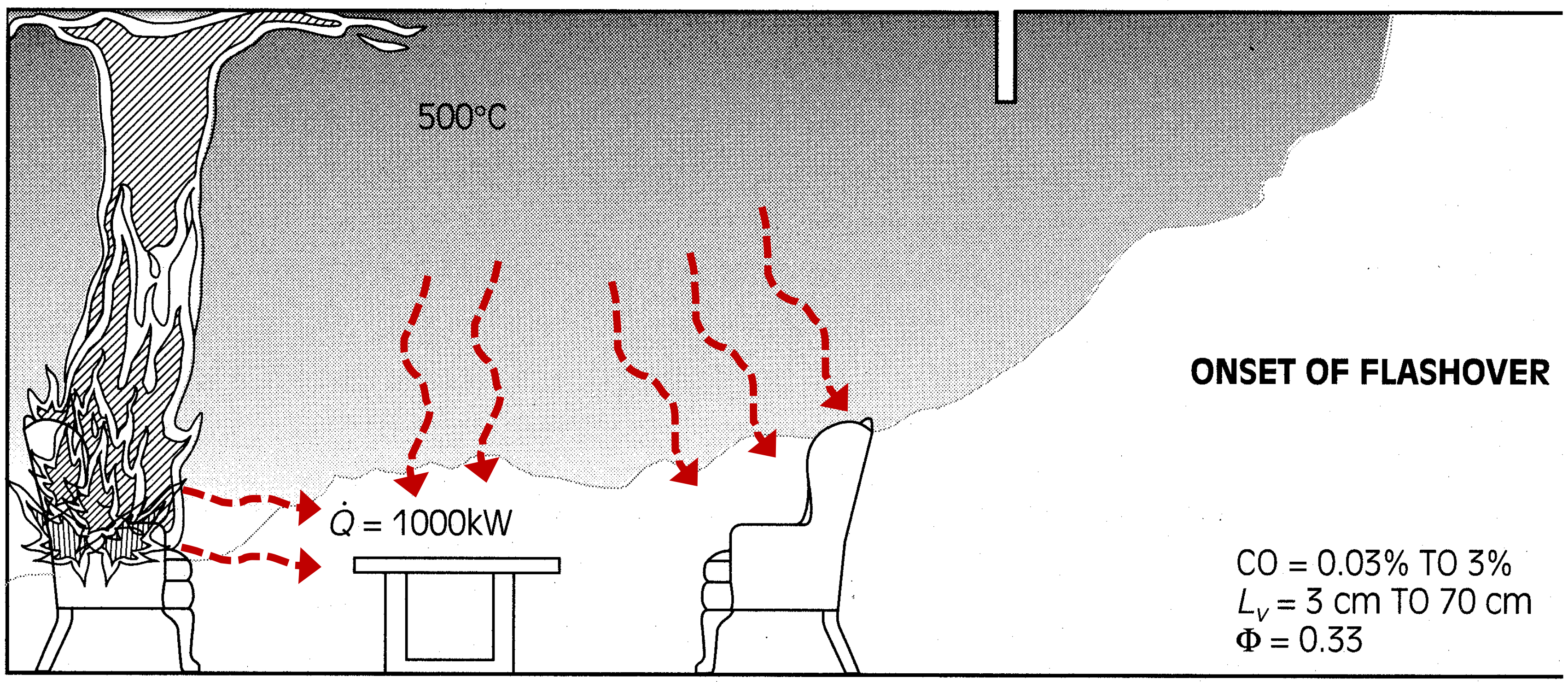
# Growth phase




Pre-flashover fire
Well ventilated and fuel controlled fire

# Fire growth - Spread to additional fuel

# Fire growth - Spread to additional fuel




Pre-flashover fire

Well-ventilated and fuel-controlled fire

# Flashover

# Definition of flashover

Formal definition from ISO:

“transition to a state of total surface involvement in a fire of combustible materials within an enclosure”

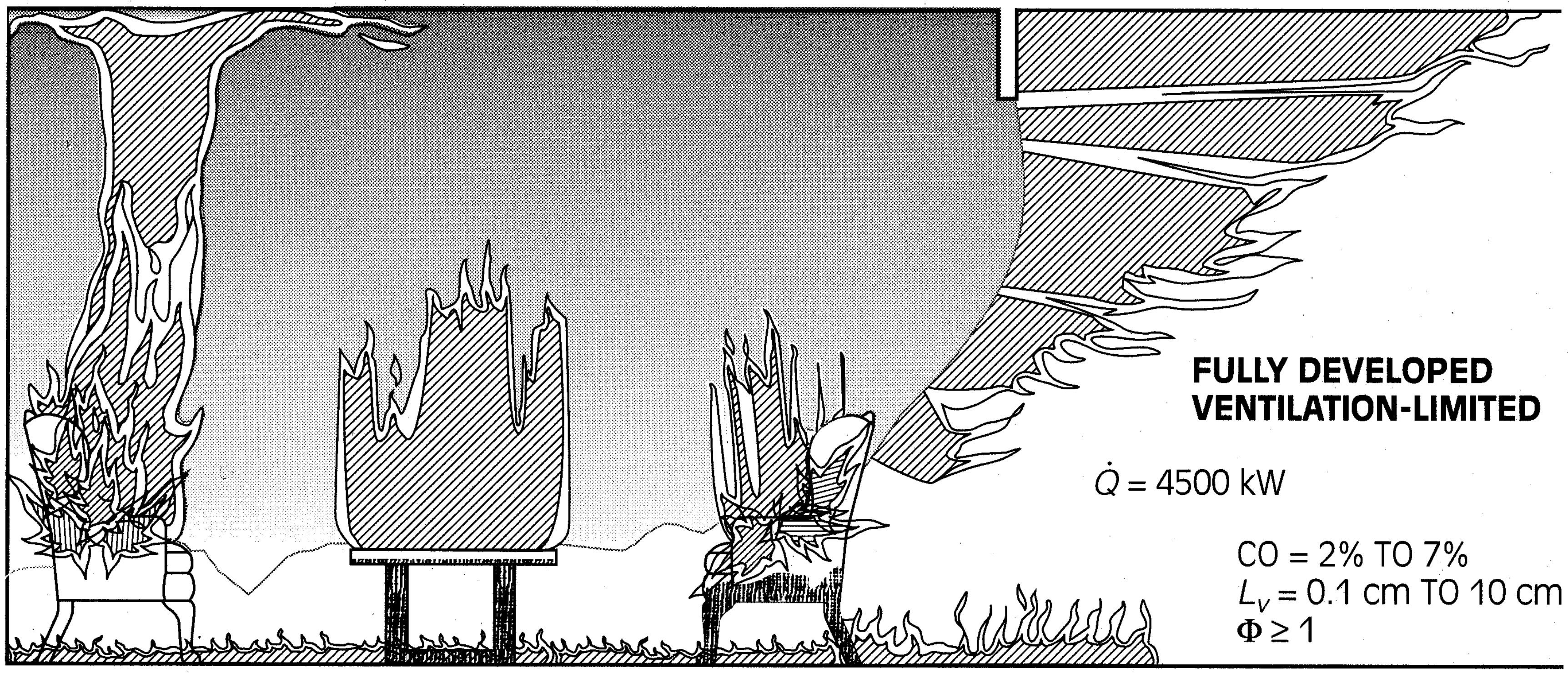
Indicators:

- 20 $kW/m^2$ heat flux to floor
  - Sufficient to ignite common combustibles
- Smoke layer temperature of 500-600$^oC$

# More indicators of flashover

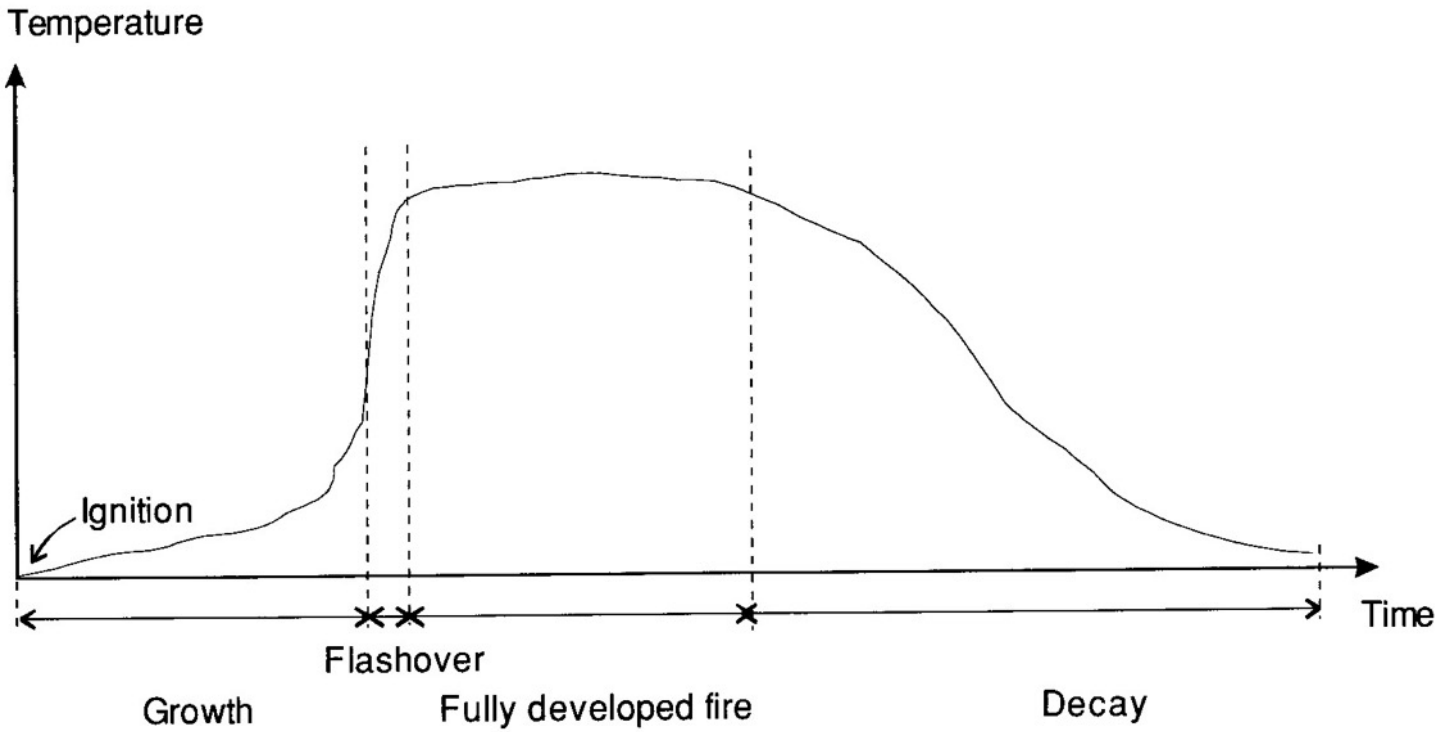
- Rapid flame spread through unburned gases at ceiling
- Small number of items burning to most fuels in compartment burning
- Transition from fuel controlled burning to ventilation controlled
- Flames extending outside compartment openings

