Introduction to Fire Dynamics for Structural Engineers

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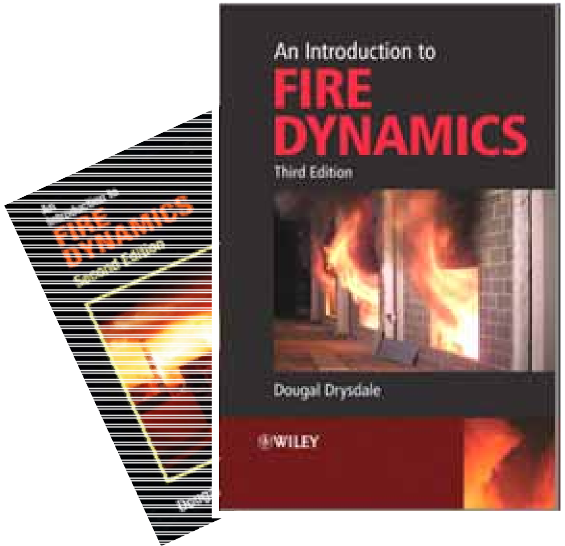
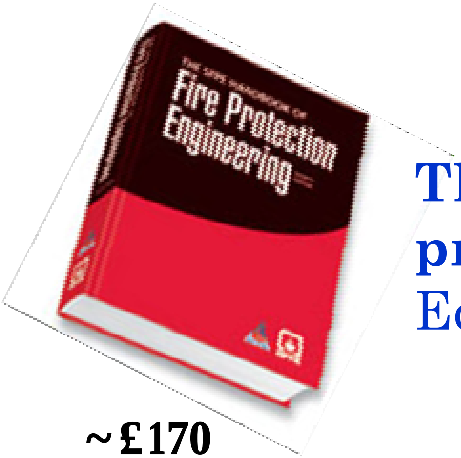
COST TU0904, Malta, April 2012

Textbooks

Introduction to fire Dynamics
by Dougal Drysdale, 3rd Edition,
Wiley 2011



~£46



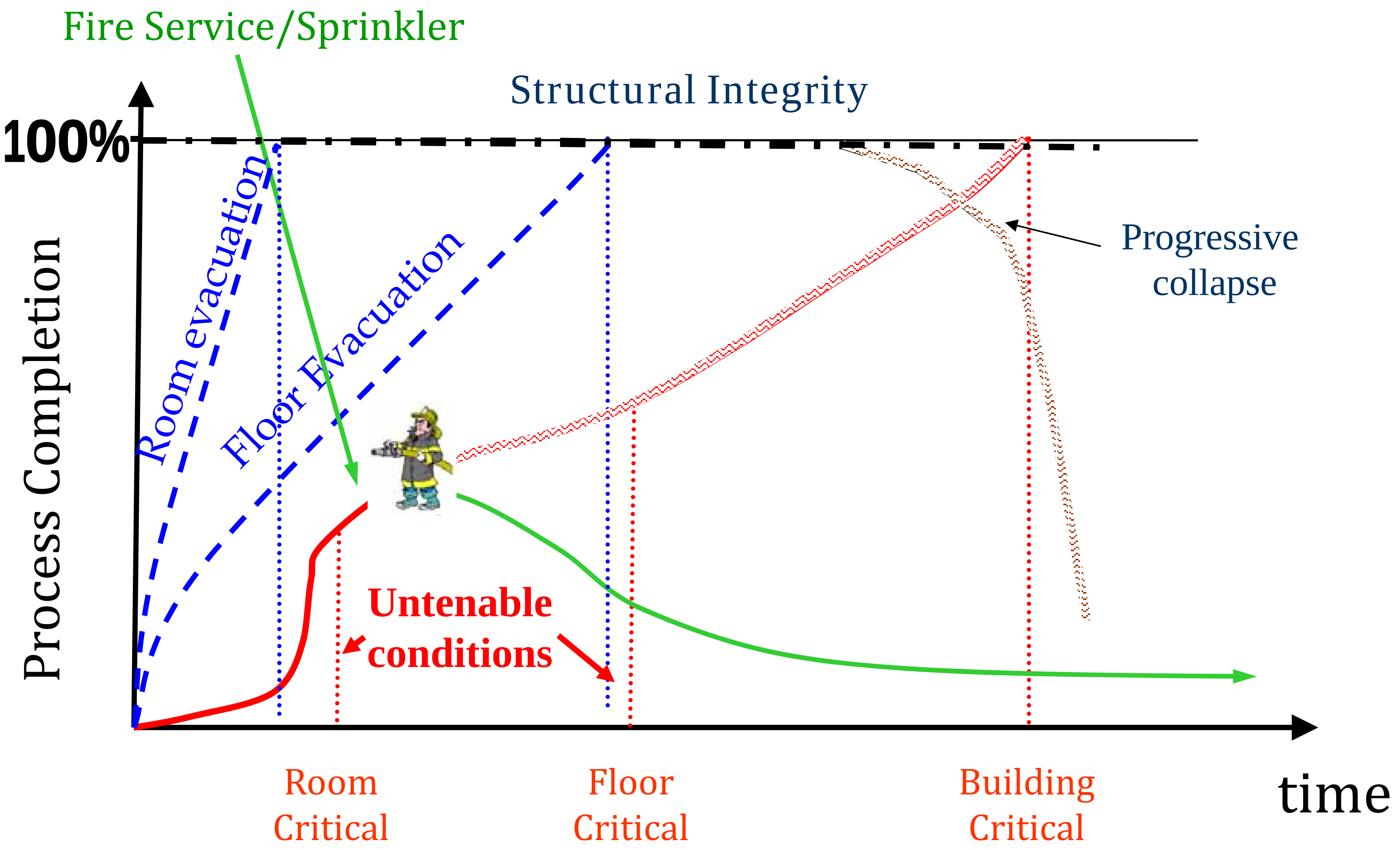
The SFPE Handbook of Fire protection Engineering, 4th Edition, 2009