# Fully developed fire

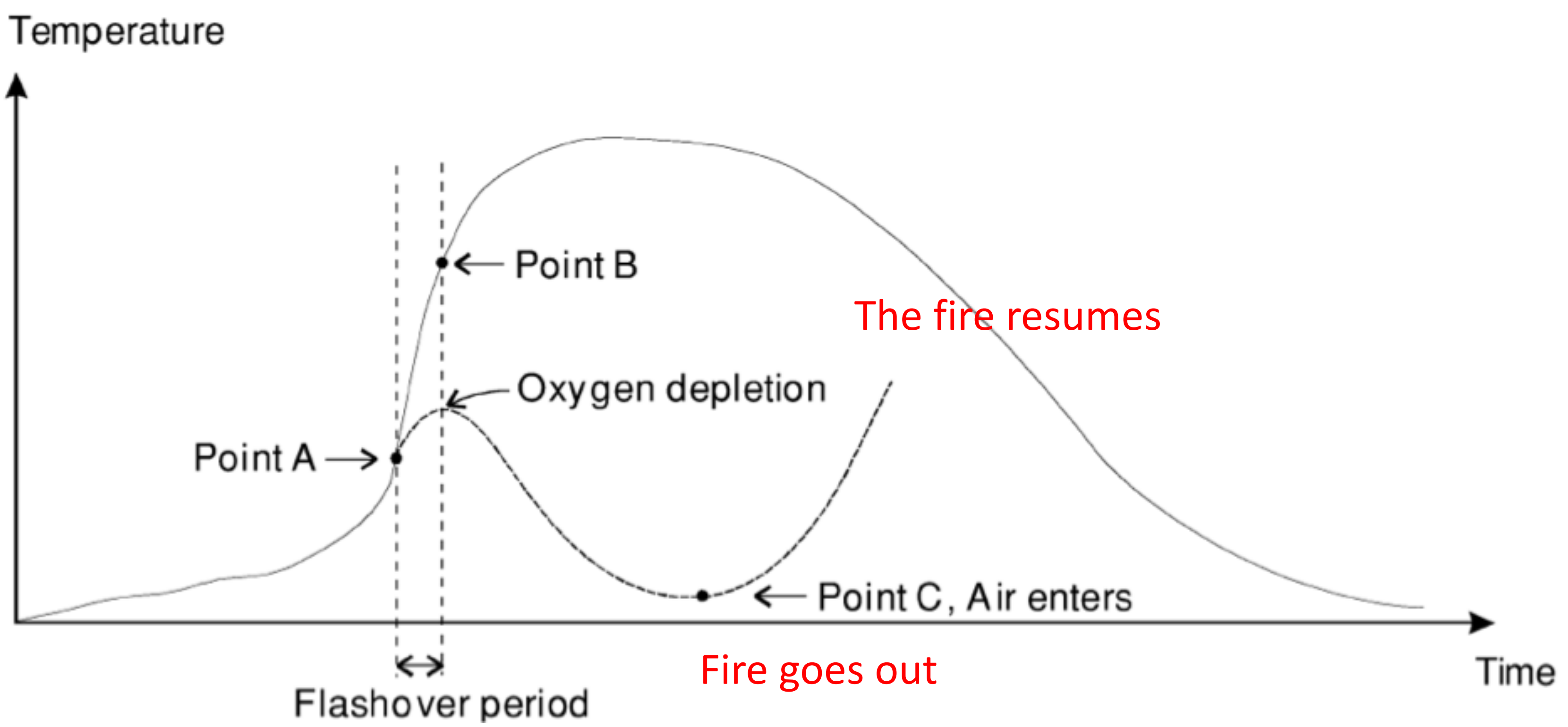



Post-flashover fire
Ventilation controlled fire

# Temperature history in an compartment fire

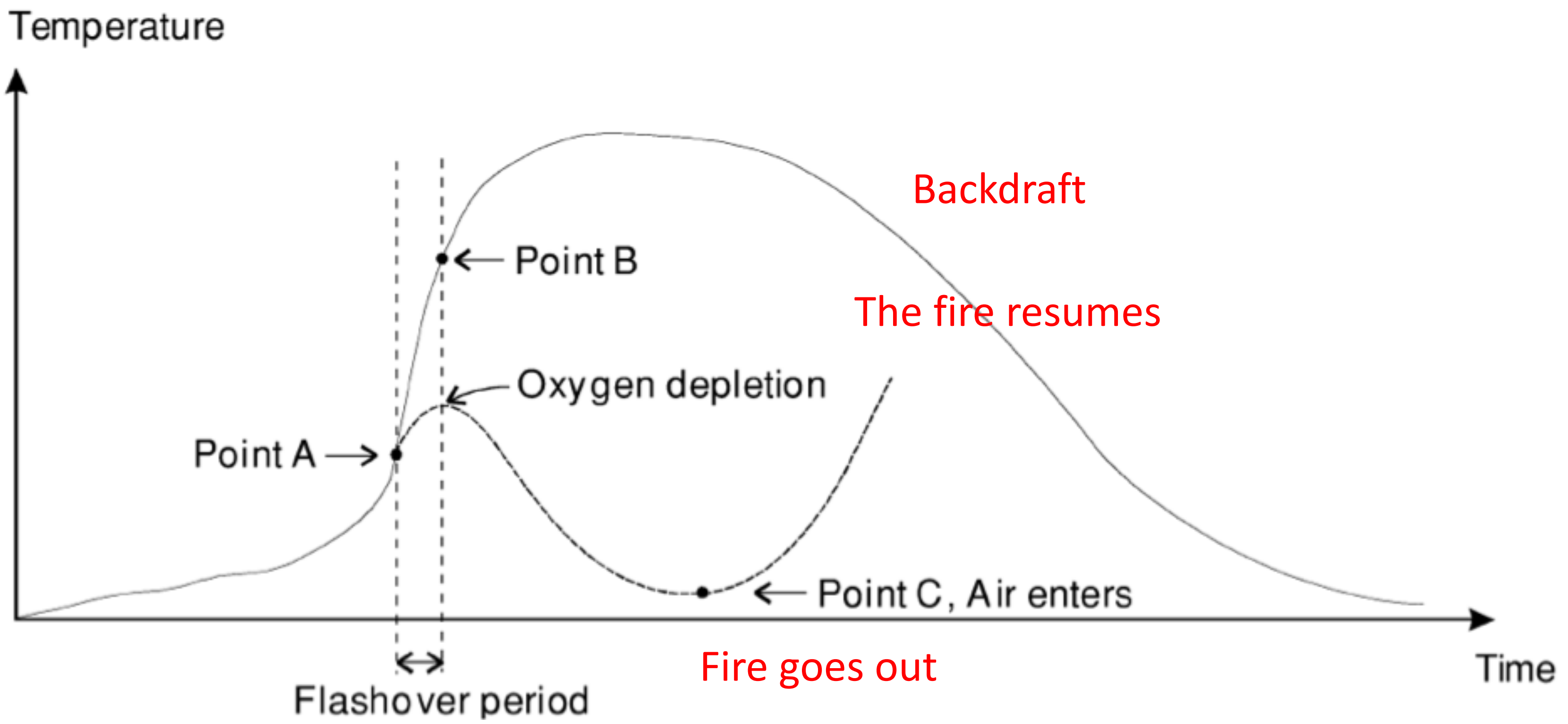


# Temperature history in a compartment fire – limited oxygen

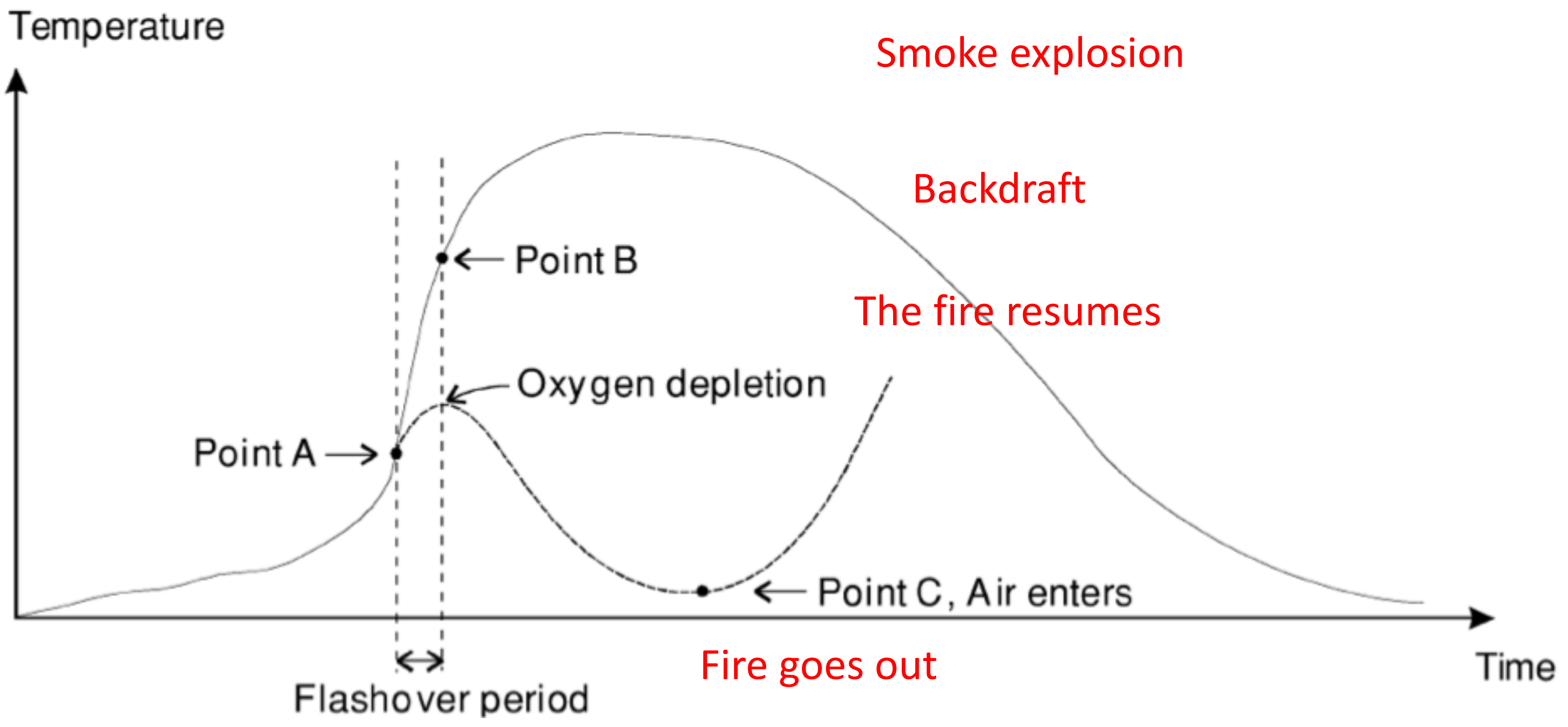


# Video: limited oxygen

# Temperature history in a compartment fire – limited oxygen



# Temperature history in a compartment fire – limited oxygen



# The design fire

# Design fire

The design fire is affected by a number of factors determined in the preceding analysis. To be able to find a design fire, the following input is most often needed:

| | Factors affecting the design fire |
|---|---|
| **Building characteristics** | Dimensions of building<br>Geometry of building<br>Nature of construction of building (materials and method) |
| **Enclosure characteristics** | Wall and ceiling linings<br>Ventilation conditions (natural or mechanical)<br>Thermal properties of enclosure boundaries |
| **Environmental conditions** | Ambient temperature conditions<br>Ambient air movement |
| **Fuel characteristics** | Fuel type<br>Fuel quantity<br>Fuel location<br>Fuel arrangement<br>Wall and linings |
| **Design fire scenario** | Ignition sources<br>Ignition location<br>Fuel involved in ignition<br>Type of fire growth<br>Unusual fire hazard<br>Events influencing fire growth e.g. window breakage. |

# Heat release rate

- Fire safety evaluation of a building requires that a number of design fires are developed
- These include a prediction of heat release rates (HRR) or "fire curves"
  - A "good" measure of the severity of the fire

*Fire Safety Journal* **18** (1992) 255–272

**Heat Release Rate: The Single Most Important Variable in Fire Hazard***

Vytenis Babrauskas & Richard D. Peacock

Building and Fire Research Laboratory, National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

(Received 4 January 1991; revised version received 23 April 1991, accepted 25 April 1991)

# How do we determine fire curves?

- With natural fires, we do not know the fuel in advance – this is a big problem!
- There are an infinite number of fire scenarios possible for a building
  - What are some for this room?
- Only a limited (small) number of fire scenarios reviewed and normally tested in fire safety analysis
  - Deterministic analysis
    - worst credible case
  - Probabilistic analysis

# How do we determine fire curves?

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    - worst credible case
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Fire tests / statistics

Guidelines / building codes

Models

# Heat release rate for **pool fires**

- Rather simple for the free burning case

$$\dot{Q}(t) = A_f(t) \cdot \dot{m}''(t) \cdot \Delta H_{effective}$$

**TABLE 3.3**
**Data for Large Pool ($D > 0.2$ m) Burning Rate Estimates**

| Material | Density (kg/m³) | $\dot{m}''_\infty$ (kg/m²s) | $\Delta H_c$ (MJ/kg) | $k\beta$ (m⁻¹) |
|---|---|---|---|---|
| | **Cryogenics** | | | |
| Liquid $H_2$ | 70 | 0.017 | 120.0 | 6.1 |
| LNG (mostly $CH_4$) | 415 | 0.078 | 50.0 | 1.1 |
| LPG (mostly $C_3H_8$) | 585 | 0.099 | 46.0 | 1.4 |
| | **Alcohols** | | | |
| Methanol ($CH_3OH$) | 796 | 0.017 | 20.0 | [a] |
| Ethanol ($C_2H_5OH$) | 794 | 0.015 | 26.8 | [b] |

# Heat release rate

Pool fire

≠ ?

Fire in a chair

# Heat release rate

- There are no general models (similar to the pool fire model) to calculate HRR in furnishings

- How often will a pool fire be the design fire?

- What shall we do when we cannot use the pool fire model?

Fire tests / statistics

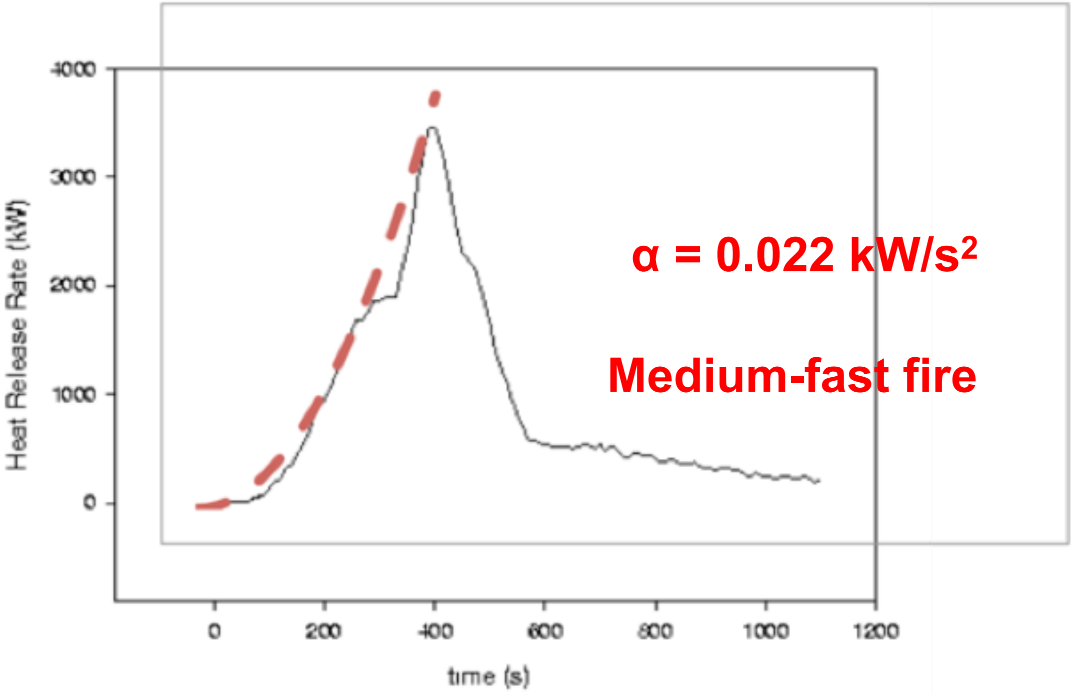
Guidelines / building codes

# Oxygen consumption calorimeter

# Sofa: How will it burn?

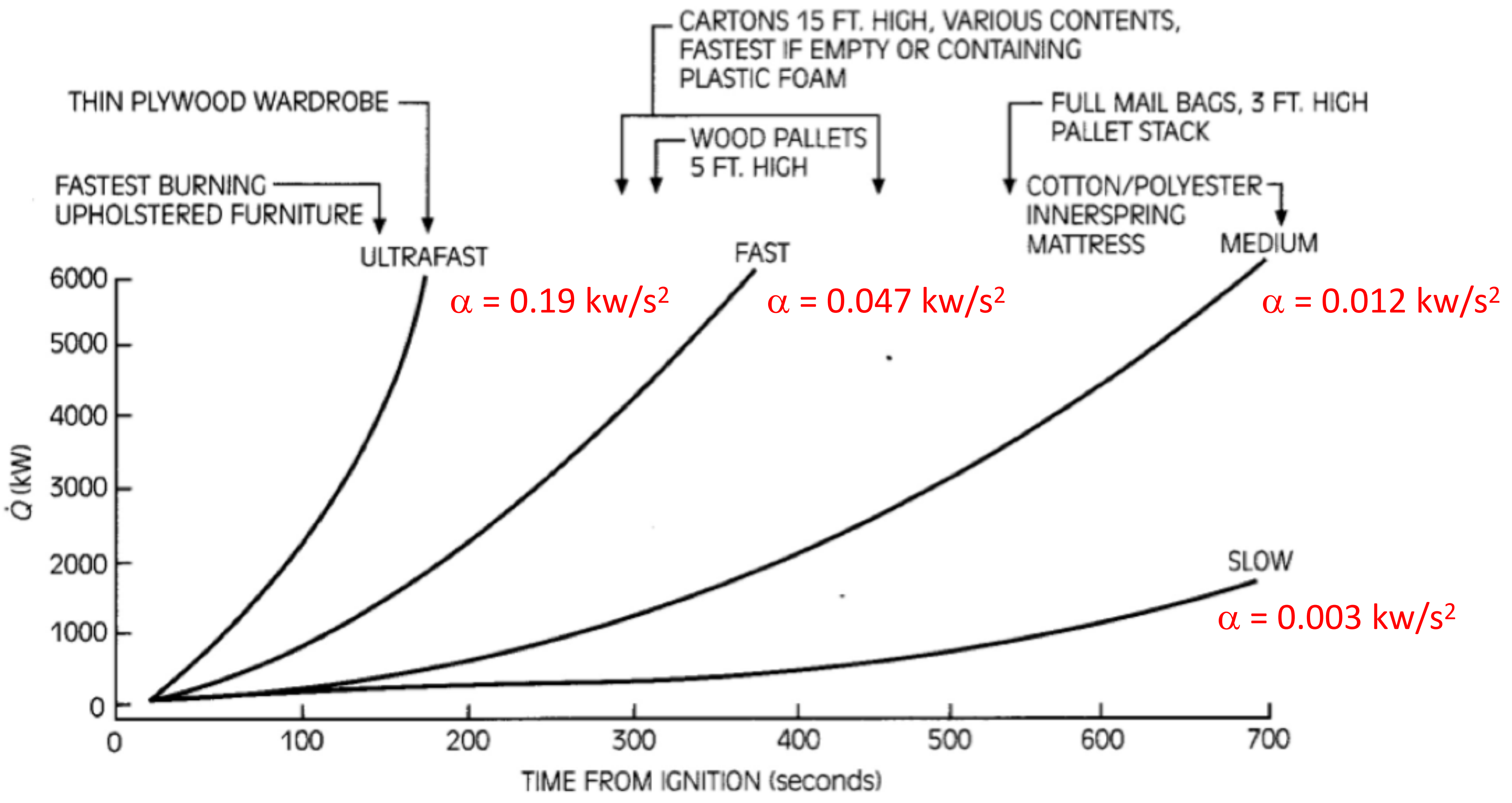
Source: http://fire.nist.gov/fire/fires/

# Sofa: HRR vs. time


Source: http://fire.nist.gov/fire/fires/

# Fire growth rates $Q = \alpha t^2$



# Fire growth rates, examples

| Description | $\alpha$ [kW/s²] | Test no. |
|---|---|---|
| Metal wardrobe 41.4 kg (total) | 0.422 | 15 |
| Chair F33 (trial loveseat) 39.2 kg | 0.0066 | 18 |
| Chair F21, 28.15 kg (initial stage of fire growth) | 0.0344 | 19 |
| Chair F21, 28.15 kg (later stage of fire growth) | 0.04220 | 19 |
| Metal wardrobe 40.8 kg (total, average growth) | 0.0169 | 21 |
| Metal wardrobe 40.8 kg (total, later growth) | 0.0733 | 21 |
| Metal wardrobe 40.8 kg (total, initial growth) | 0.1055 | 21 |
| Chair F24, 28.3 kg | 0.0086 | 22 |
| Chair F23, 31.2 kg | 0.0066 | 23 |
| Chair F22, 31.9 kg | 0.0003 | 24 |
| Chair F26, 19.2 kg | 0.0264 | 25 |
| Chair F27, 29.0 kg | 0.0264 | 26 |
| Chair F29, 14.0 kg | 0.1055 | 27 |
| Chair F28, 29.2 kg | 0.0058 | 28 |
| Chair F25, 27.8 kg (later stage of fire growth) | 0.2931 | 29 |
| Chair F25, 27.8 kg (initial stage of fire growth) | 0.1055 | 29 |
| Chair F30, 25.2 kg | 0.2931 | 30 |
| Chair F31, (loveseat) 39.6 kg | 0.2931 | 31 |
| Chair F31, (loveseat) 40.4 kg | 0.1648 | 37 |
| Chair F32, (sofa) 51.5 kg | 0.1055 | 38 |
| ½ inch plywood wardrobe w/ fabrics 68.8 kg | 0.8612 | 39 |
| ½ inch plywood wardrobe w/ fabrics 68.32 kg | 0.8612 | 40 |
| 1/8 inch plywood wardrobe w/ fabrics 36.0 kg | 0.6594 | 41 |
| 1/8 inch plywood wardrobe w/ fire-ret. (int. fin. initial) | 0.2153 | 42 |

| Description | $\alpha$ [kW/s²] | Test no. |
|---|---|---|
| 1/8 inch plywood wardrobe w/ fire-ret. (int. fin. later) | 1.1722 | 42 |
| Repeat of ½ inch plywood wardrobe 67.62 kg | 1.1722 | 43 |
| 1/8 inch plywood wardrobe w/ fire-ret. latex paint 37.26 kg | 0.1302 | 44 |
| Chair F21, 28.34 kg (large hood) | 0.1055 | 45 |
| Chair F21, 28.34 kg | 0.5210 | 46 |
| Chair, adjustable back metal frame, foam cushion, 20.8 kg | 0.0365 | 47 |
| Easy chair CO7 11.52 kg | 0.0344 | 48 |
| Easy chair 15.68 kg (F-34) | 0.0264 | 49 |
| Chair metal frame minimum cushion, 16.52 kg | 0.0264 | 50 |
| Chair moulded fibreglass no cushion 5.82 kg | 0.0733 | 51 |
| Moulded plastic patient chair, 11.26 kg | 0.0140 | 52 |
| Chair metal frame w/padded seat and back 15.5 kg | 0.0086 | 53 |
| Loveseat metal frame w/foam cushions 27.26 kg | 0.0042 | 54 |
| Group chair metal frame w/foam cushions, 6.08 kg | Never exceeded 50 kW | 55 |
| Chair wood frame w/latex foam cushion, 11.2 kg | 0.0042 | 56 |
| Loveseat wood frame w/foam cushions, 54.6 kg | 0.0086 | 57 |
| Wardrobe, ¾ inch particle board, 120.33 kg | 0.0469 | 61 |
| Bookcase plywood w/aluminium frame, 30.39 kg | 0.2497 | 62 |
| Easy chair moulded flexible urethane frame, 15.98 kg | 0.0011 | 64 |
| Easy chair, 23.02 kg | 0.1876 | 66 |
| Mattress and box spring, 62.36 kg (initial fire growth) | 0.0086 | 67 |
| Mattress and box spring, 62.36 kg (initial fire growth) | 0.0009 | 67 |

# When will the fire stop growing?

- At some point $Q_{max}$ is reached, what will limit the growth?