~£170

Principles of Fire Behavior
by James G. Quintiere

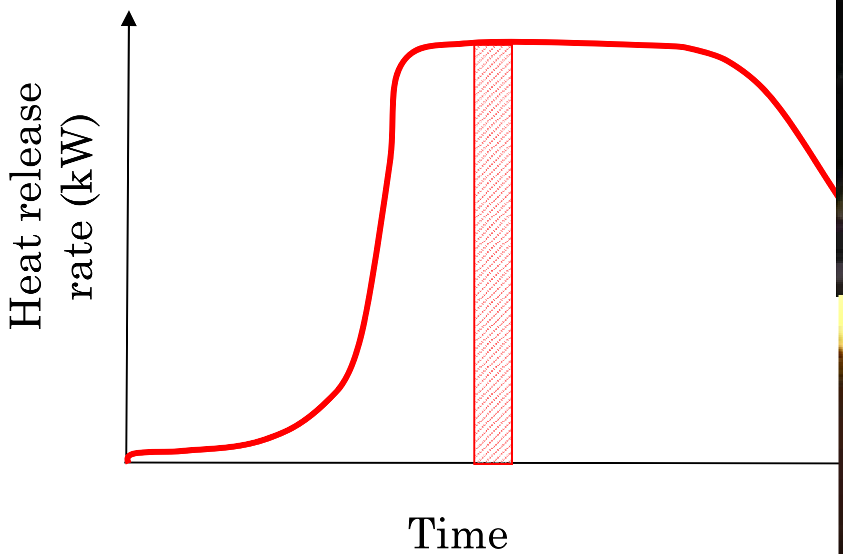
~£65

Fire Safety: protect Lives, Property and Business

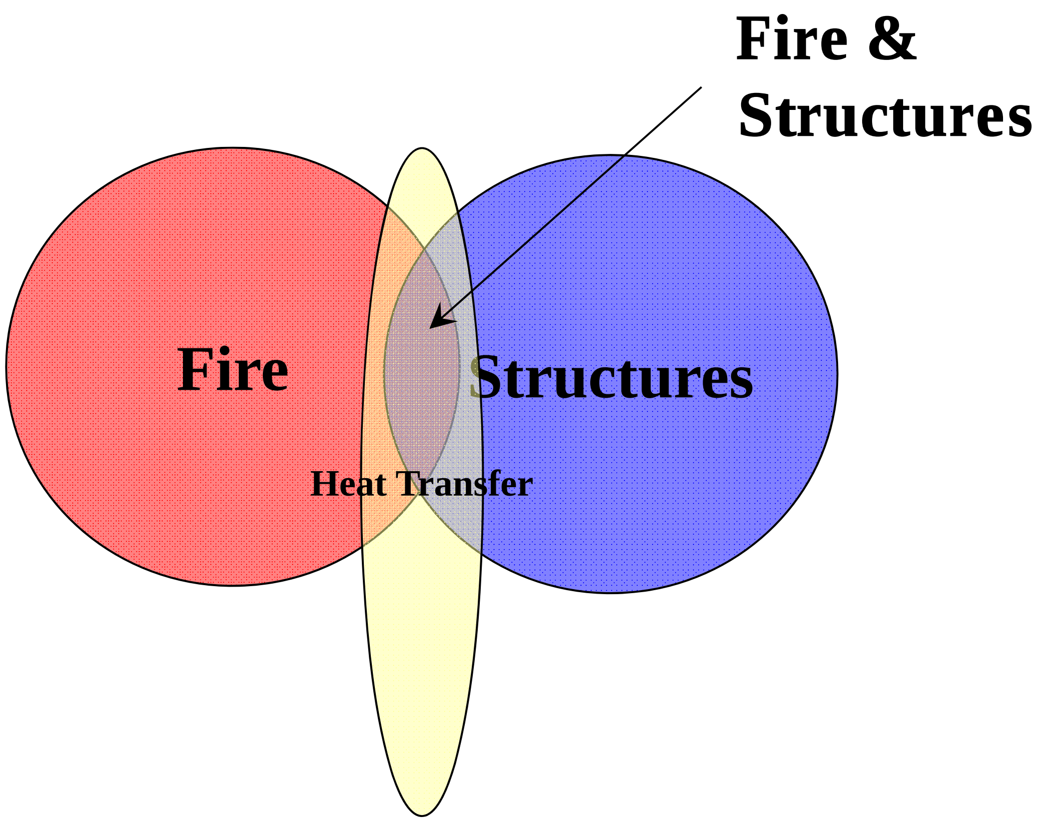


from Physical Parameters Affecting Fire Growth, Torero and Rein, CRCpress

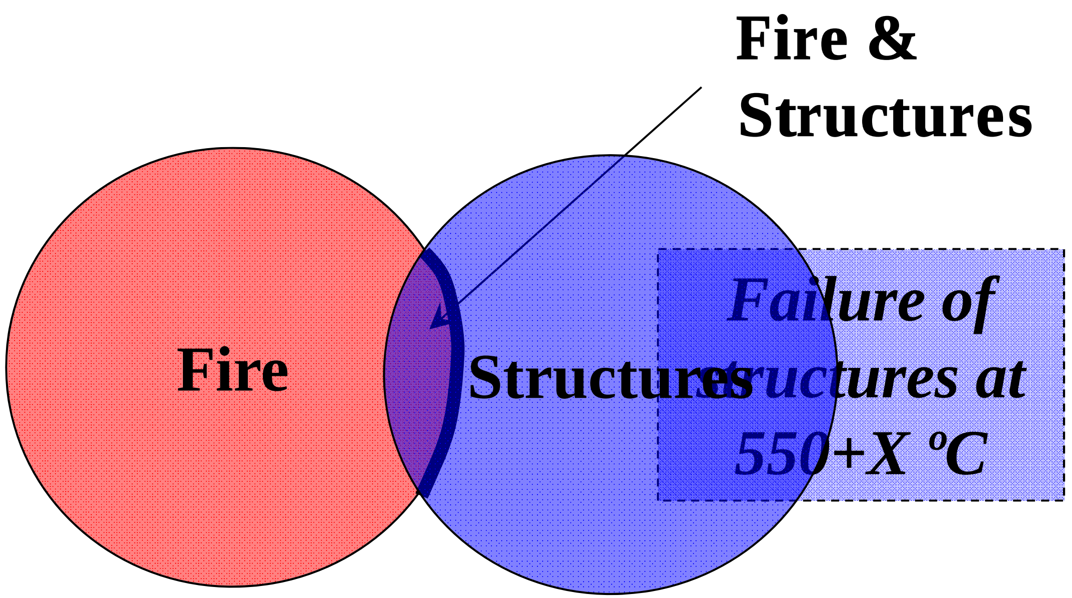
Boundary at 256s



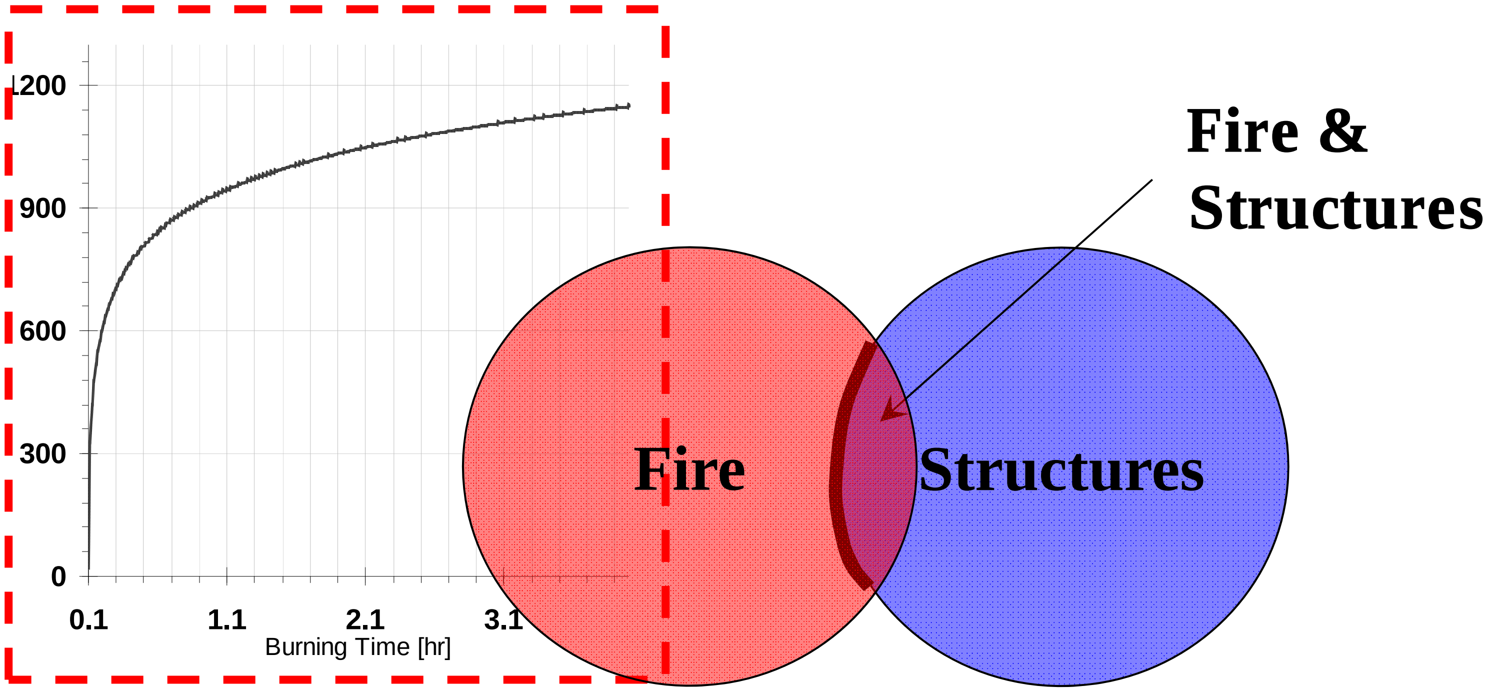
Discipline Boundaries



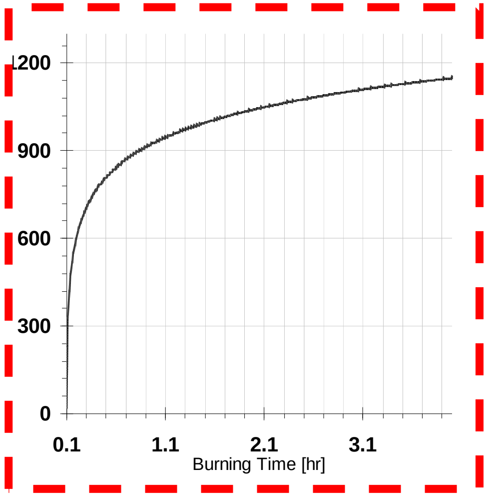
Lame Substitution of 1st kind

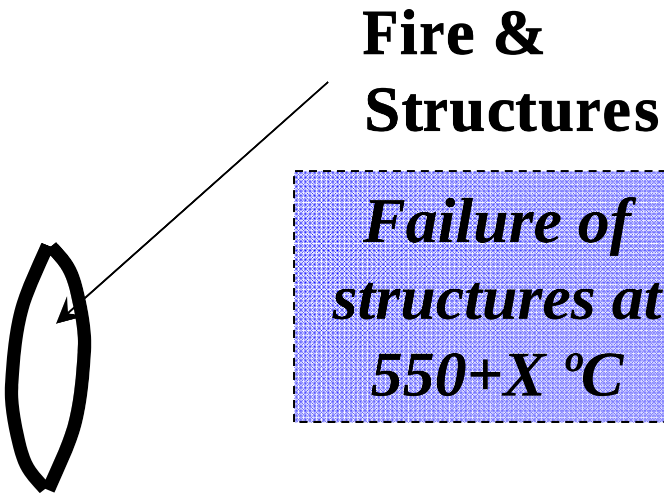


Lame Substitution of 2nd kind



Lame Substitution of 3rd kind





Failure of structures at 550+X ºC

Ignition – fuel exposed to heat

- Material start to decompose giving off gasses: pyrolysis

- Ignition takes place when a flammable mixture of fuel vapours is formed over the fuel surface

Before ignition

After 5 minutes

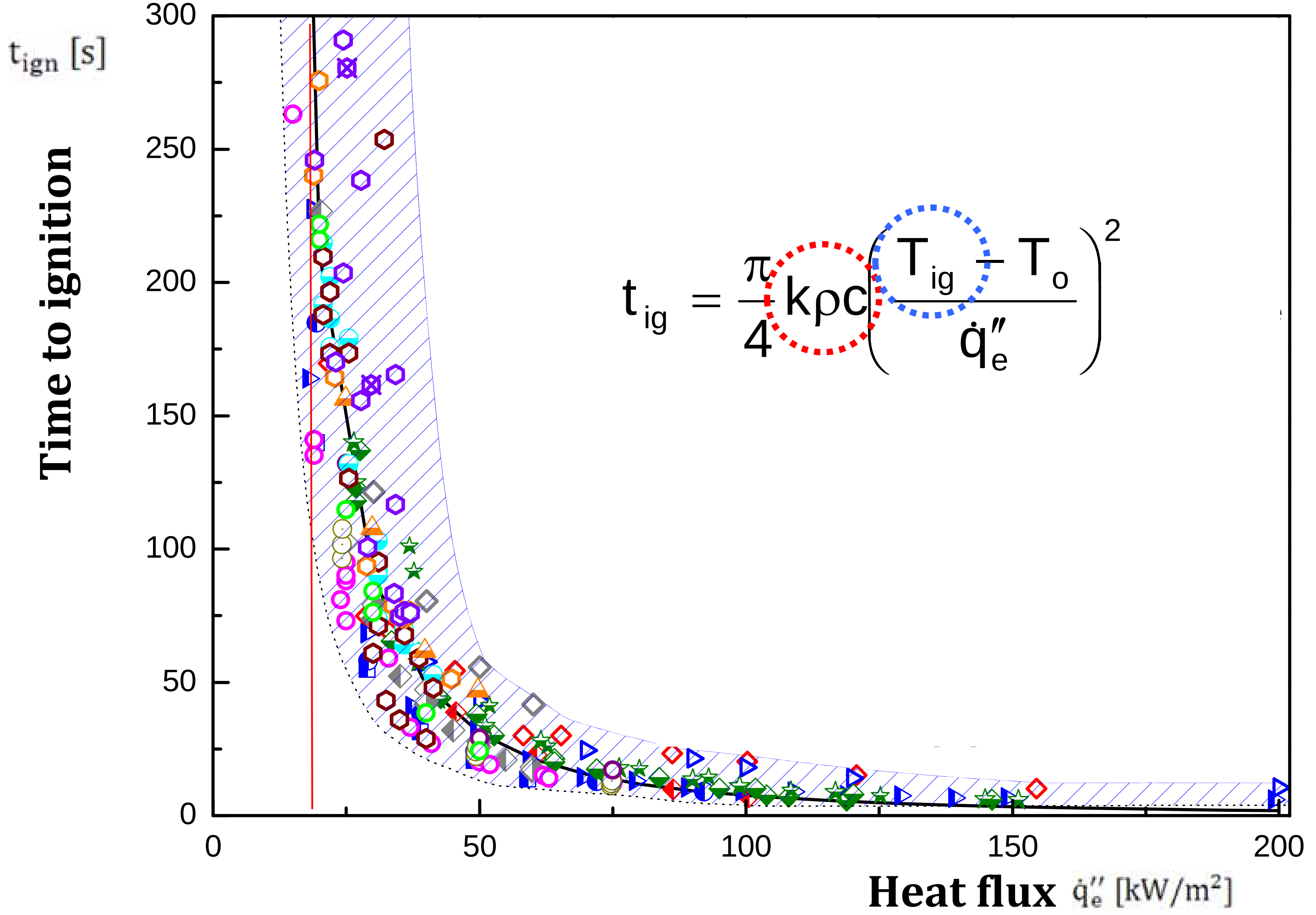
After 15 minutes

Pyrolysis video

Iris Chang and Frances Radford, 2011 MEng project

Time to ignition

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



Flammability

Ignition Data from ASTM E-1321 per Quintiere

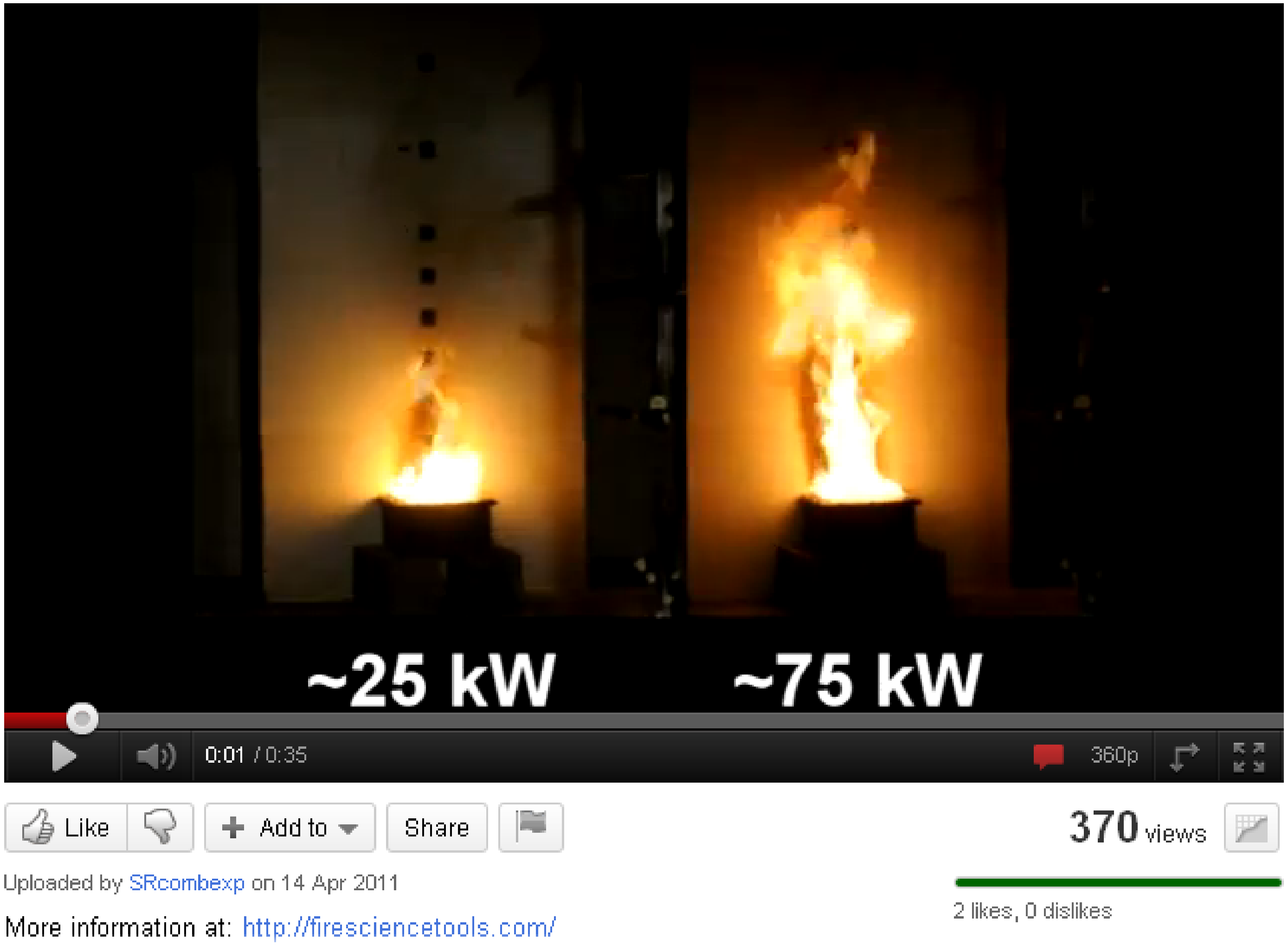
Material	T_{ig} [°C]	$k\rho C$ [$(kW/m^2\ K)^2\ s$]
Wood fiber board	355	0.46
Wood hardboard	365	0.88
Plywood	390	0.54
PMMA	380	1.00
Flexible foam plastic	390	0.32
Rigid foam plastic	435	0.03
Acrylic carpet	300	0.42
Wallpaper on plasterboard	412	0.57
Asphalt shingle	378	0.70
Glass-reinforced plastic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

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

Video from WPI (USA)

Effect of heat Release Rate on Flame height

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



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**

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

Firepower – 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
1.	Δh_c	Heat of combustion (kJ/kg-fuel) ~ constant
2.	$\dot{m}$	Burning rate (kg/s) - evolves with time
	$\dot{m}''$	Burning rate per unit area (m^2) ~ constant
3.	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

Heat of Combustion

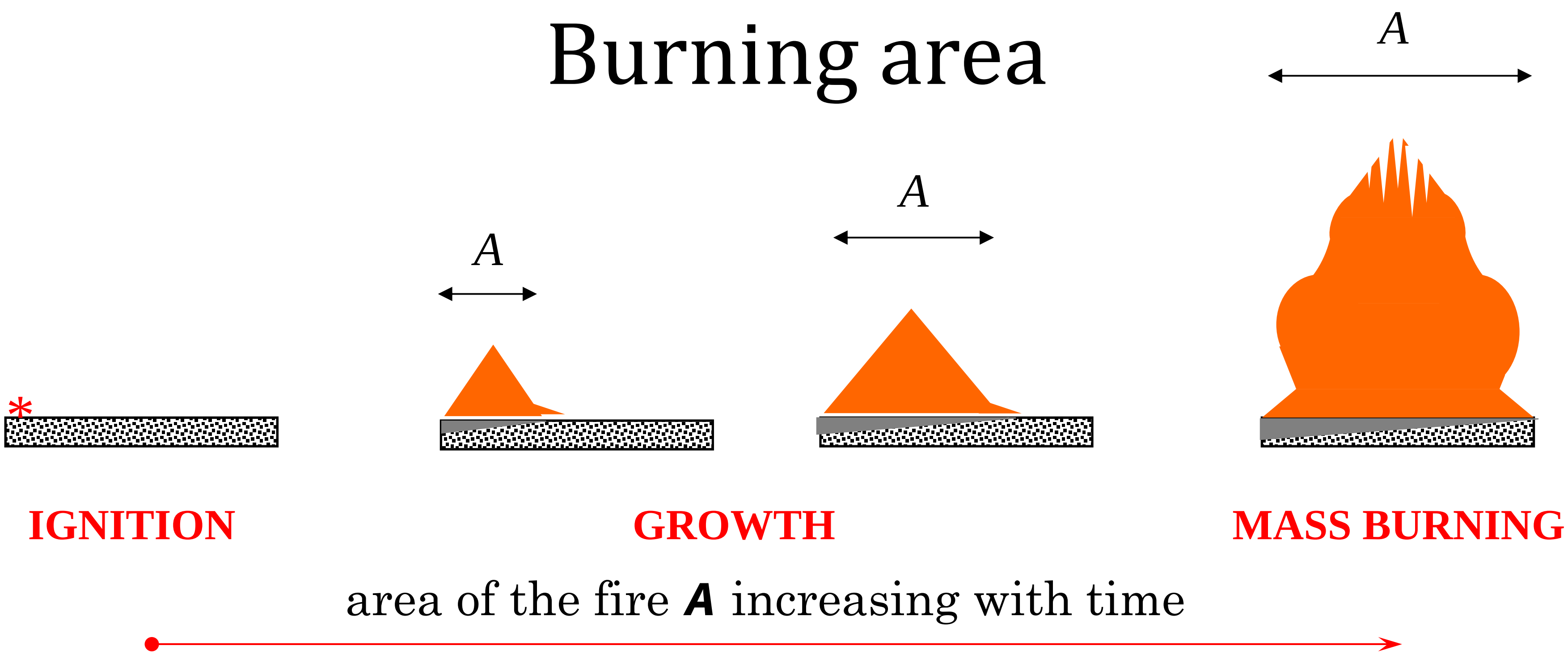
Table 1.13 Heats of combustion[a] of selected fuels at 25°C (298 K)