- Fuel
  - We need to rely on empirical data to estimate $Q_{max}$
    - Estimate fuel surface and heat release per unit area
- Oxygen
  - Effect of the enclosure ventilation
- Suppression

# Fuel controlled fire

**TABLE 3.6**
**Energy Release Rate Data**

| Description | kW/m² of floor area |
|---|---|
| Fire retarded treated mattress (including normal bedding) | 17 |
| Lightweight type C upholstered furniture[b] | 170[a] |
| Moderate-weight type C upholstered furniture[b] | 400[a] |
| Mail bags (full) stored 5 ft high | 400 |
| Cotton/polyester innerspring mattress (including bedding) | 565[a] |
| Lightweight type B upholstered furniture[b] | 680[a] |
| Medium-weight type C upholstered furniture[b] | 680[a] |
| Methyl alcohol pool fire | 740 |
| Heavyweight type C upholstered furniture[b] | 795[a] |
| Polyurethane innerspring mattress (including bedding) | 910[a] |

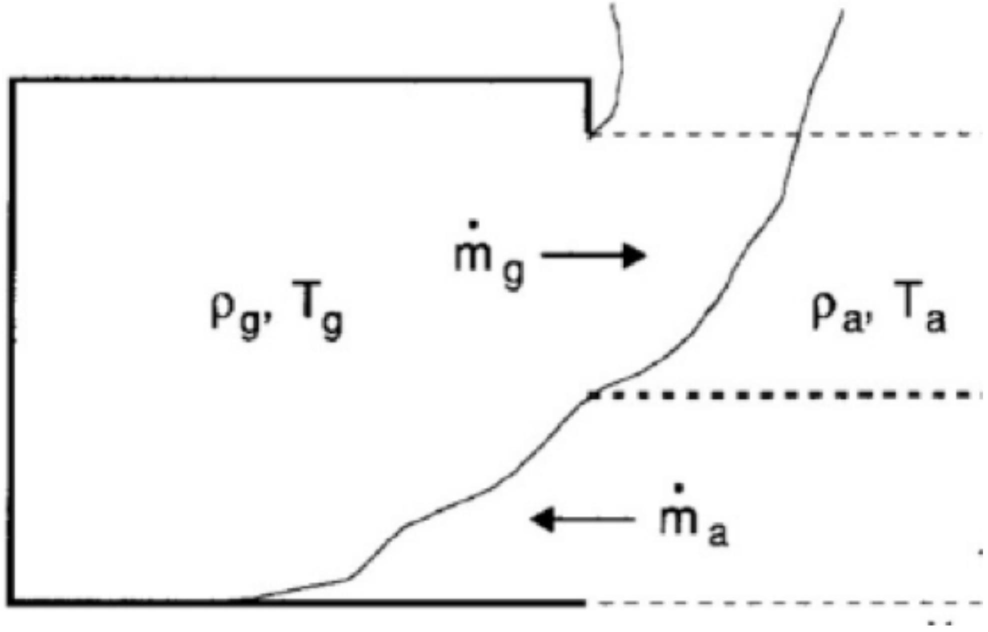
# Ventilation controlled fire

- The maximum mass flow through a opening in a fully developed fire

$$\dot{m} = 0.5 \cdot A_o\sqrt{H_0}$$

- The HRR is governed by the size of the openings

$$\dot{Q}_{\max} = 1.518 \cdot A_o\sqrt{H_o}$$

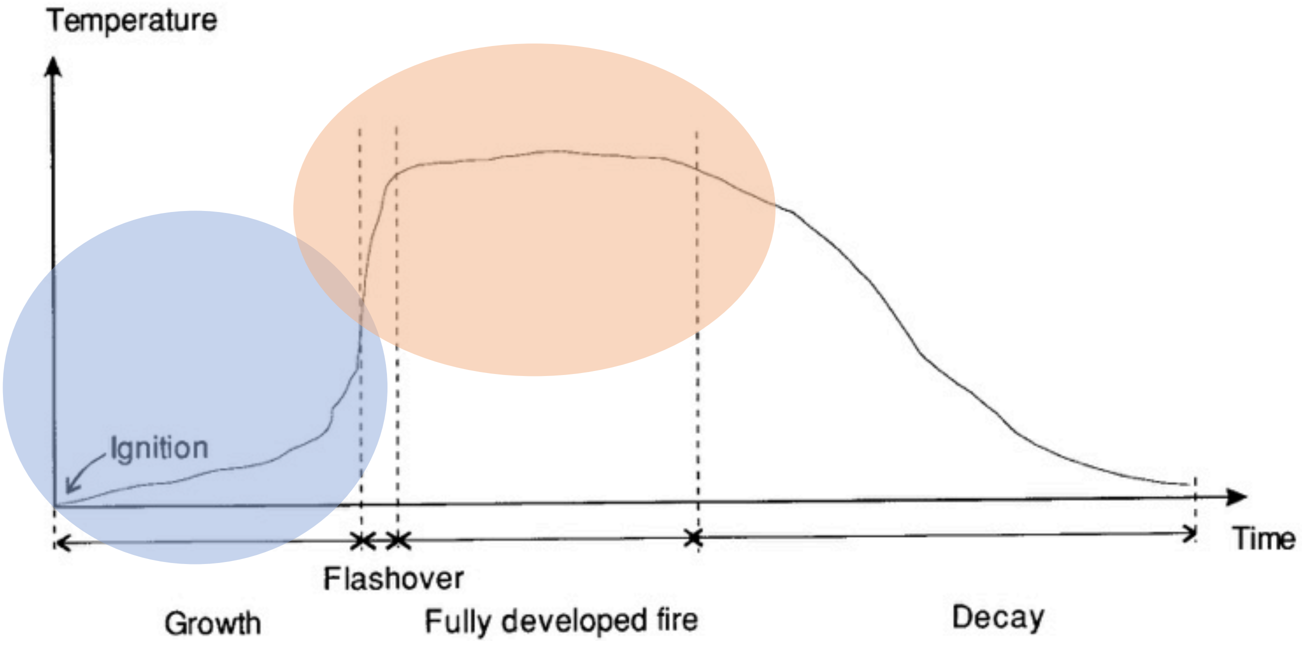


# Gas temperatures

# Why is the gas temperature important?

- Life Safety
- Structural fire protection

- Results in vent mass flows
    - Spread of smoke away from fire
- Heating of fuel
- Activation of detection systems
- Impact on suppression
    - By rescue service or sprinkler system



# How can the gas temperature be calculated?

CFD models

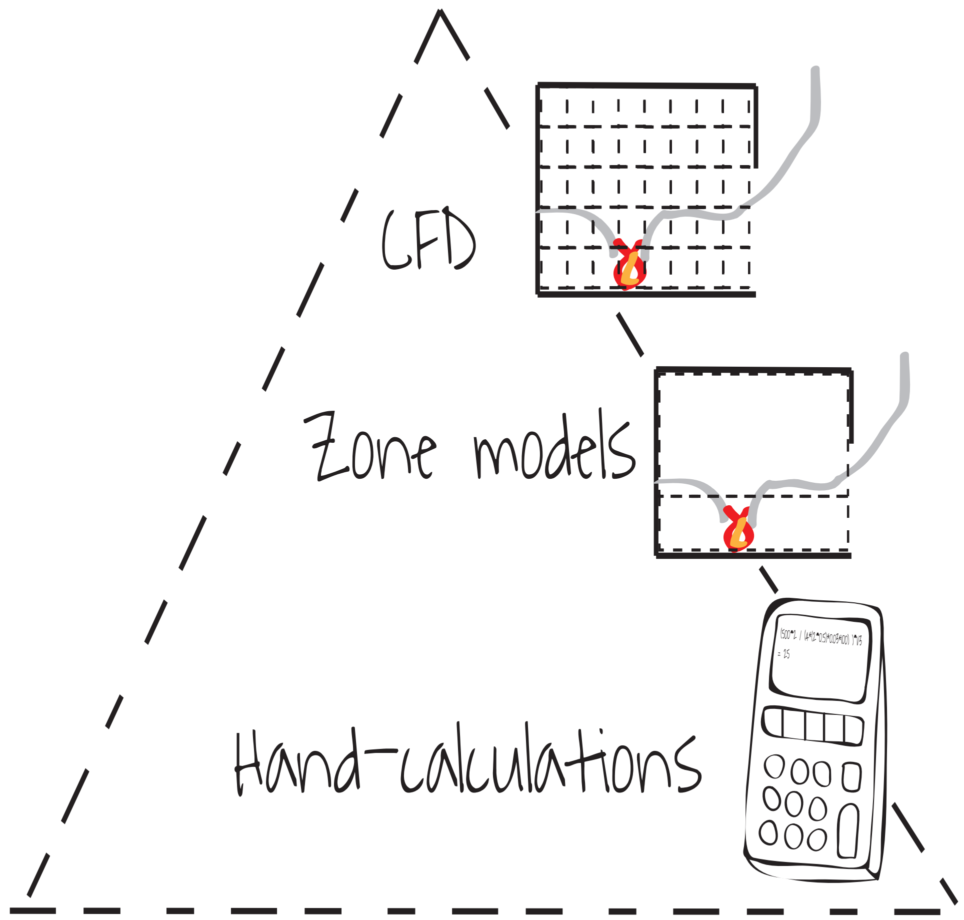
- Complex, requires expertise on software. Can yield in black box syndrome

Two-zone models

- Rather simple, suitable for the compartment fire

Hand-calculation methods

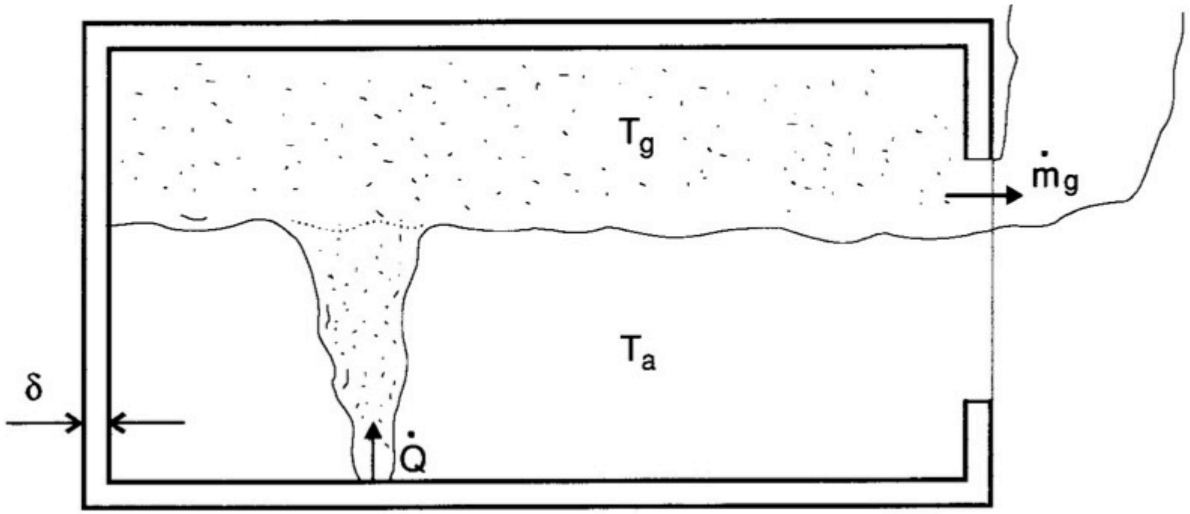
- (Too?) simple, suitable for the compartment fire



# Pre-flashover temperature

- Method of McCaffrey, Quintiere and Harkleroad (MQH-correlation)
- Conservation of energy relation (balance) for a ventilated compartment

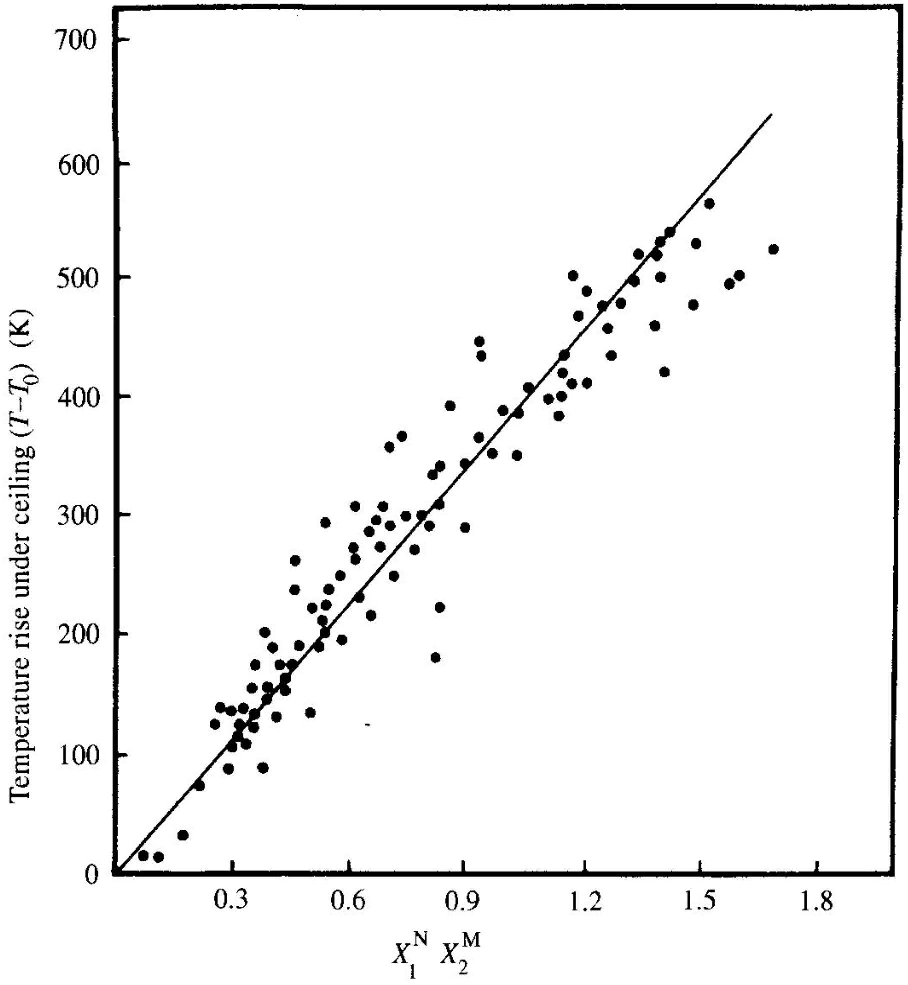
$$\begin{bmatrix}\text{Rate of energy} \\ \text{released in} \\ \text{compartment}\end{bmatrix} = \begin{bmatrix}\text{Rate of energy} \\ \text{lost through} \\ \text{vent flow, } \dot{q}_{vent}\end{bmatrix} + \begin{bmatrix}\text{Rate of energy lost by} \\ \text{hot gases to compartment} \\ \text{boundaries, } \dot{q}_{loss}\end{bmatrix}$$



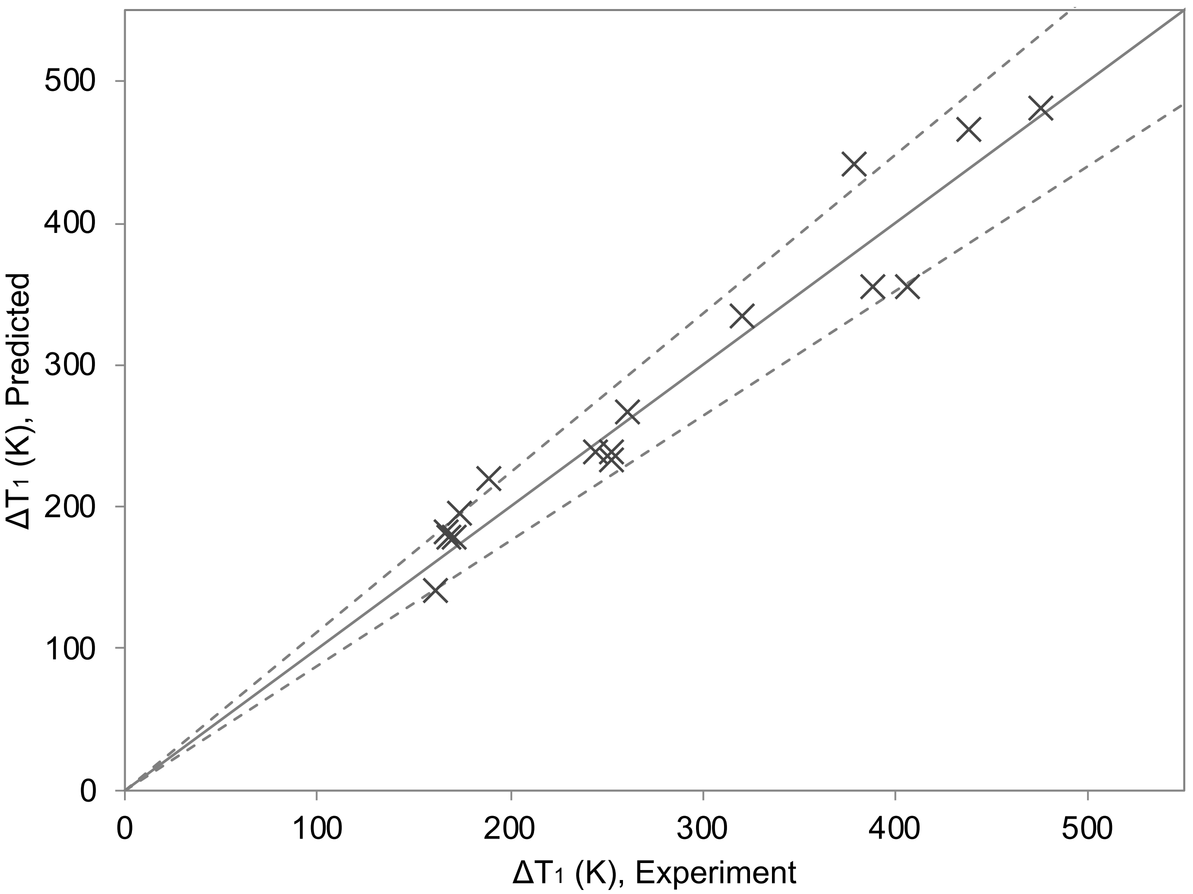
# Pre-flashover temperature

- Method of McCaffrey, Quintiere and Harkleroad (MQH-correlation)
- Conservation of energy relation (balance) for a ventilated compartment
- Experiments used to find relationship constants
- Allows simple solution without a computer