		$-\Delta H_c$ (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_2H_6	1423	47.45	2.96	11.21
Ethene	C_2H_4	1411	50.35	3.42	14.74
Ethyne	C_2H_2	1253	48.20	3.65	15.73
Propane	C_3H_8	2044	46.45	2.97	12.80
n-Butane	n-C_4H_{10}	2650	45.69	2.97	12.80
n-Pentane	n-C_5H_{12}	3259	45.27	2.97	12.80
n-Octane	n-C_8H_{18}	5104	44.77	2.97	12.80
c-Hexane	c-C_6H_{12}	3680	43.81	2.97	12.80
Benzene	C_6H_6	3120	40.00	3.03	13.06
Methanol	CH_3OH	635	19.83	3.07	13.22
Ethanol	C_2H_5OH	1232	26.78	2.99	12.88
Acetone	$(CH_3)_2CO$	1786	30.79	3.25	14.00
D-Glucose	$C_6H_{12}O_6$	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.

from **Introduction to fire Dynamics,** Drysdale, Wiley

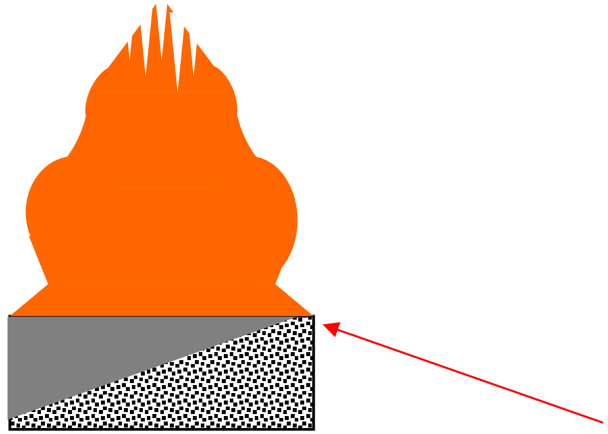
Burning area



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

Burn-out and travelling flames

a)



b)

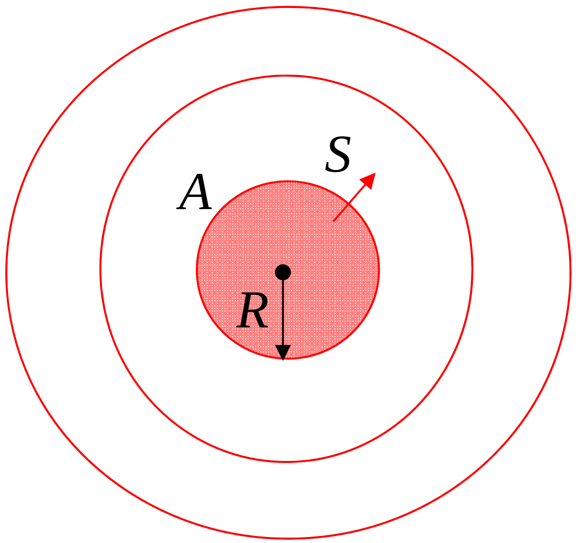
Flame Spread vs. Angle

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

- On a uniform layer of fuel ignited, spread is circular



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

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

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

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

~material properties

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

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

t-square growth fires

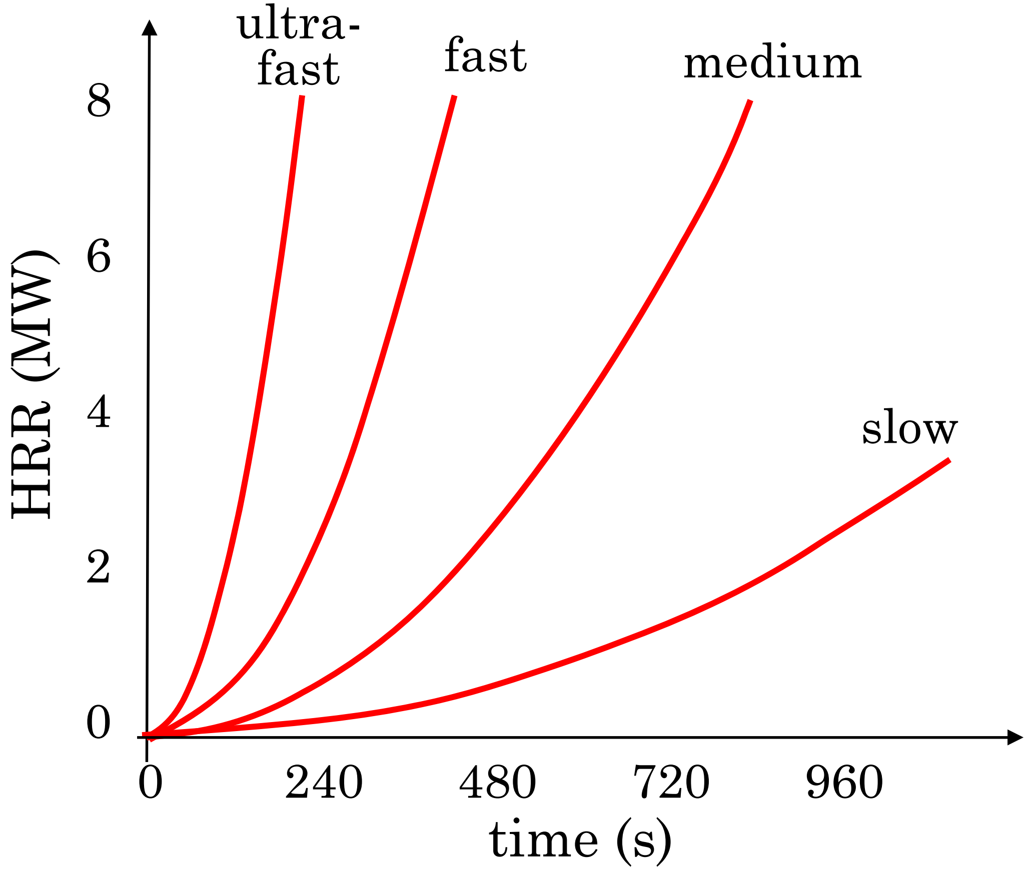
➢ Tabulated fire-growths of different fire types

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

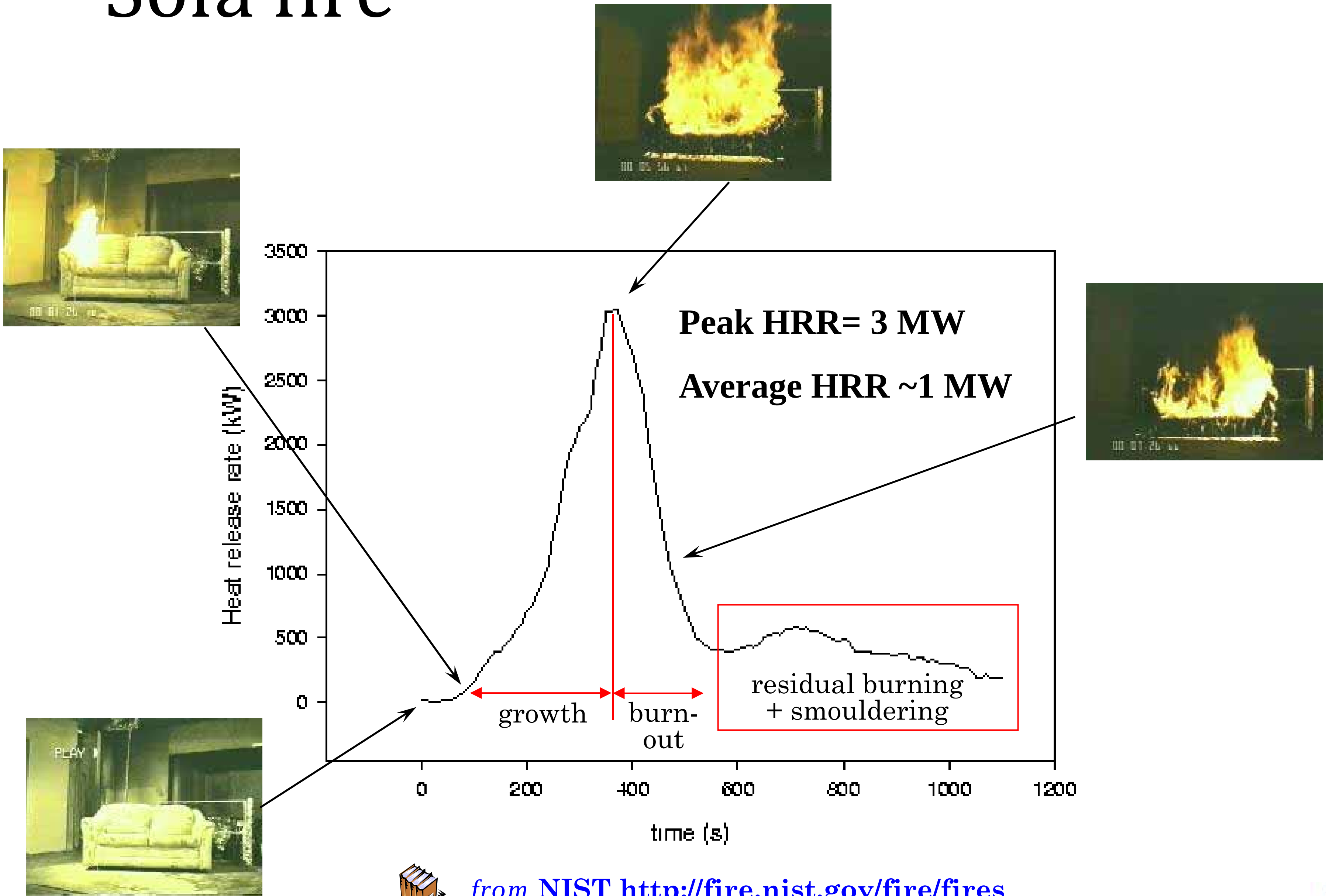
Table 9.6 Parameters used for '*t*-squared fires' (Evans, 1995)

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).



Sofa fire



from **NIST http://fire.nist.gov/fire/fires**

Fire Test at BRE commissioned by Arup 2009
4x4x2.4m – small premise in shopping mall

190s

bre
ARUP

285s

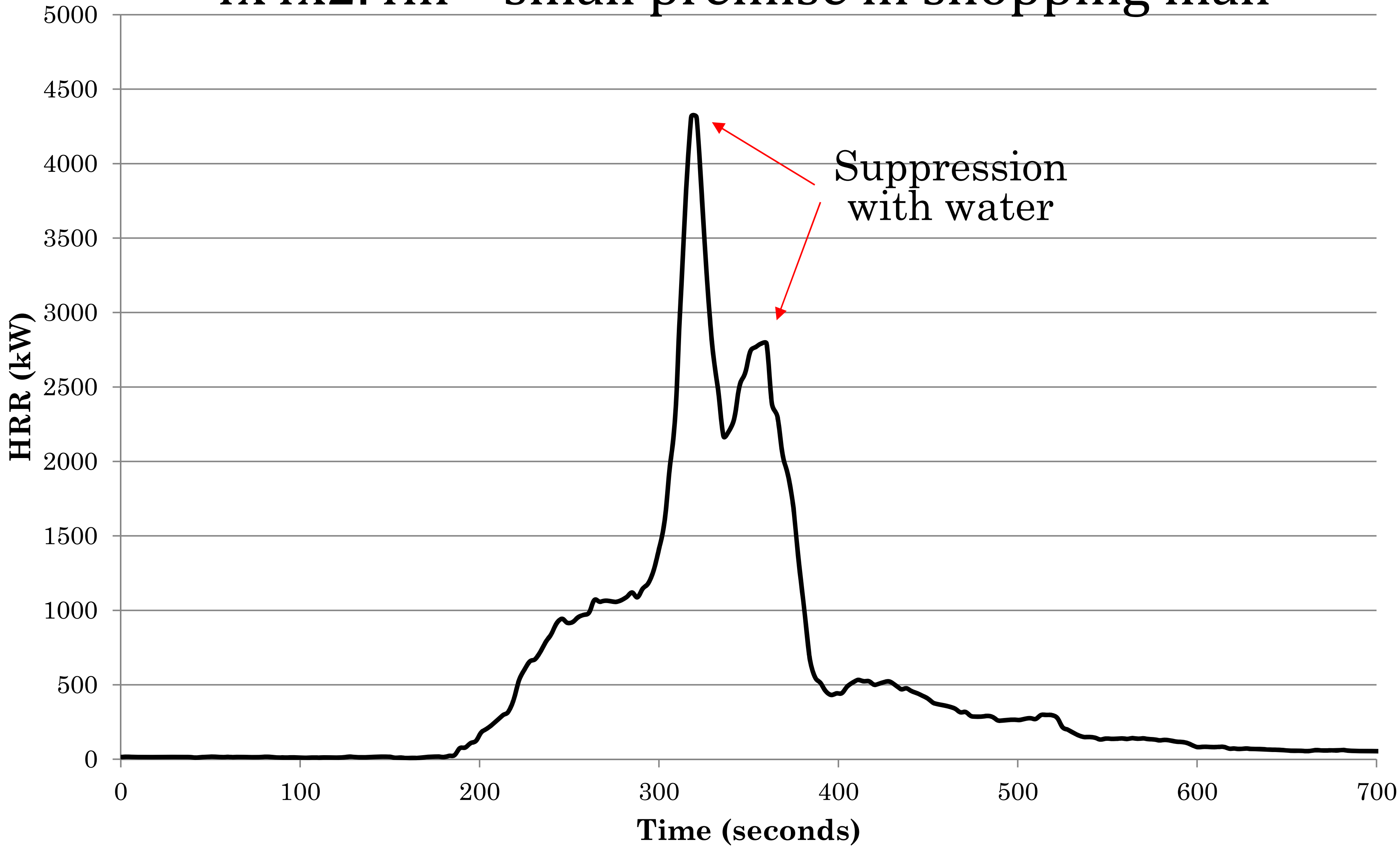
bre

ARUP

316s

bre
ARUP

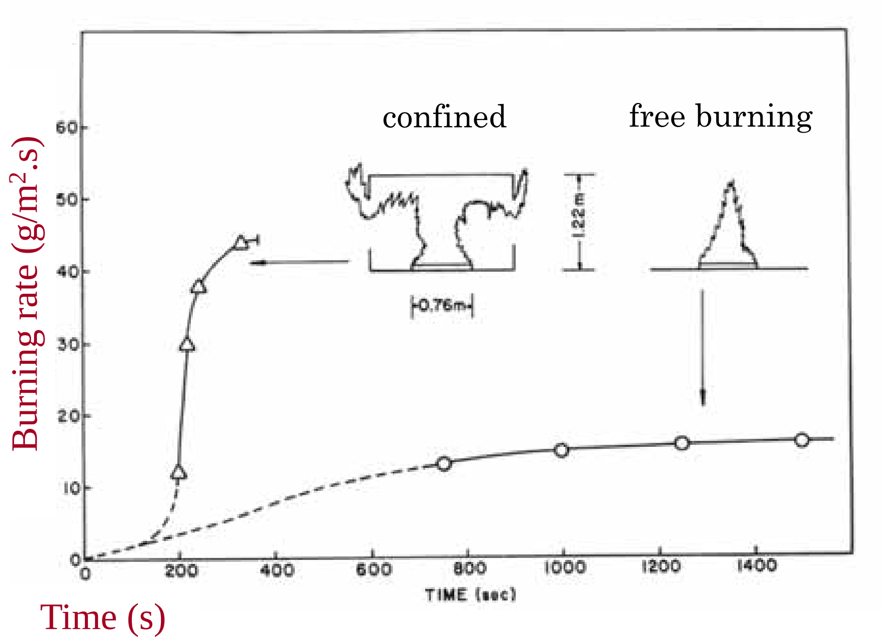
Fire Test at BRE commissioned by Arup 2009
4x4x2.4m – small premise in shopping mall



bre
ARUP

Free burning vs. Confined burning

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



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

Smoke and walls radiate downwards to fuel items in the compartments

Sudden and generalized ignition (*flashover*)

What is flashover?

Sudden period of very rapid growth caused by generalized ignition of fuel items in the room.

Some indicators:

- **Average smoke temperature of ~500-600 ˚C**
- **Heat flux ~20 kW/m^2 at floor level**
- **Flames out of openings** (ventilation controlled)

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

Flashover

Mechanism for flashover:

Fire produces a plume of **hot smoke**

Hot smoke layer **accumulates** under the ceiling

Hot smoke and heated surfaces **radiate downwards**

Flame spread rate and rate of secondary ignition increases

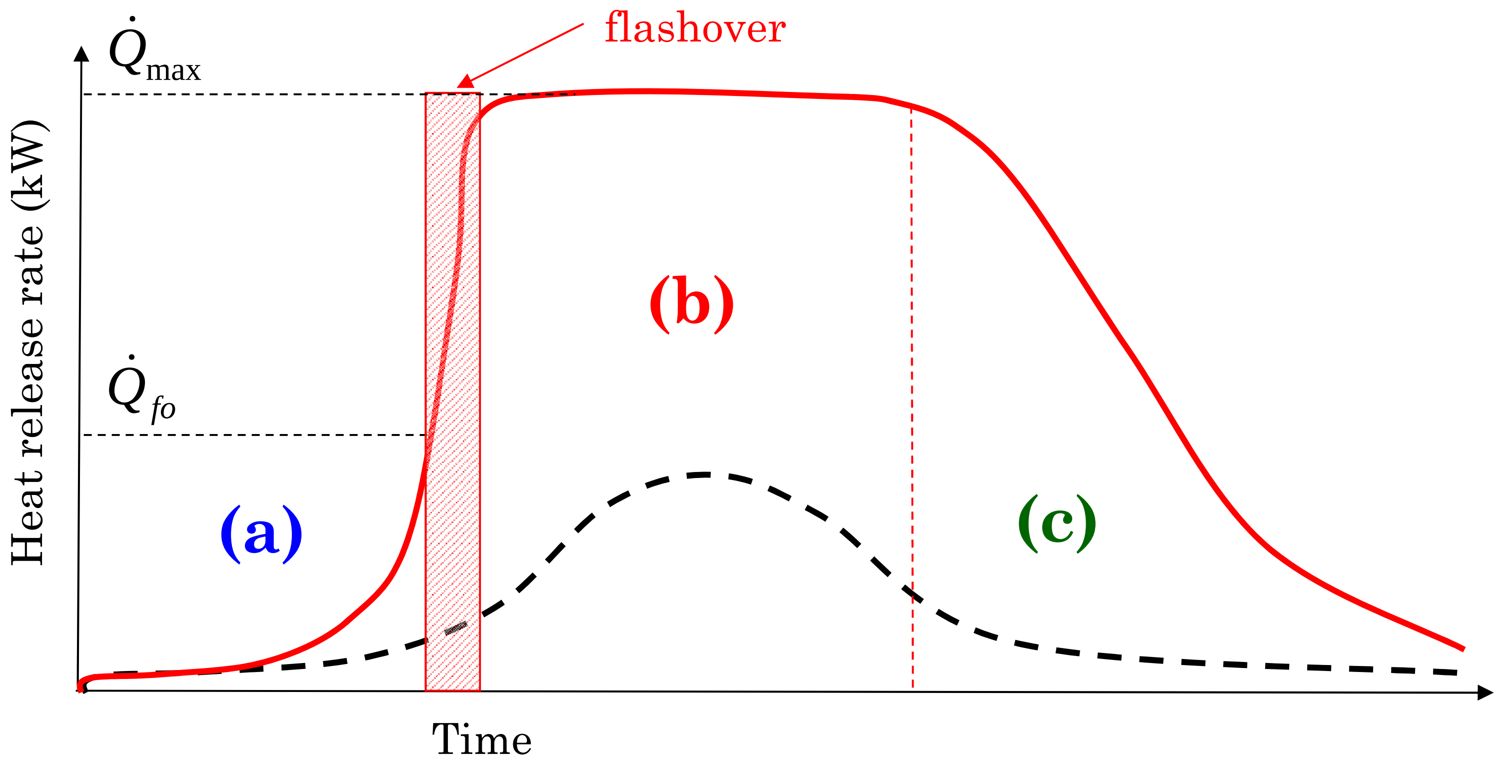
Rate of burning increases

Firepower larger and smoke hotter

Feedback loop

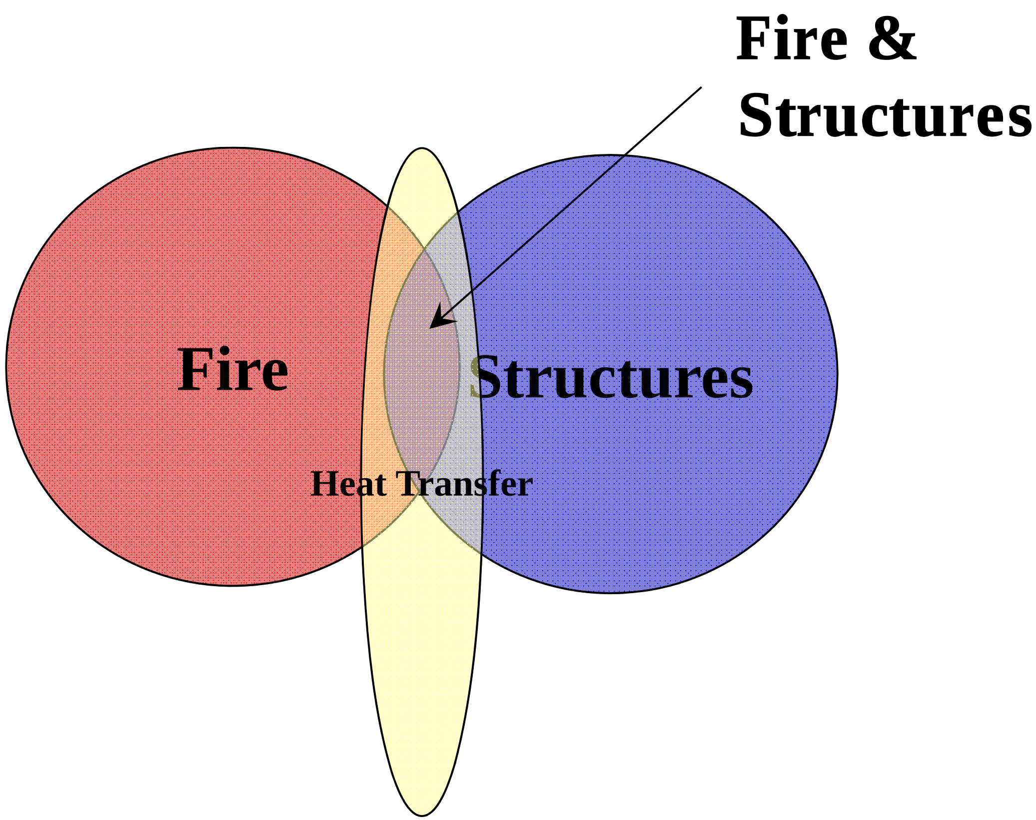
Compartment fires

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



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

Discipline Boundaries



GI $\Rightarrow$ GO

- **If the input is incomplete/flawed, the subsequent analysis is flawed and cannot be trusted for design**

- Fire is the input (boundary condition) to subsequent structures analysis

Design Fires

"The Titanic complied with all codes.

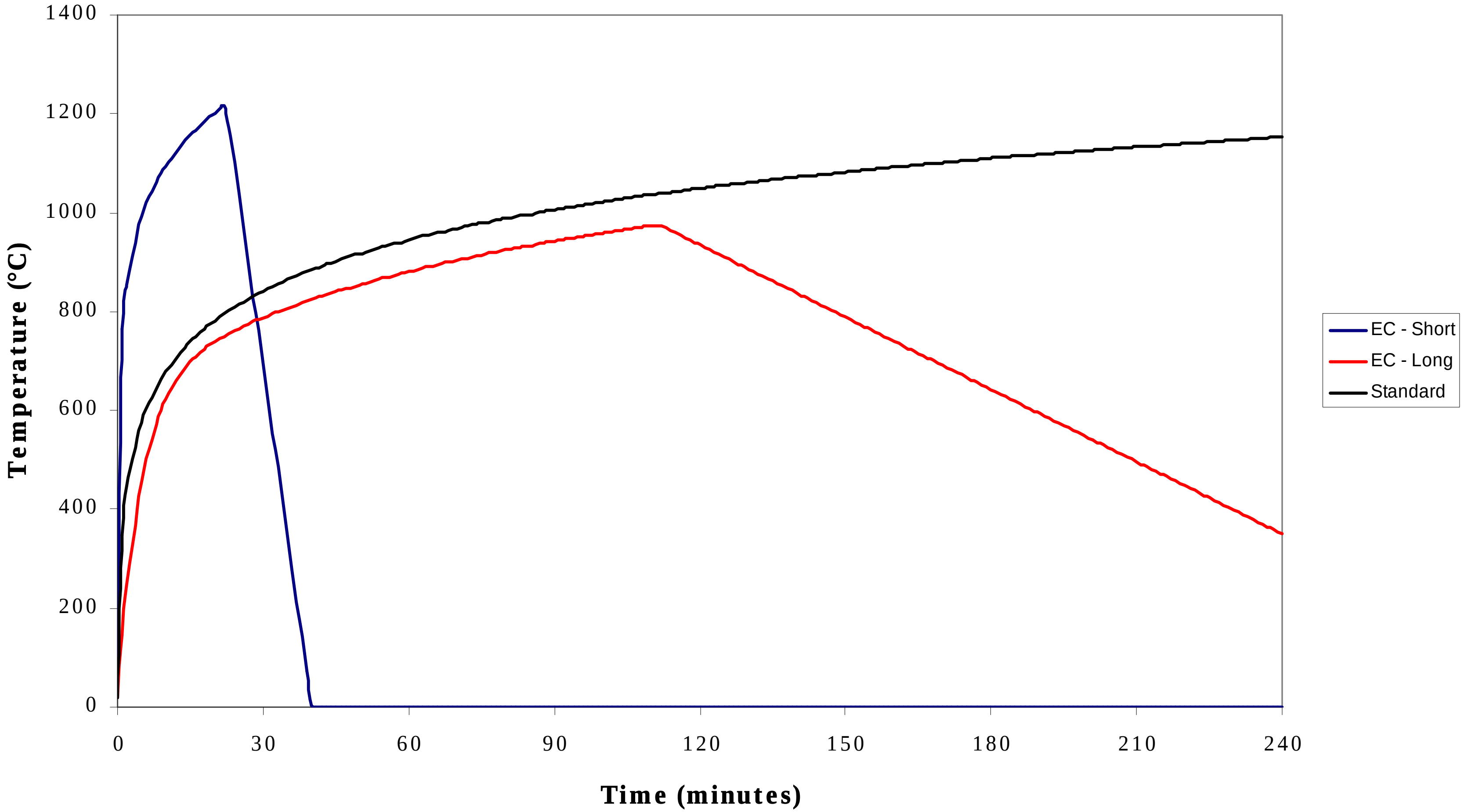
Lawyers can make any device legal,

only engineers can make them safe"