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}h_k A_T}\right)^{1/3}$$



# Pre-flashover temperature MQH method

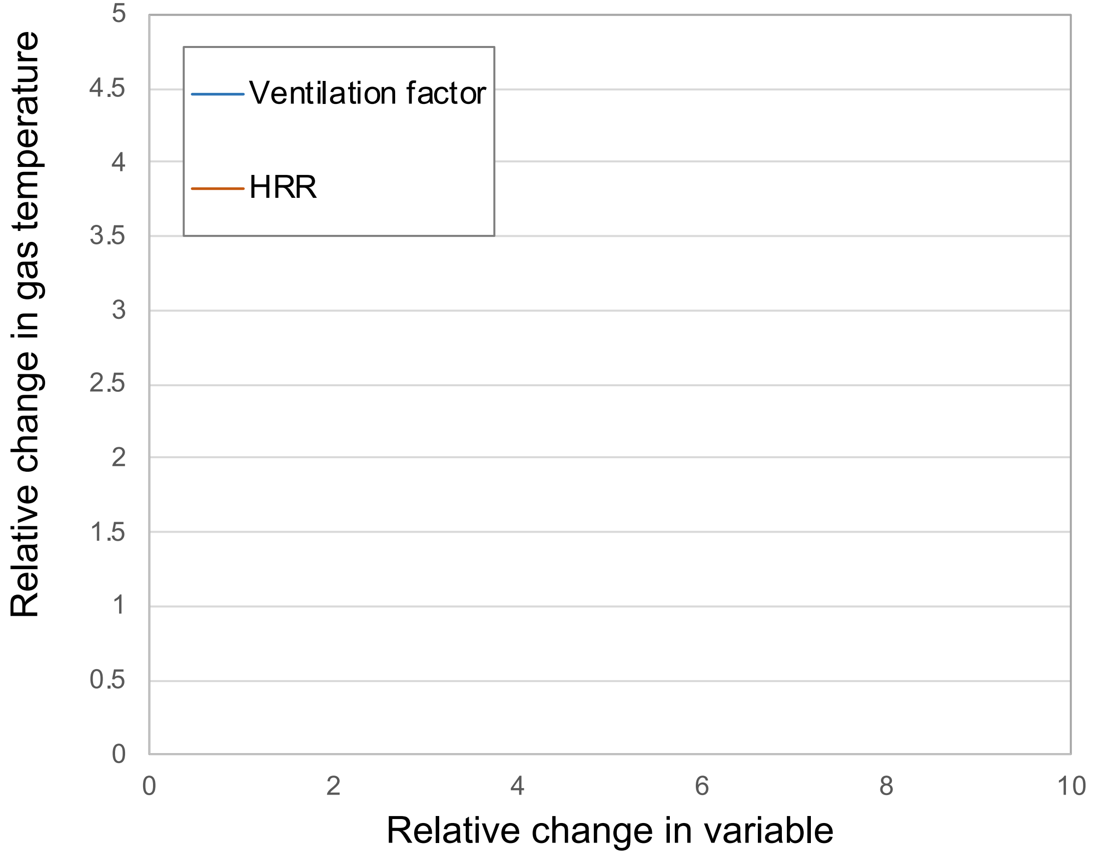



Works well within its bounds of limitations

# Pre-flashover temperature MQH method

The role of the ventilation factor

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}h_k A_T}\right)^{1/3}$$

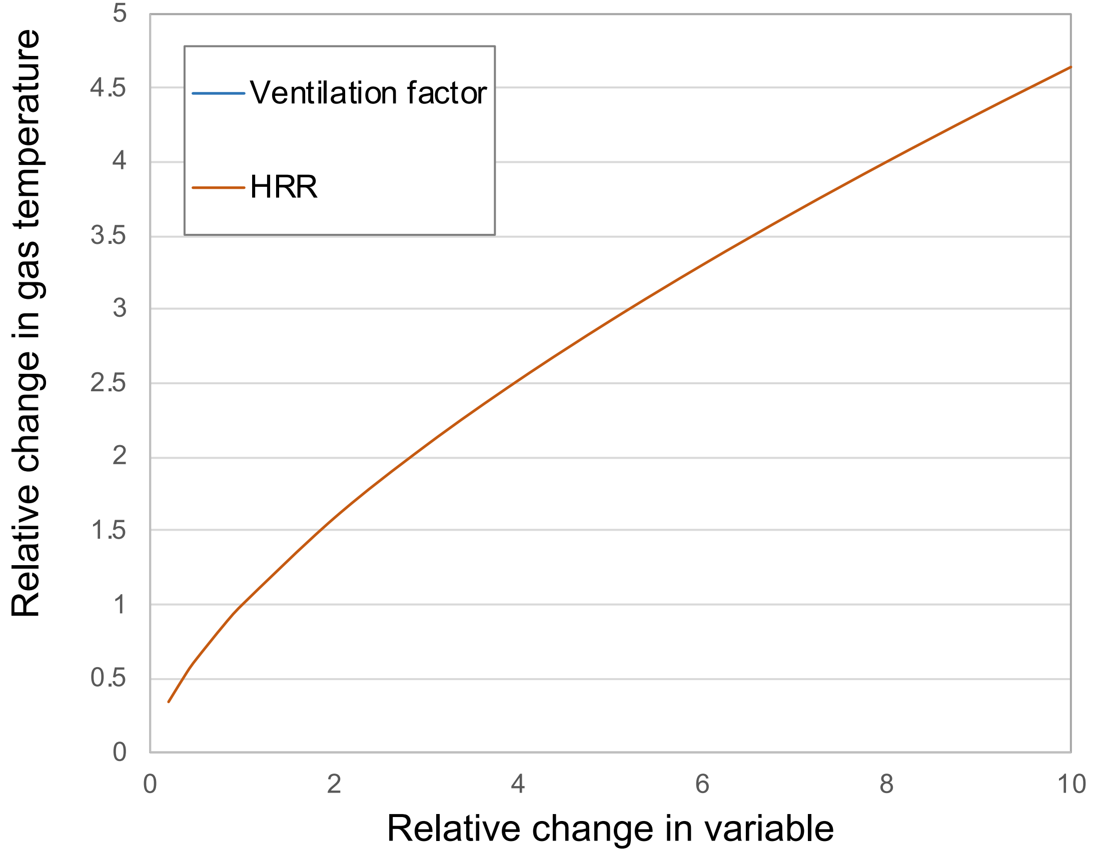


# Pre-flashover temperature MQH method

The role of the ventilation factor

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}h_k A_T}\right)^{1/3}$$

Double HRR:
58% increase of gas temperature



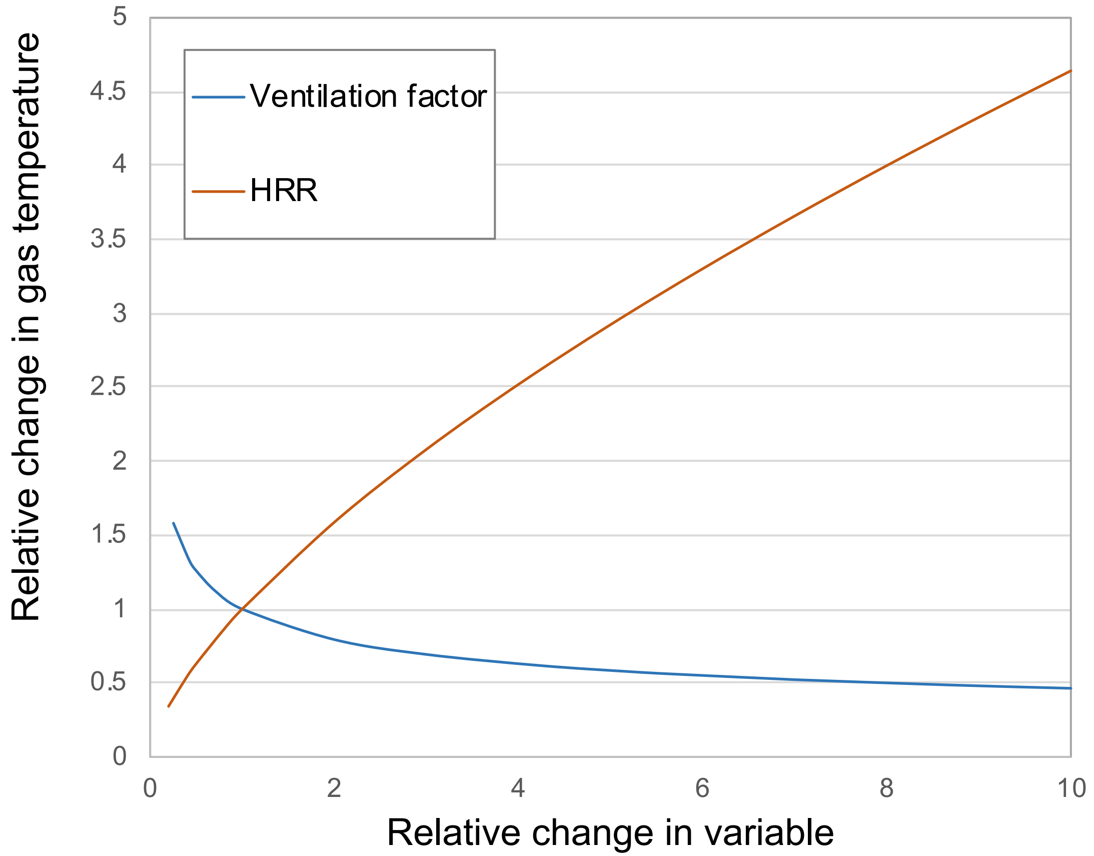
# Pre-flashover temperature MQH method

The role of the ventilation factor

$$\Delta T = 6.85\left(\frac{\dot{Q}^2}{A_0\sqrt{H_0}h_k A_T}\right)^{1/3}$$

Double HRR:
58% increase of gas temperature

Double ventilation factor:
21% decrease of gas temperature



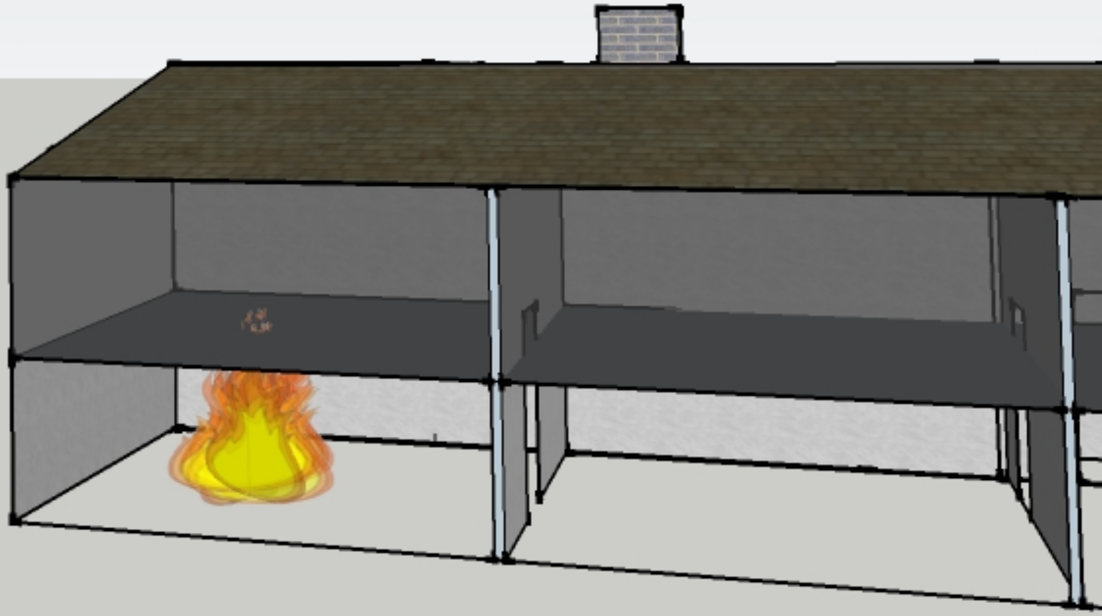
# Pre-flashover temperature multi-room

- A relevant scenario in fire safety engineering can often be smoke spread to adjacent rooms
- Example, smoke spread to corridor used for as egress route
  - Often necessary to use computer models.
  - However, a few engineering methods are available

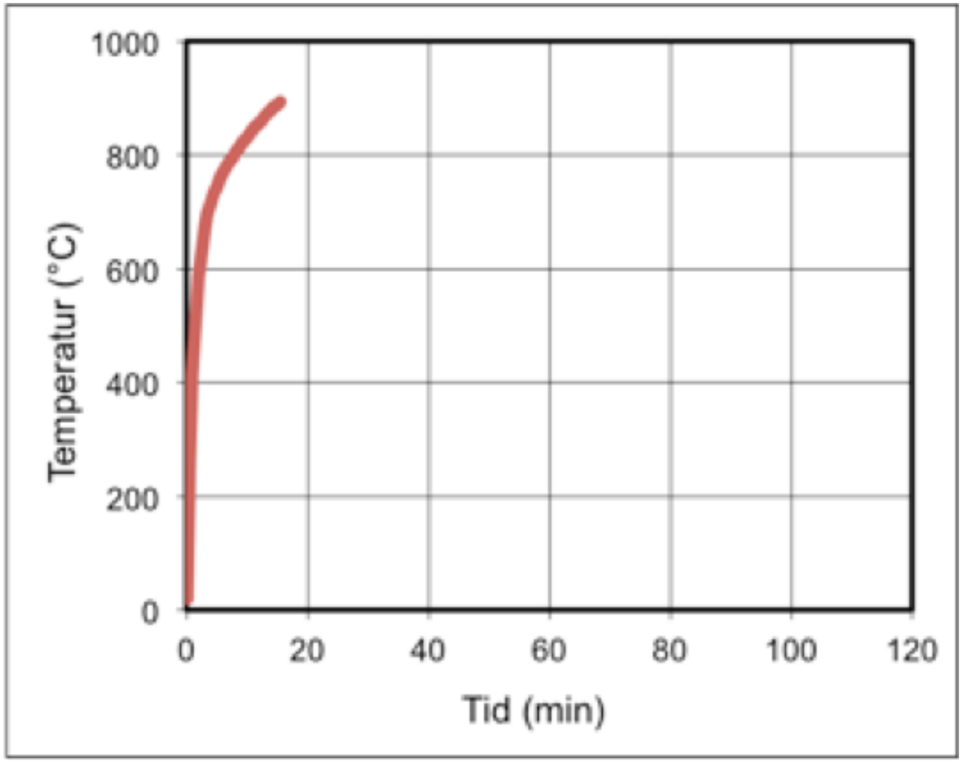
$$\Delta T_2 = 10.4 \frac{\dot{Q}^{0.73}\left(A_{O,1}\sqrt{H_{O,1}}\right)^{0.24}}{A_{T,1}^{0.45} A_{T,2}^{0.33}\left(A_{O,2}\sqrt{H_{O,2}}\right)^{0.19} {h_k}^{0.34}}$$

Double ventilation factor:

12% decrease of gas temperature



# Post-flashover temperature




Method in Eurocode 1 (EN 1991-1-2)