Prof VM Brannigan
University of Maryland

Traditional Design Fires

- Standard Fire ~1917
- Swedish Curves ~1972
- Eurocode Parametric Curve ~1995



Traditional Methods

- Traditional methods are based on experiments conducted in **small compartment** experiments (~3 m^3)

1. Traditional methods assume **uniform fires** that lead to uniform fire temperatures (?)

2. Traditional methods have been said to be **conservative** (?)

Stern-Gottfried et al, *Fire Risk Management* 2009

Limitations

For example, limitations according Eurocode:

⌘ Near **rectangular** enclosures

⌘ Floor areas **< 500 m^2**

⌘ Heights **< 4 m**

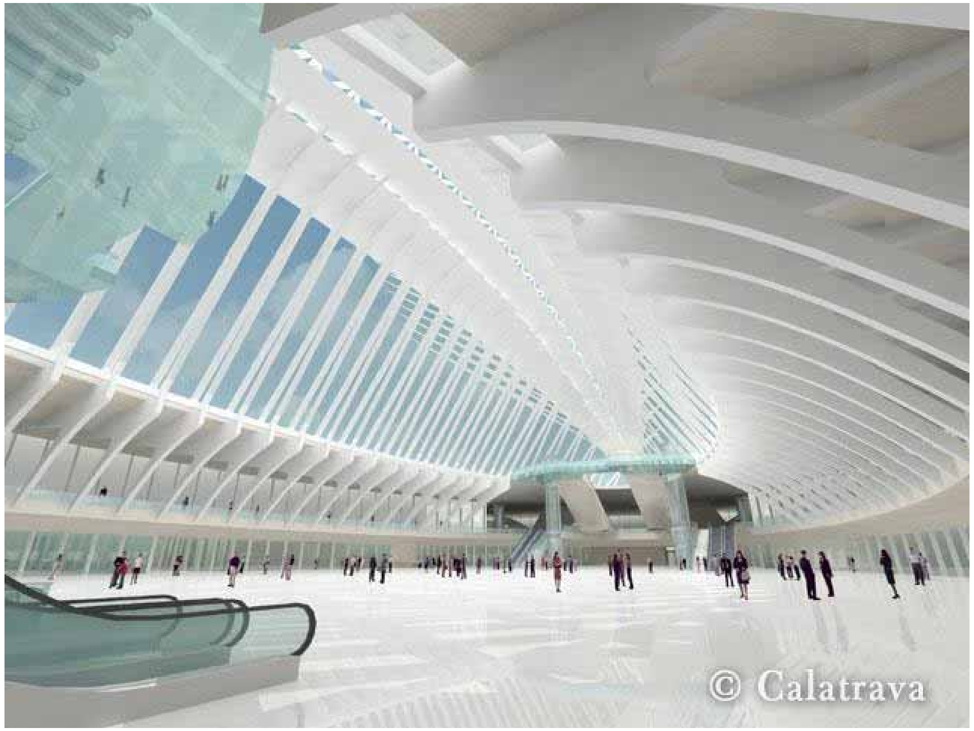
⌘ No ceilings **openings**

⌘ Only medium thermal-inertia **lining**

< 500 m2 floor?
<4 m high?

Excel, London

Rectangular?

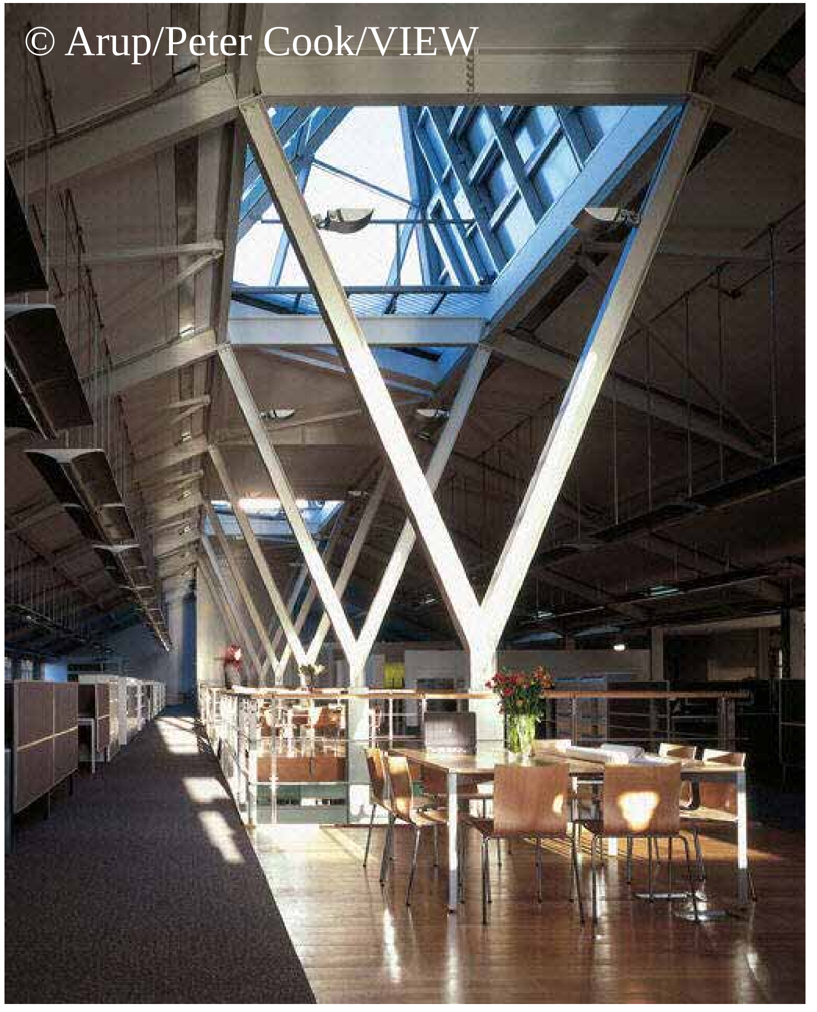


Proposed WTC Transit Hub

Insulating lining?

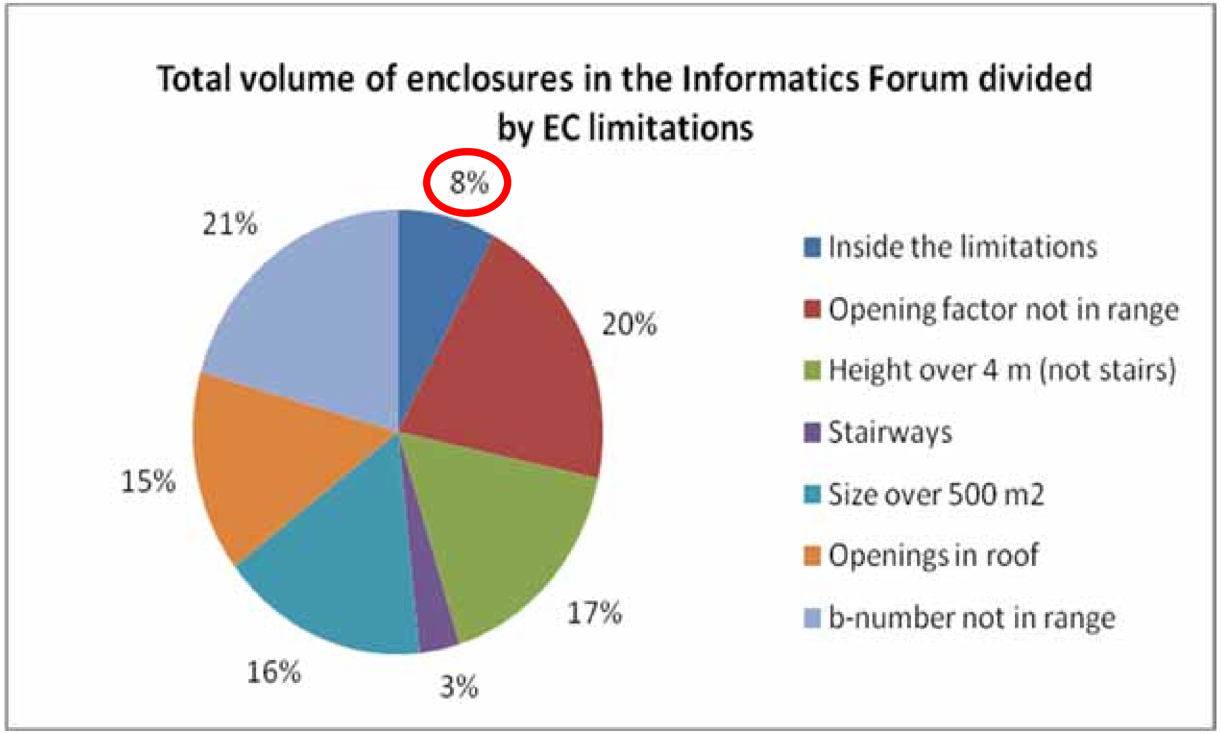
Shard

No ceiling opening?



Arup Campus

Edinburgh Survey 3,080 compartments



- 1850-1990 buildings: **66%** of volume within limitations
- 2008 building: **8%**

Modern architecture increasingly produces buildings out of range

Jonsdottir et al
Fire Risk Management 2009

Traditional Methods

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Stern-Gottfried et al, *Fire Risk Management* 2009

Fuel Load

- Mixed livingroom/office space
- Fuel load is ~ 32 kg/m^2
- Set-up Design for robustness and high repeatability

Compartment Temperature

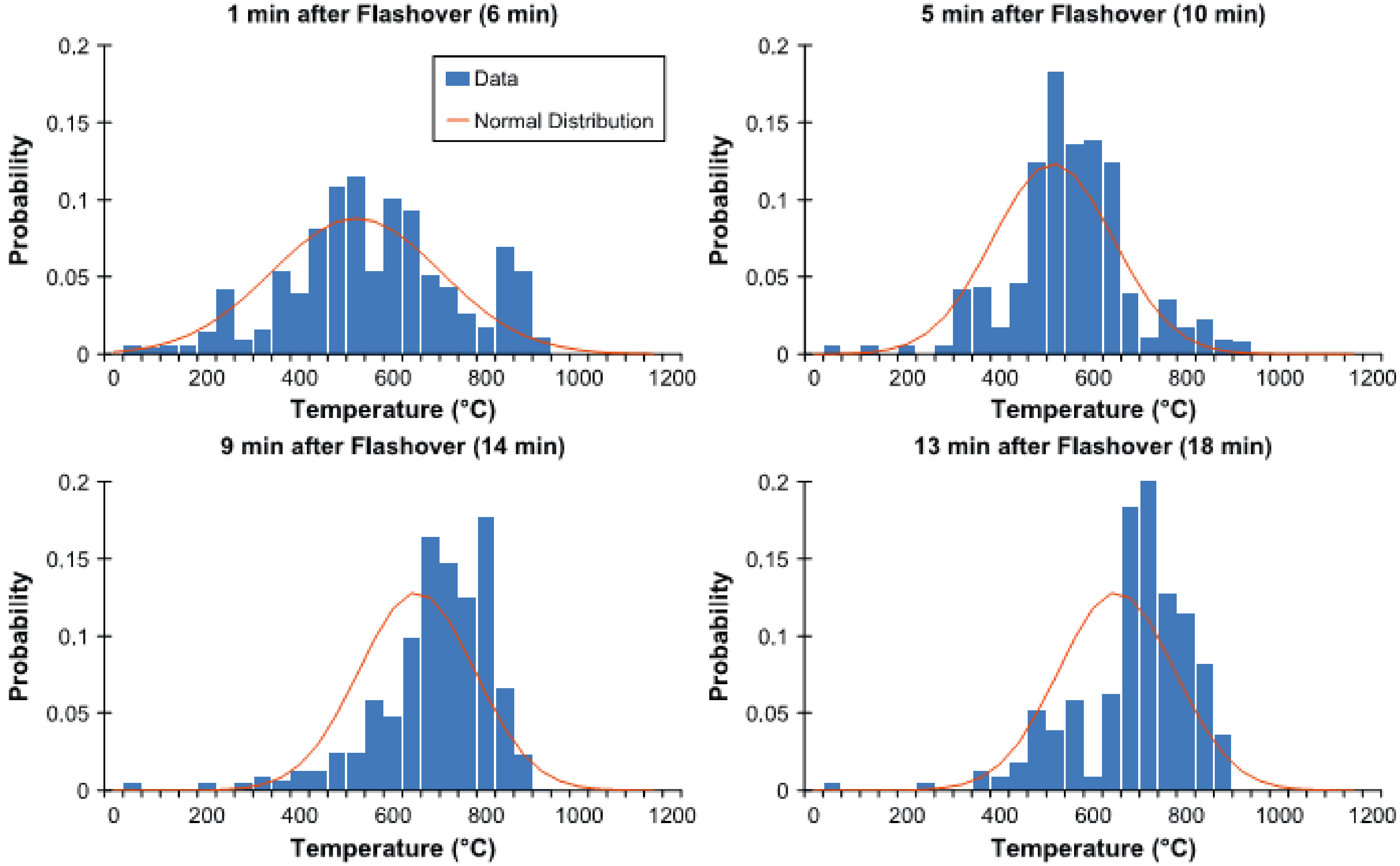
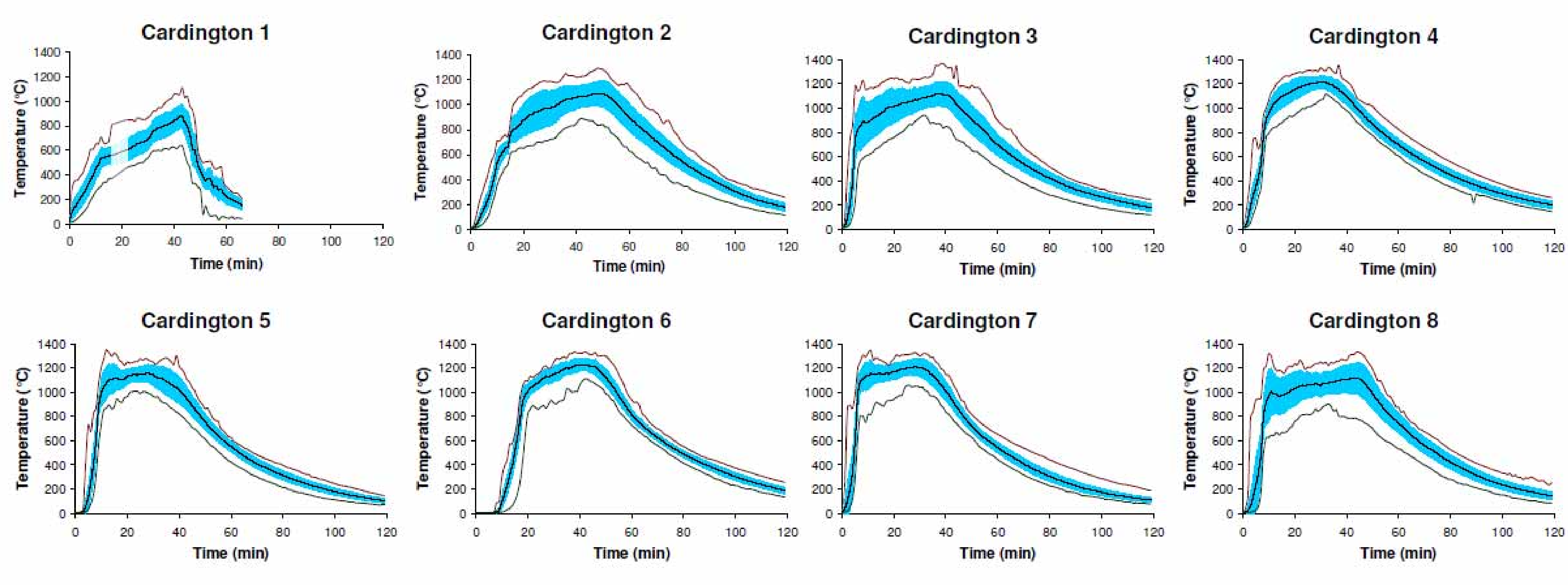