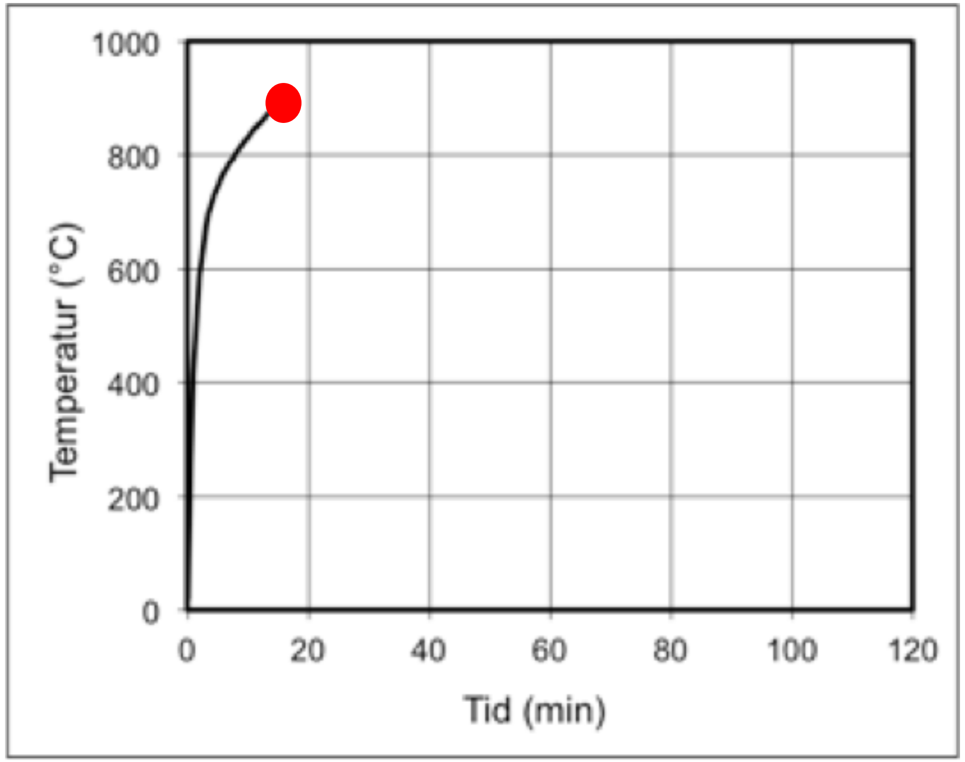
- Temperature curve divide into two parts
  - Heating phase

$$T_g = 20 + 1325\left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right)$$

  - t* is the modified time, according to: $t^* = t \cdot \left(\frac{A_o\sqrt{H_o}/A_t}{\sqrt{k\rho c}}\right)^2 \left(\frac{1160}{0.04}\right)^2$

  - t* = t when $A_o\sqrt{H_o}/A_t = 0.04$ and $\sqrt{k\rho c} = 1160$

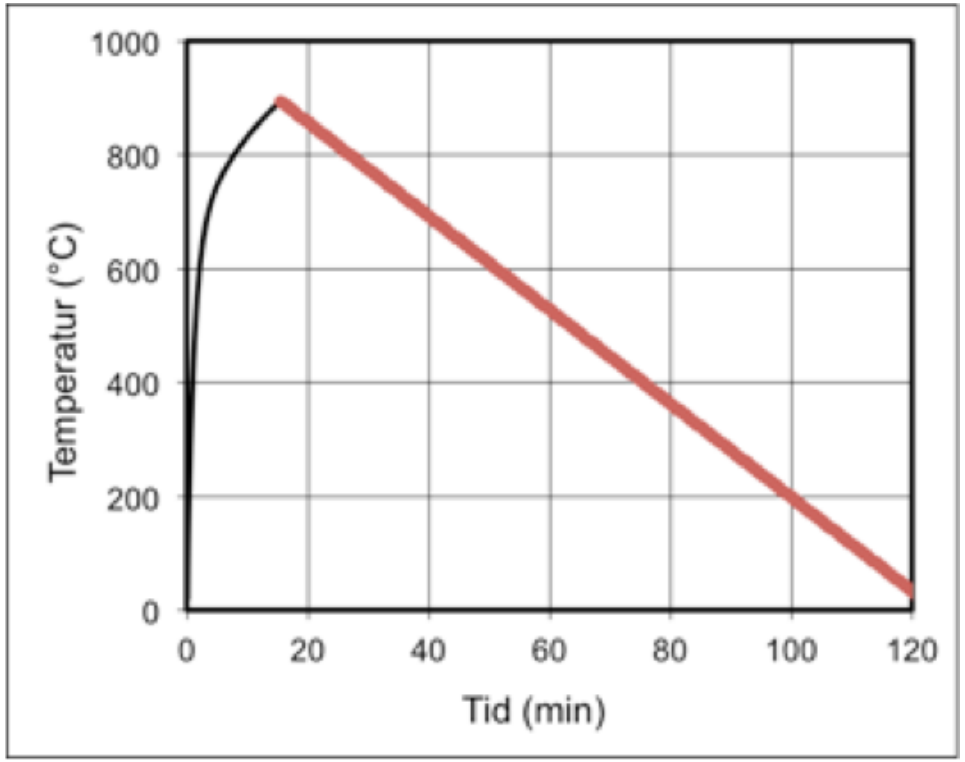
# Post-flashover temperature




Method in Eurocode 1 (EN 1991-1-2)

- Temperature curve divide into two parts
  - Heating phase
  - Last until $t_d = \left( \dfrac{0.13 \cdot 10^{-3} \cdot Q_t''}{A_o \sqrt{H_o} / A_t} \right)$ correspond to $t_d^* = t_d \cdot \left( \dfrac{A_o \sqrt{H_o} / A_t}{\sqrt{k \rho c}} \right)^2 \left( \dfrac{1160}{0.04} \right)^2$
  - Max temperature $T_{g,\max}$ is reached when $t_d^* = t^*$

# Post-flashover temperature




Method in Eurocode 1 (EN 1991-1-2)

- Temperature curve divide into two parts
  - Decay phase

$$T_g = T_{g,\max} - 625\left(t^* - t_d^*\right) \qquad \text{for } t_d^* \leq 0.5$$

$$T_g = T_{g,\max} - 250\left(3 - t_d^*\right)\left(t^* - t_d^*\right) \qquad \text{for } 0.5 < t_d^* < 2$$

$$T_g = T_{g,\max} - 250\left(t^* - t_d^*\right) \qquad \text{for } t_d^* \geq 2$$

# Post-flashover temperature

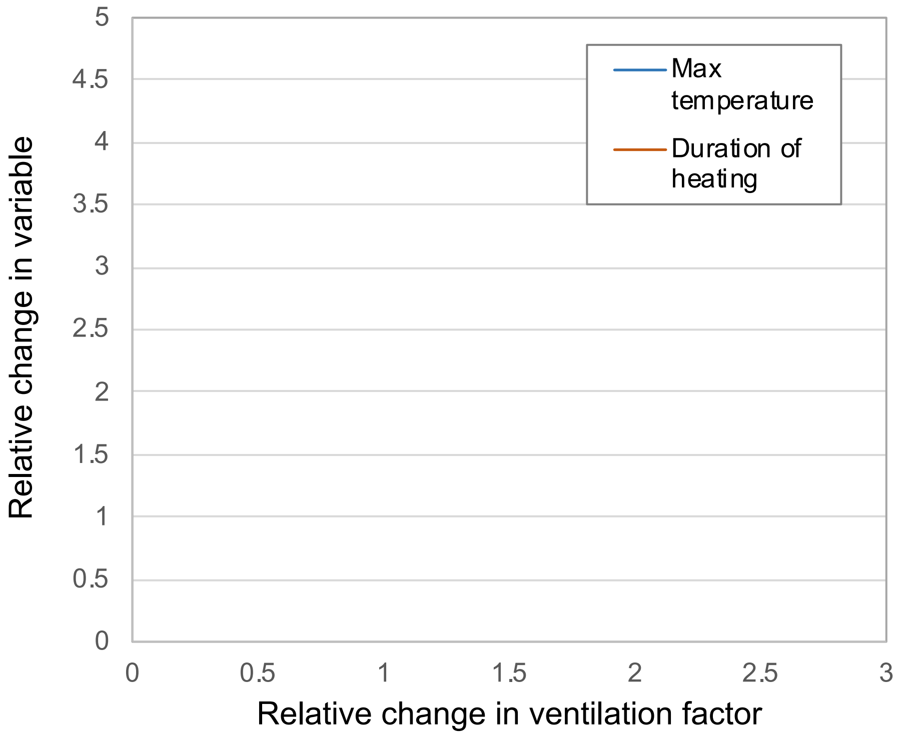
The role of the ventilation factor

$$t^* = t \cdot \left( \frac{A_o \sqrt{H_o} / A_t}{\sqrt{k\rho c}} \right)^2 \left( \frac{1160}{0.04} \right)^2$$

$$t_d = \left( \frac{0.13 \cdot 10^{-3} \cdot Q_t''}{A_o \sqrt{H_o} / A_t} \right)$$

$Q''_t = 200\ MJ/m^2$

$A_t = 200\ m^2$



# Post-flashover temperature

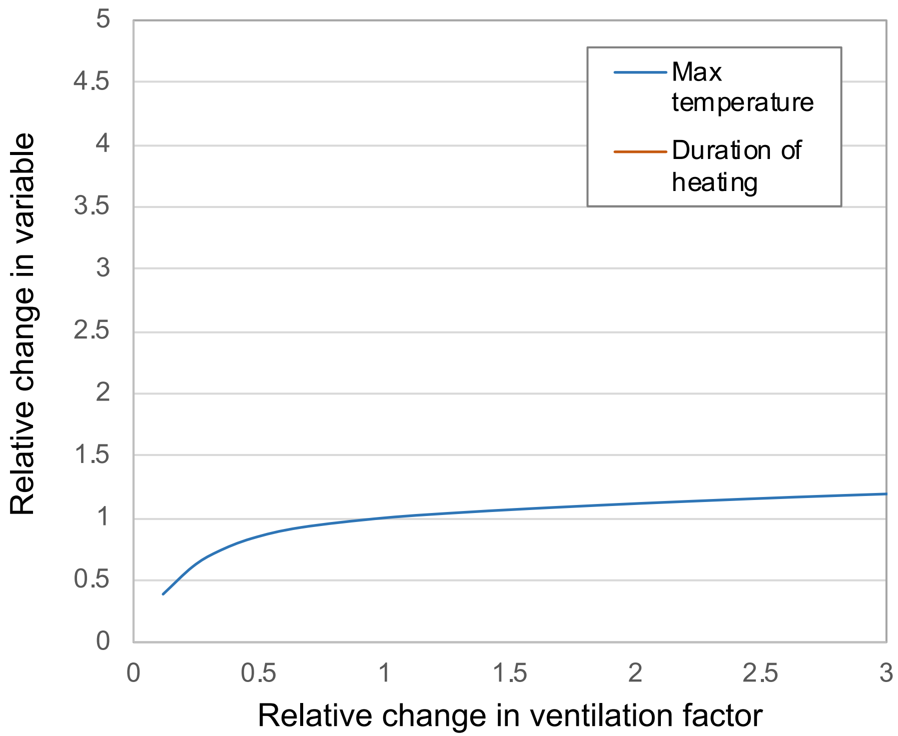
The role of the ventilation factor

$$t^* = t \cdot \left( \frac{A_o \sqrt{H_o} / A_t}{\sqrt{k\rho c}} \right)^2 \left( \frac{1160}{0.04} \right)^2$$

$$t_d = \left( \frac{0.13 \cdot 10^{-3} \cdot Q_t''}{A_o \sqrt{H_o} / A_t} \right)$$