Fig. 6. Comparisons of the measured temperature distributions against the associated normal distributions at 4 min intervals after flashover for Dalmarnock Test One.

Stern-Gottfried et al., Fire Safety Journal 45, pp. 249–261, 2010. doi:10.1016/j.firesaf.2010.03.007

Cardington Results



Temperature Distributions

Test	Min σ (°C)	Mean σ (°C)	Max σ (°C)	Max T_{avg} (°C)
Dalmarnock Test One	105	132	233	733
Cardington 1	38	84	136	857
Cardington 2	31	83	153	1075
Cardington 3	31	100	208	1103
Cardington 4	31	52	93	1199
Cardington 5	18	56	135	1147
Cardington 6	25	44	129	1218
Cardington 7	20	51	159	1200
Cardington 8	32	83	213	1107
Standard Fire Tests	8	12	39	N/A

- **Peak local temperatures range from 23% to 75% above compartment average, with a mean of 38%**
- **Local minimum temperatures range from 29% to 99% below compartment average, with a mean of 49%**

Travelling Fires

- Real fires have been observed to travel
  - ⌘ WTC Towers 2001
  - ⌘ Torre Windsor 2005
  - ⌘ Delft Faculty 2008

- Experimental data indicate fires travel in large compartments

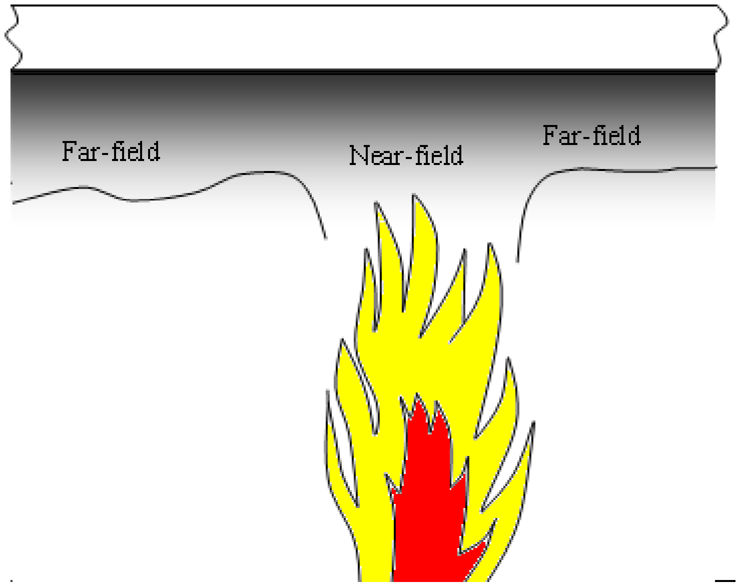
- In larger compartments, the fire does not burn uniformly but burns locally and spreads

Design Fires

"Problems cannot be solved by the level of awareness that created them"

Attributed to A Einstein

Travelling Fires

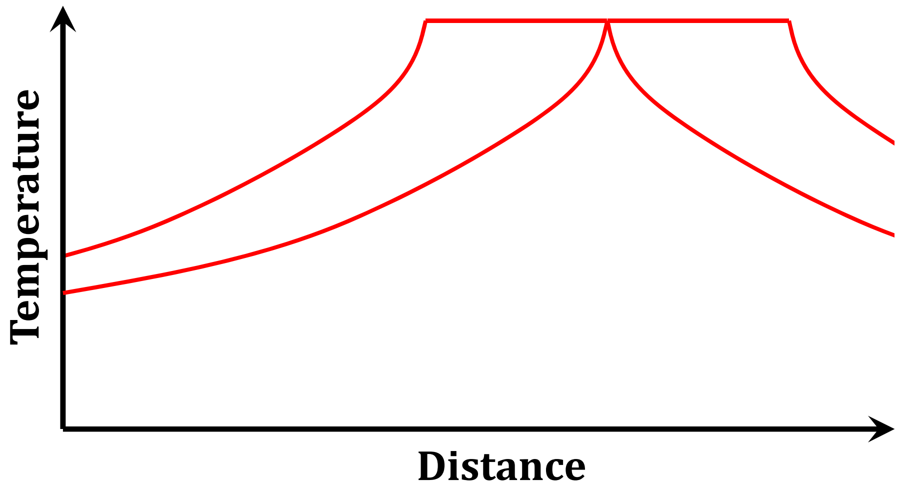


Fire environment split into two:

Near-field ≈ 1000-1200 ºC

Far-field ≈ 200-1200 ºC

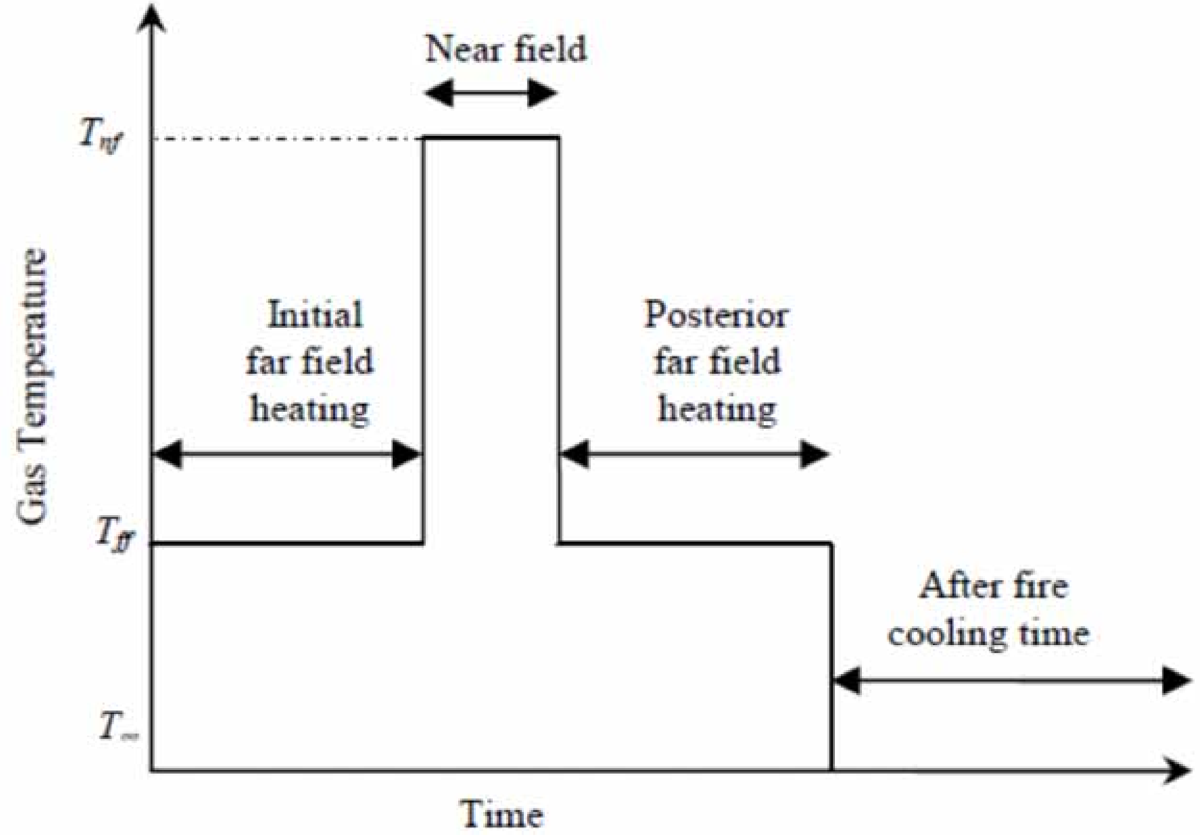
(Alper's correlation)



Total burning duration is a function of the area of the fire

Travelling Fires

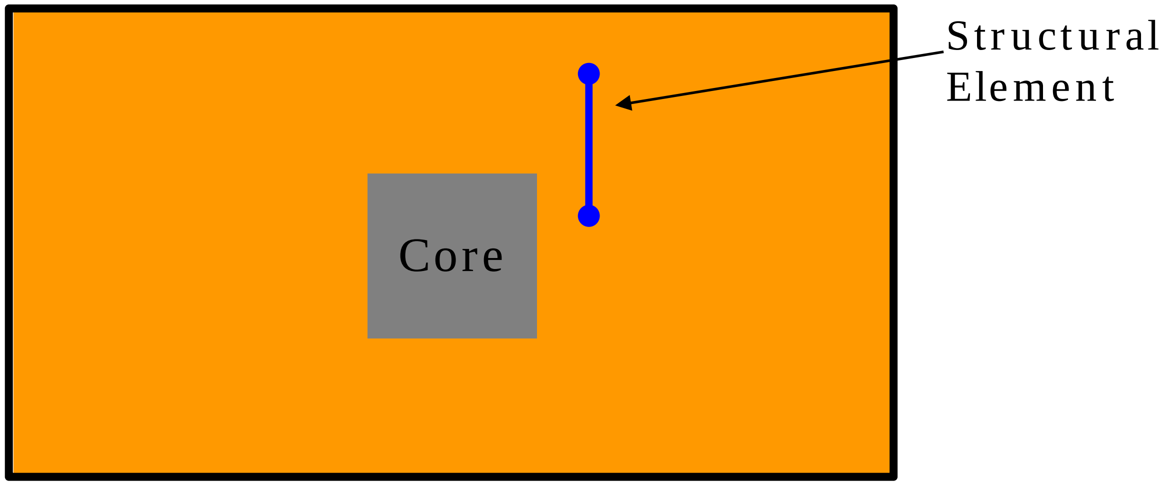
- Each structural element sees a combination of Near Field and Far Field temperatures as the fire travels

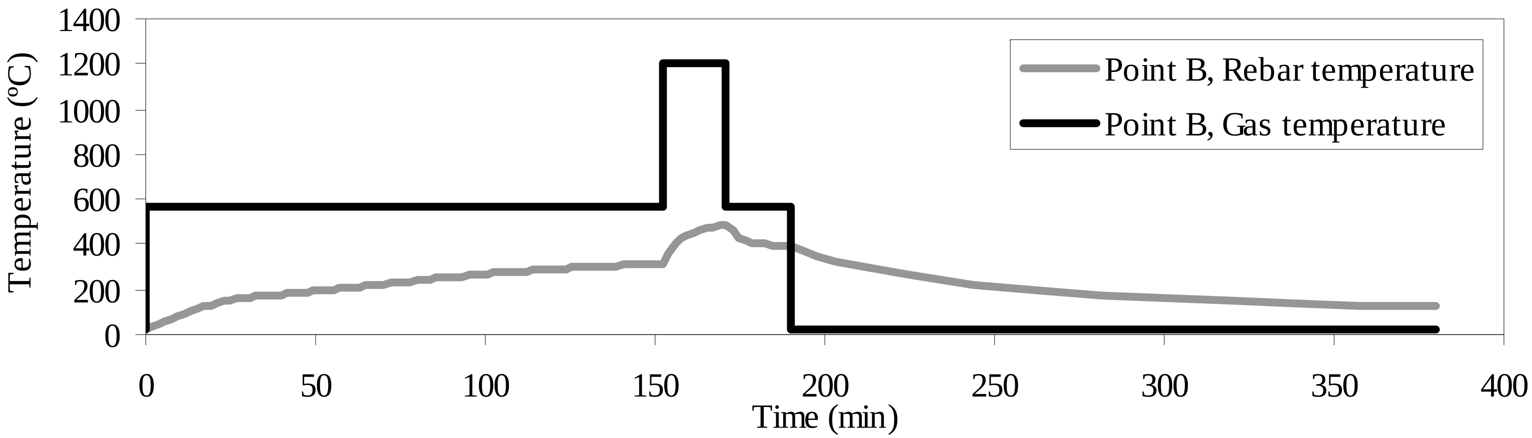


Stern-Gottfried et al, SPFE PBD, 2010, Lund

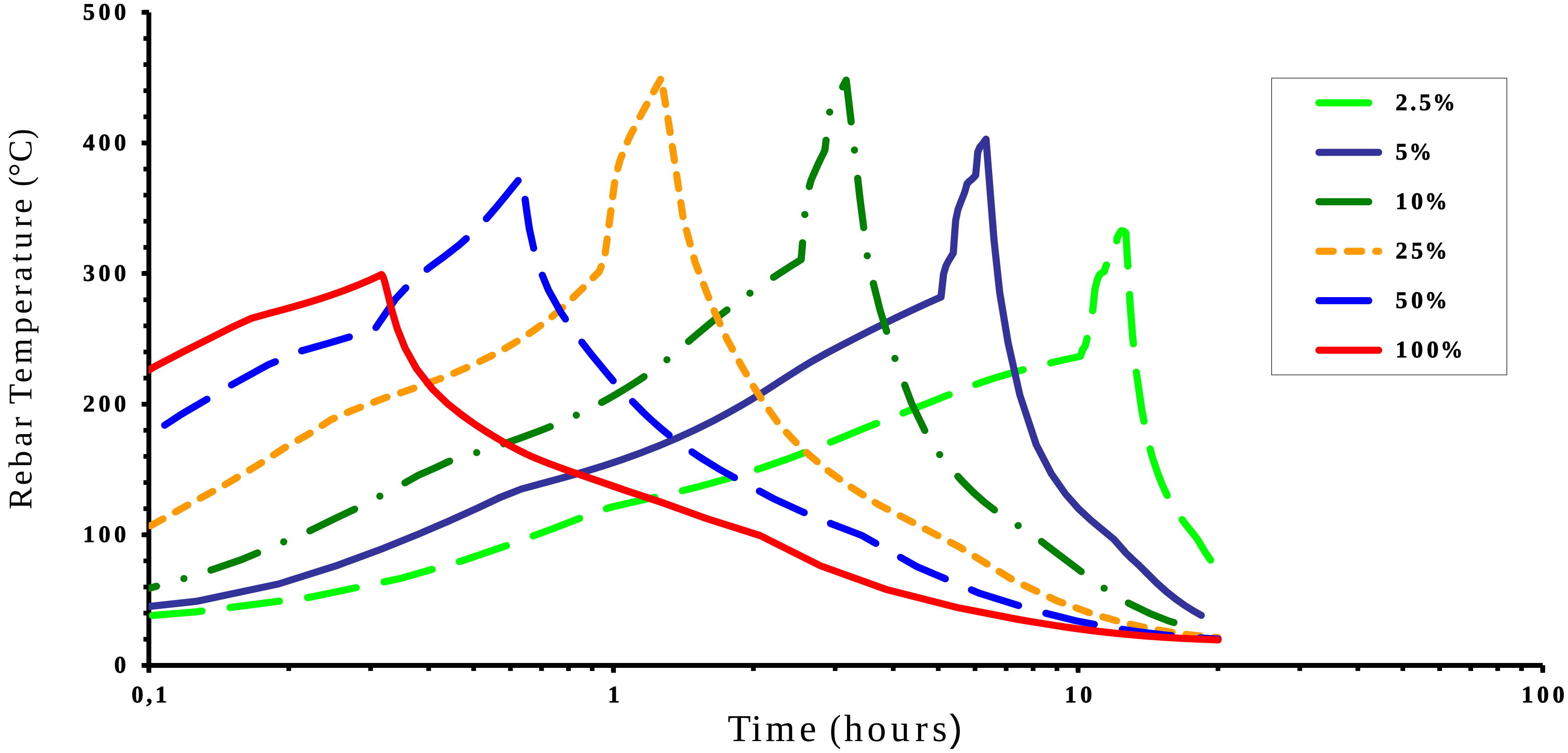
Example – 25% Floor Area fire in a 1000 m^2

- Near field temperature 1200°C for 19 min
- Far field temperature ~ 800°C for 76 min

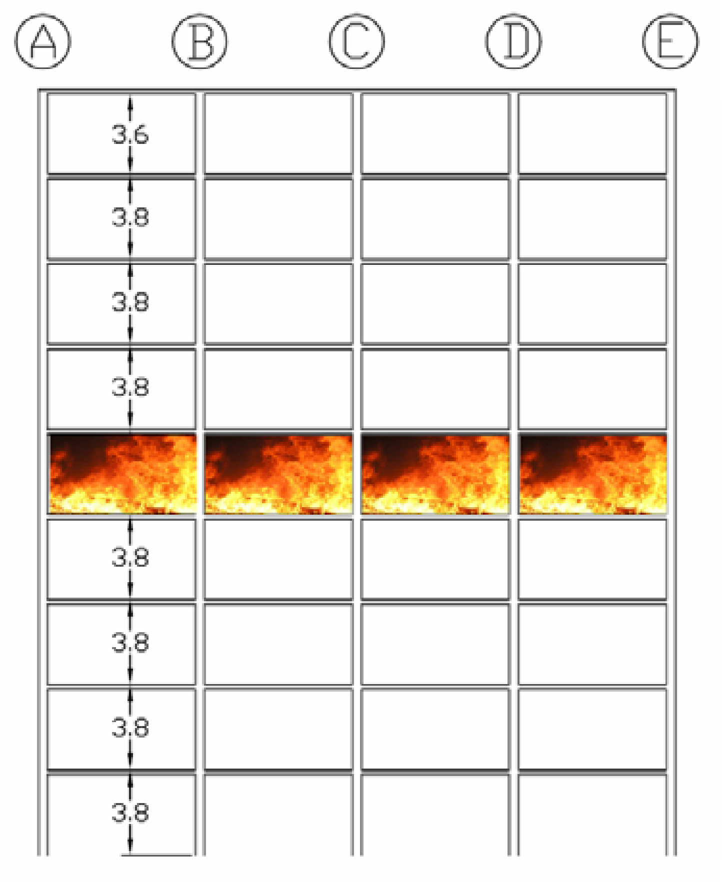


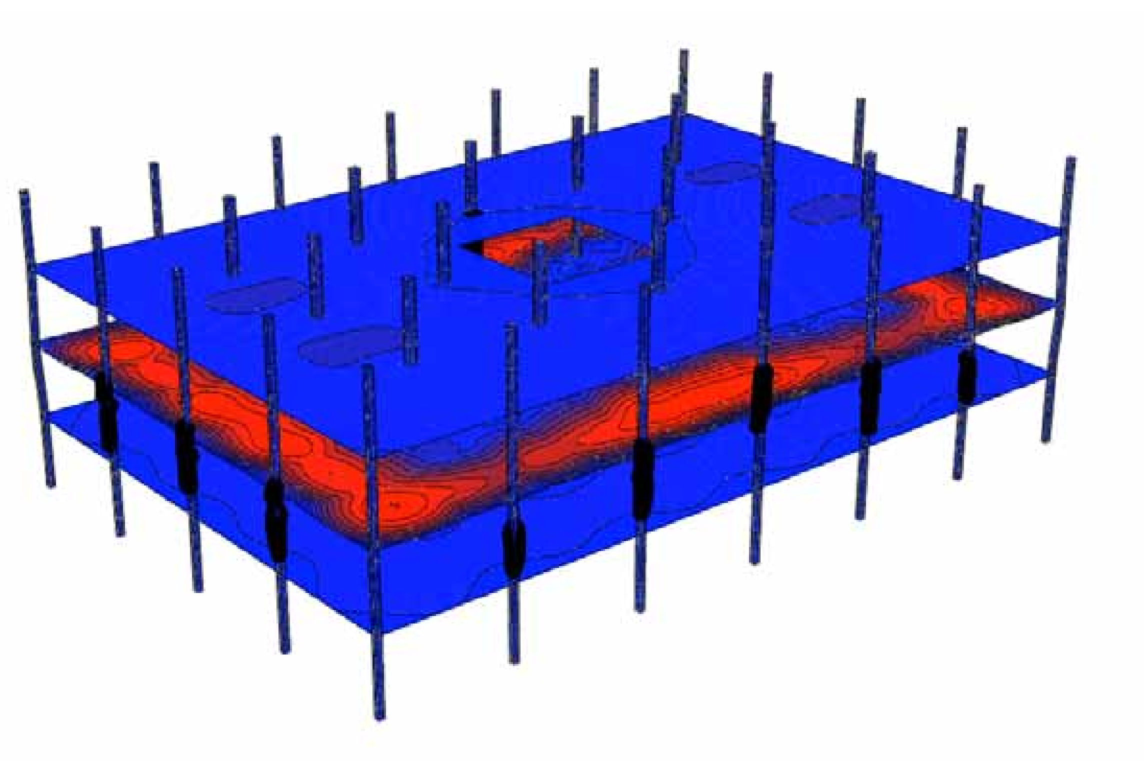


Structural Results – Rebar Temperature



Case Study:
Generic Multi-Storey Concrete Structure



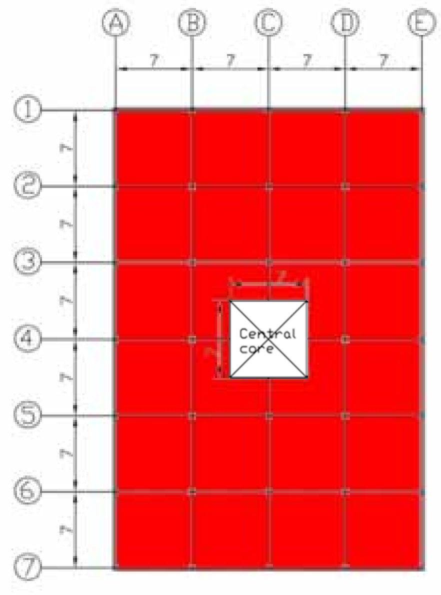


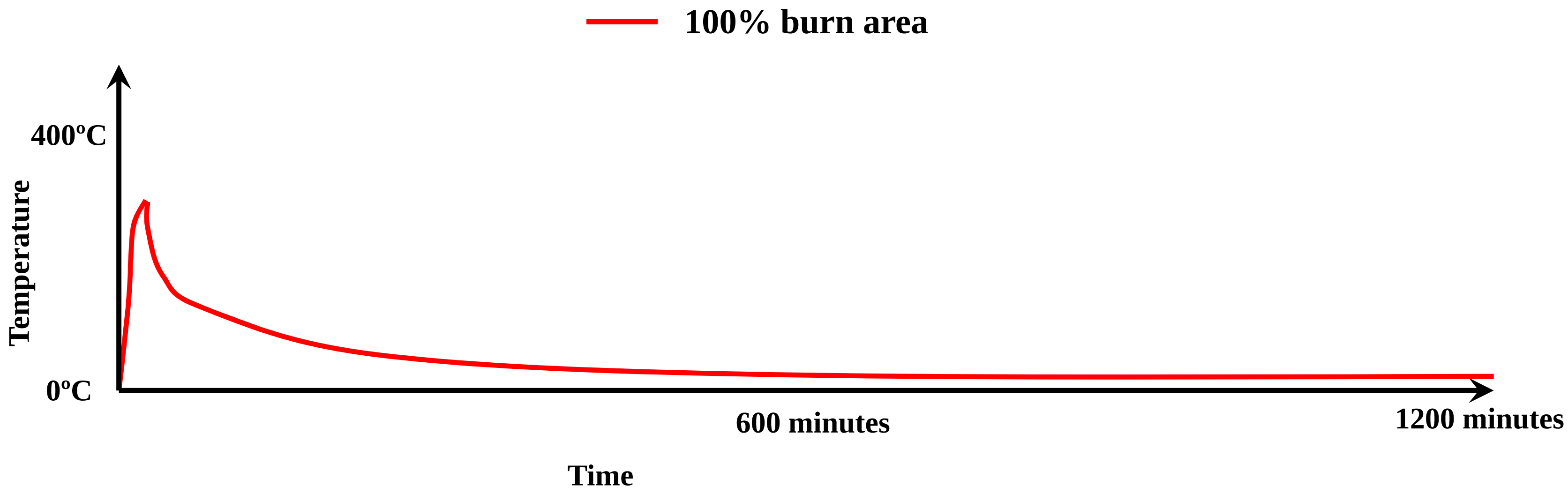
Stern-Gottfried et al, SPFE PBD, 2010, Lund