$Q''_t = 200\ MJ/m^2$

$A_t = 200\ m^2$



# Post-flashover temperature

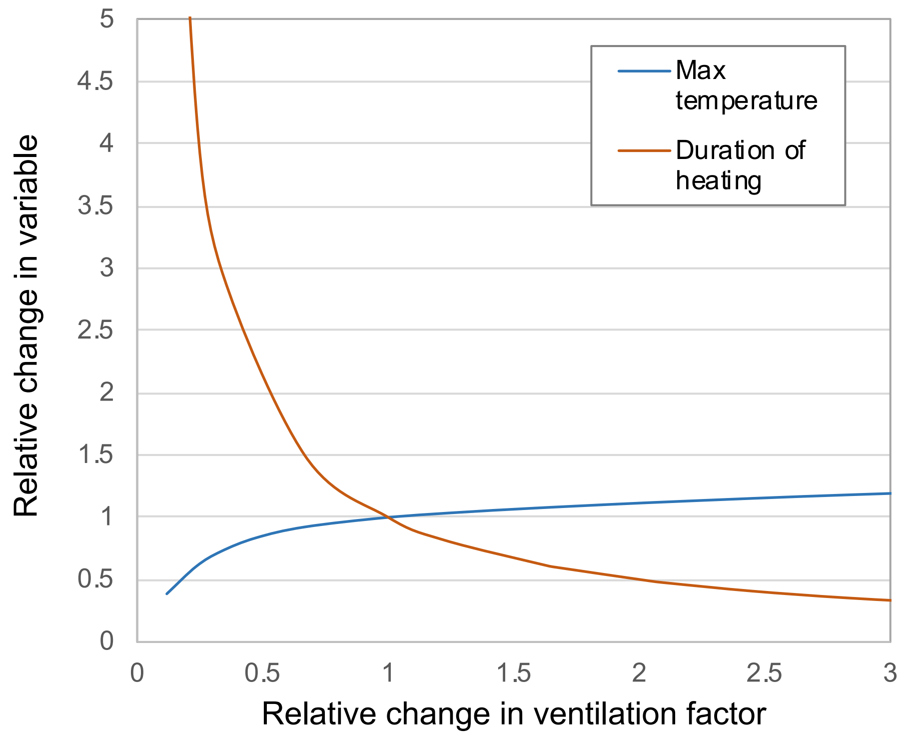
## The role of the ventilation factor

$$t^* = t \cdot \left( \frac{A_o \sqrt{H_o} / A_t}{\sqrt{k \rho c}} \right)^2 \left( \frac{1160}{0.04} \right)^2$$

$$t_d = \left( \frac{0.13 \cdot 10^{-3} \cdot Q_t''}{A_o \sqrt{H_o} / A_t} \right)$$

$Q''_t = 200$ MJ/m$^2$

$A_t = 200$ m$^2$

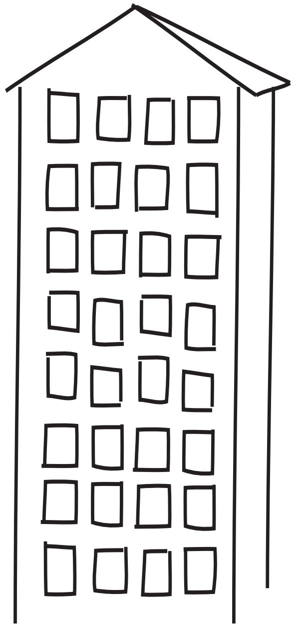


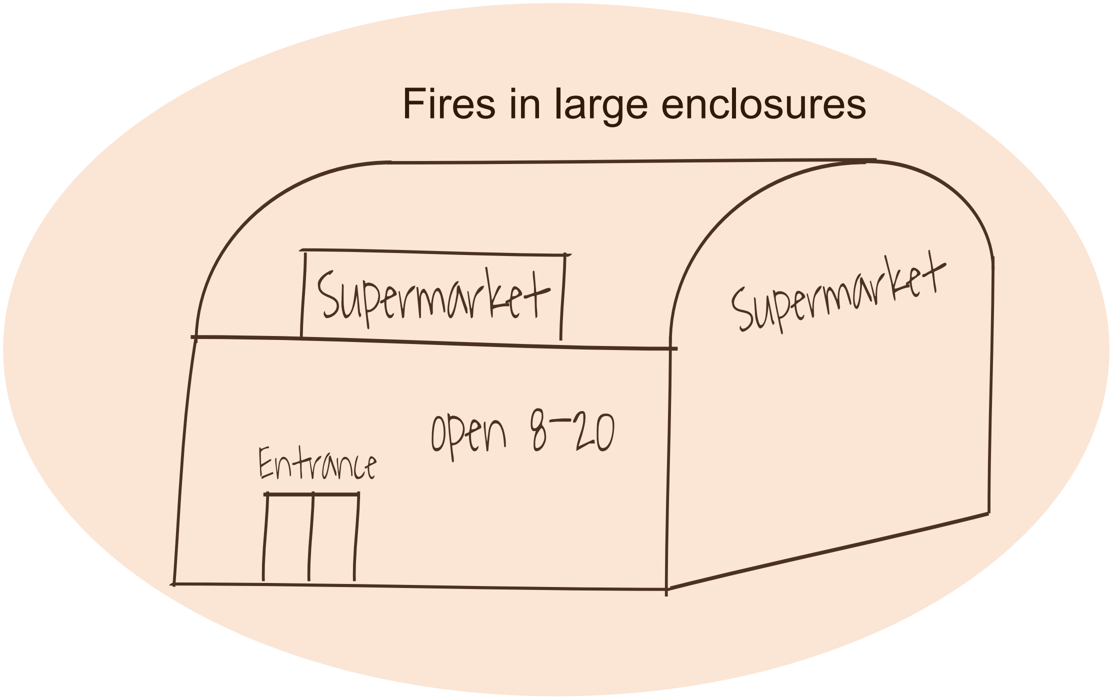
Back to where we started:

# Fires in enclosures

# Fires in enclosures

Compartment fires





# Fires in large enclosures

How can these be modelled?

CFD models

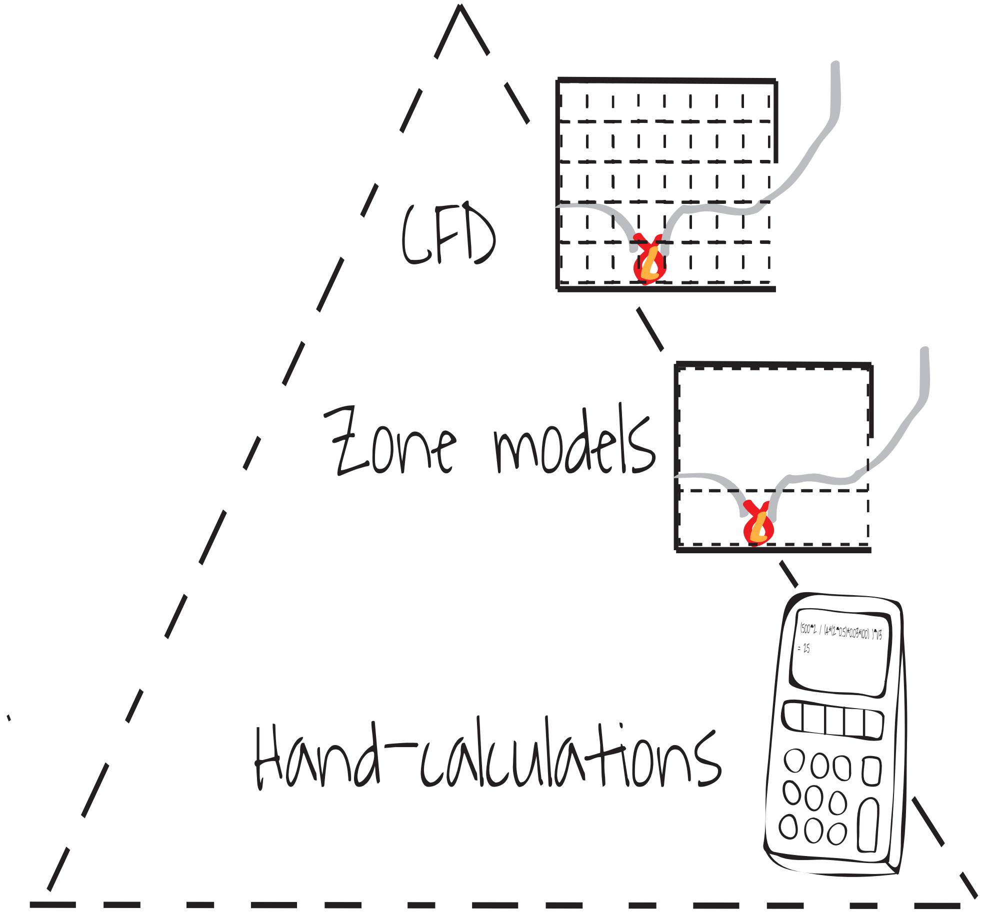
- Large volume, computationally heavy

Two-zone models

- Outside the model limitations (?)

Hand-calculation methods

- Few or no methods available

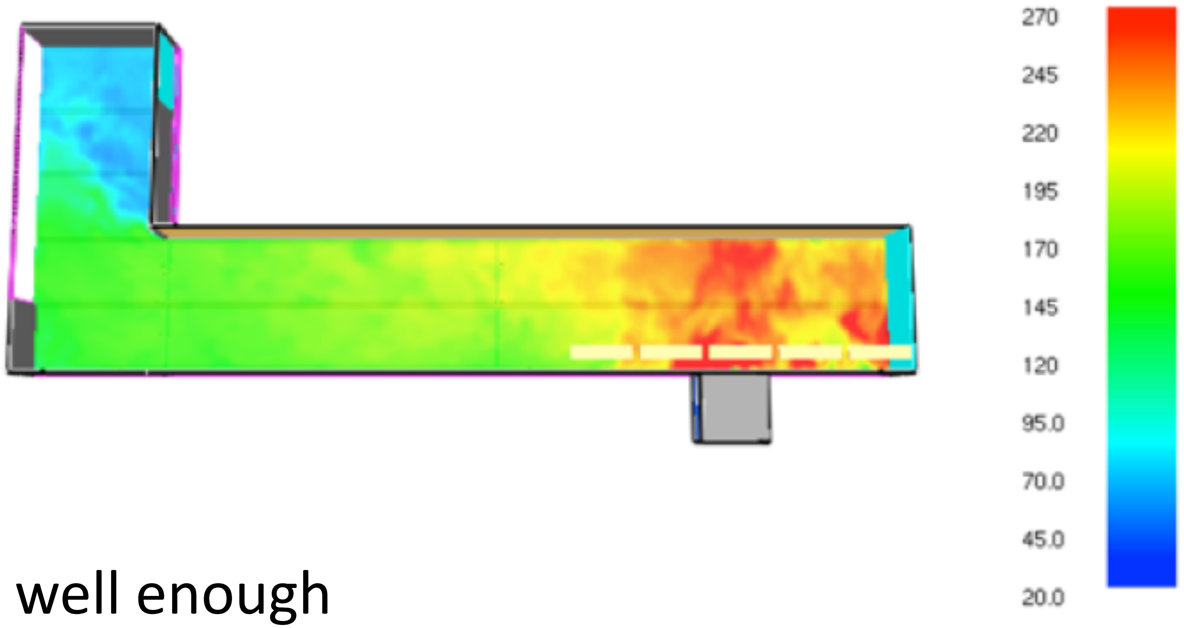


# Fires in large enclosures

Flashover might not be relevant

CFD is currently the only real alternative

- If done correctly
  - Reasonable results
- Calculation time is long
  - Large cells can be used…
  - However, the fire needs to be resolved well enough



# Questions ?

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A demonstration of fire engineering calculations will be done this afternoon