Law et al, *Engineering Structures* 2011

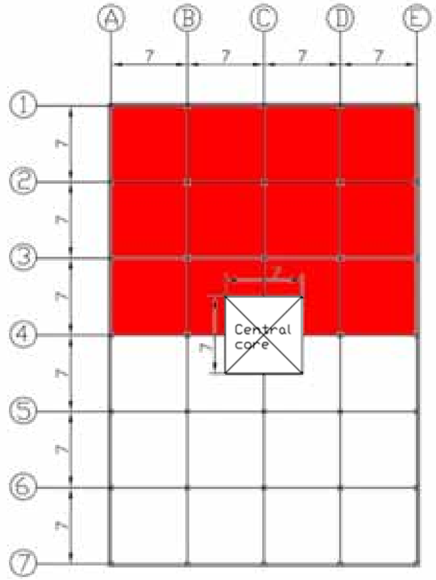
Rebar Temperature

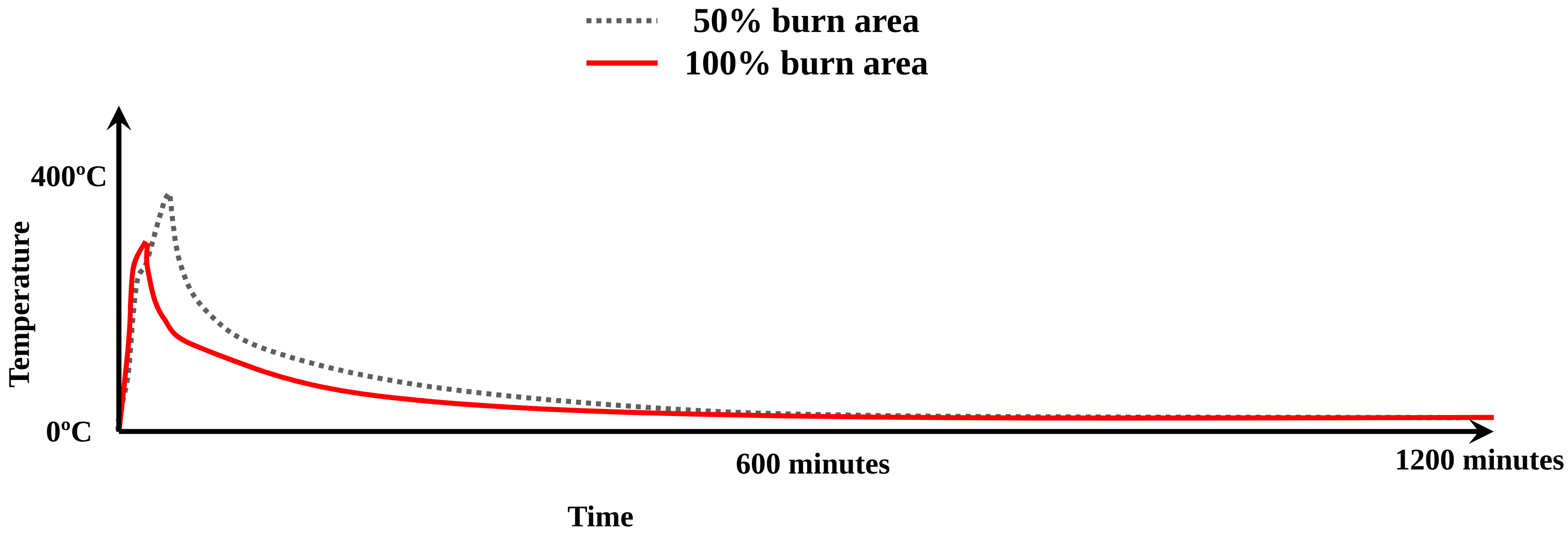
- Using a 3D Finite Element Model



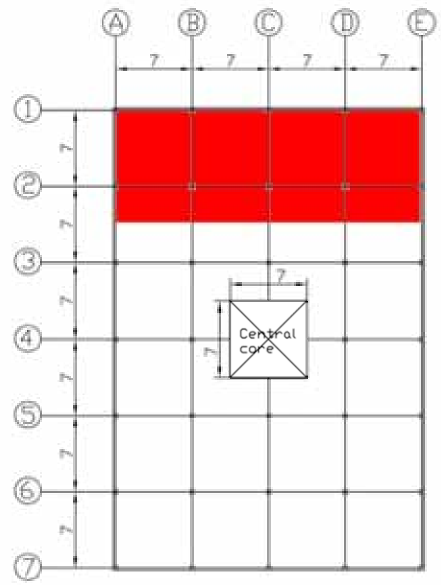


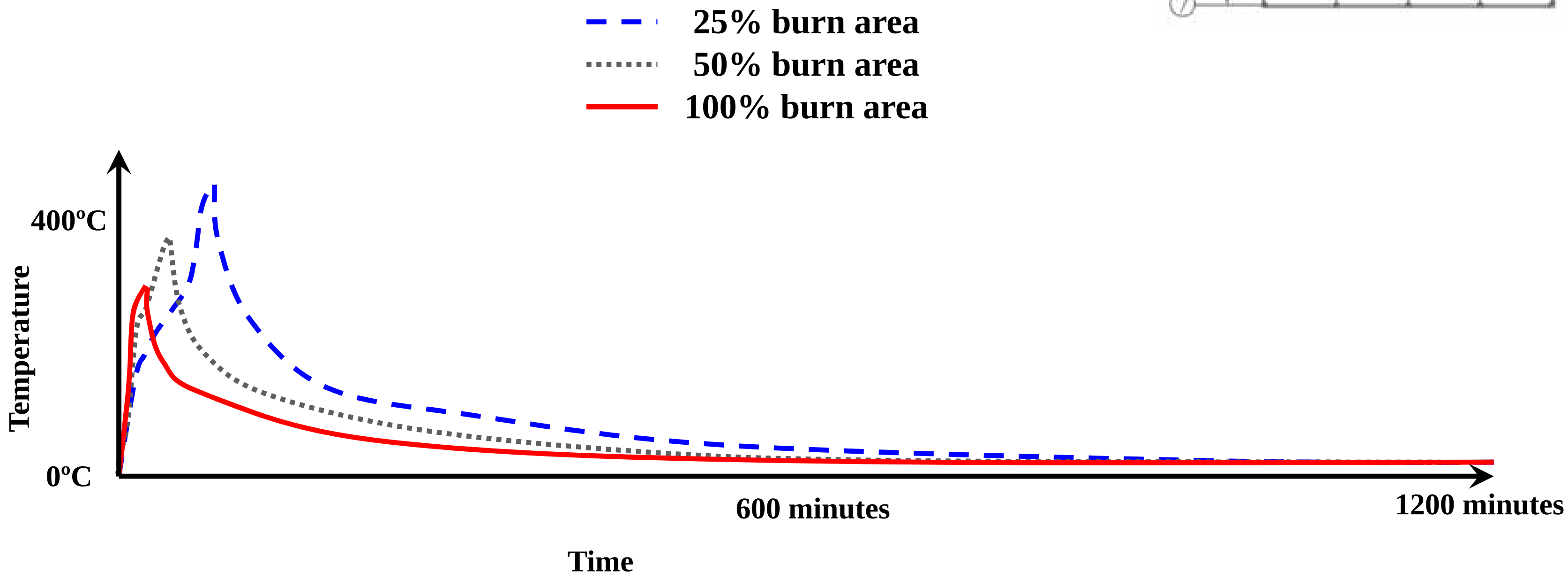
Rebar Temperature



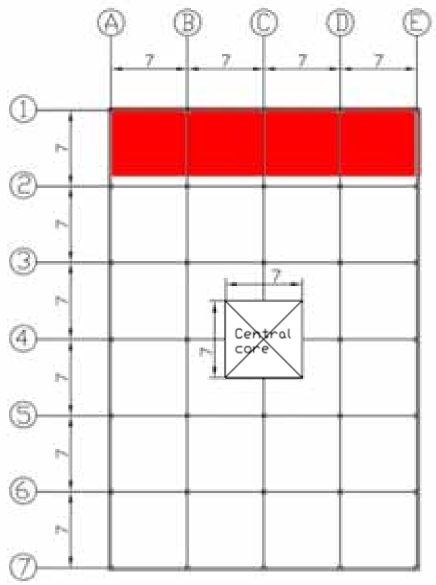


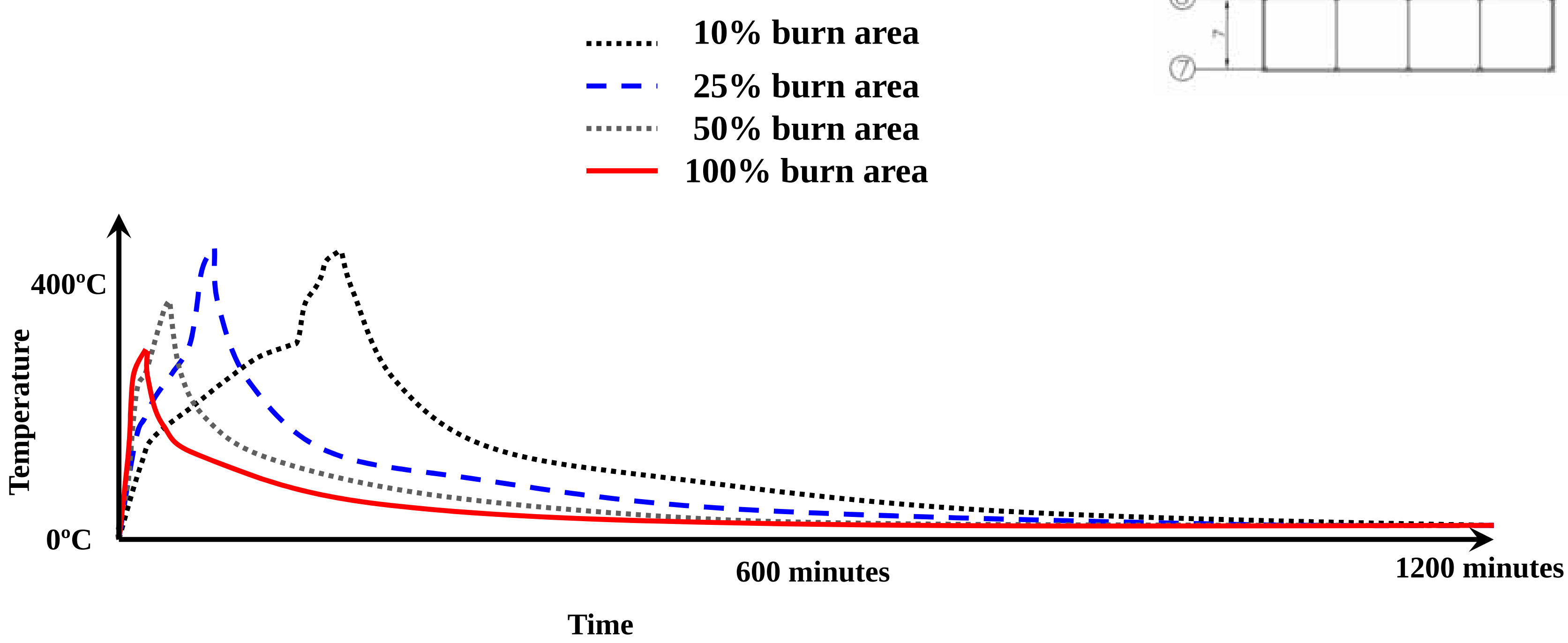
Rebar Temperature



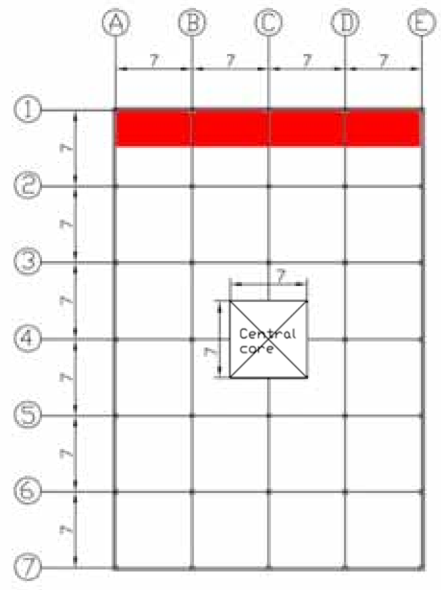


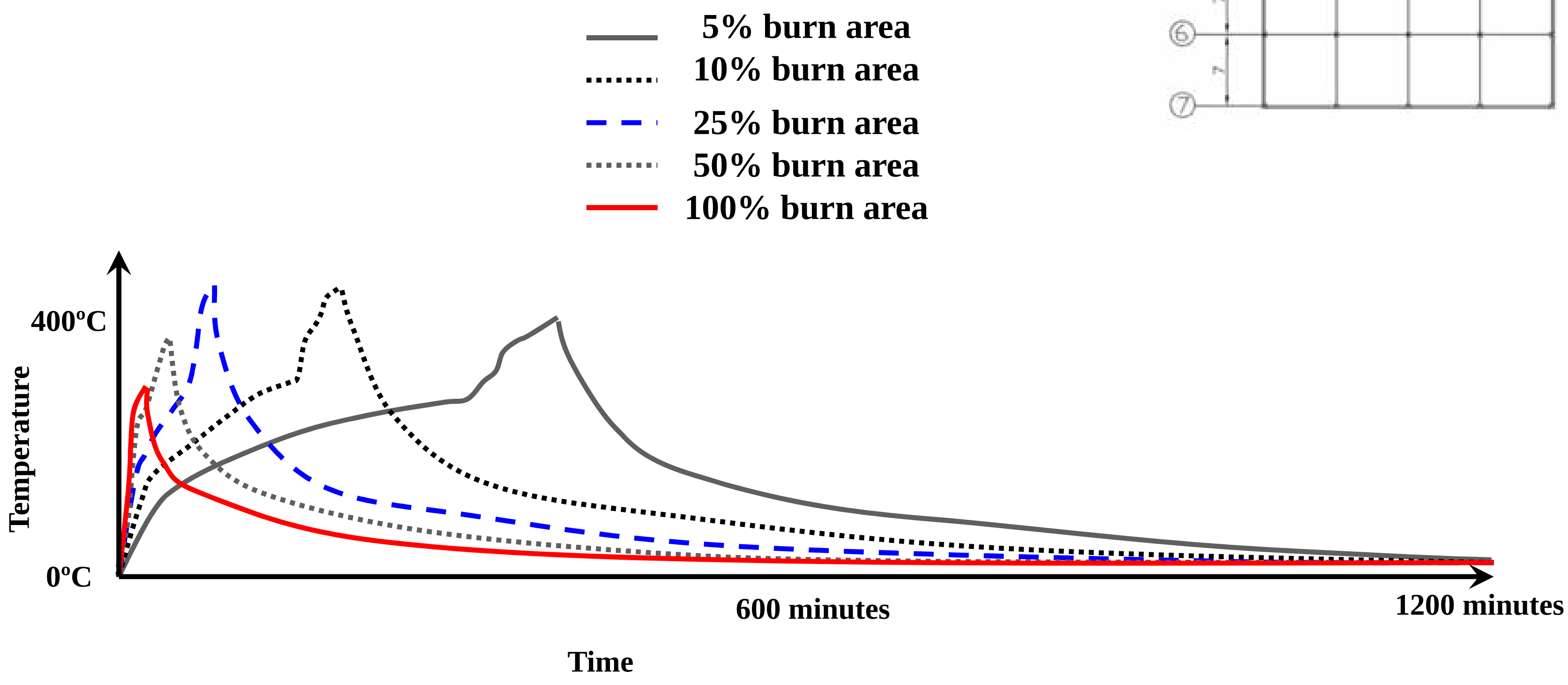
Rebar Temperature



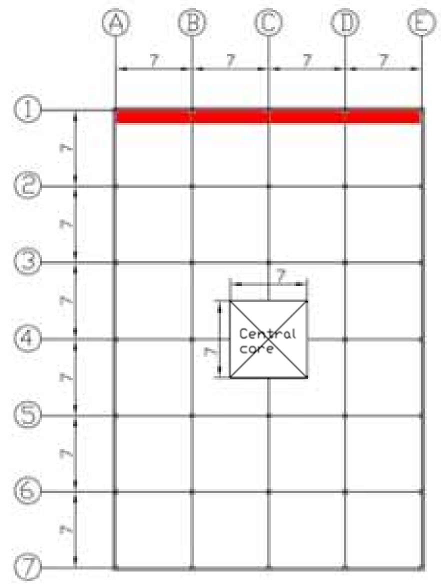


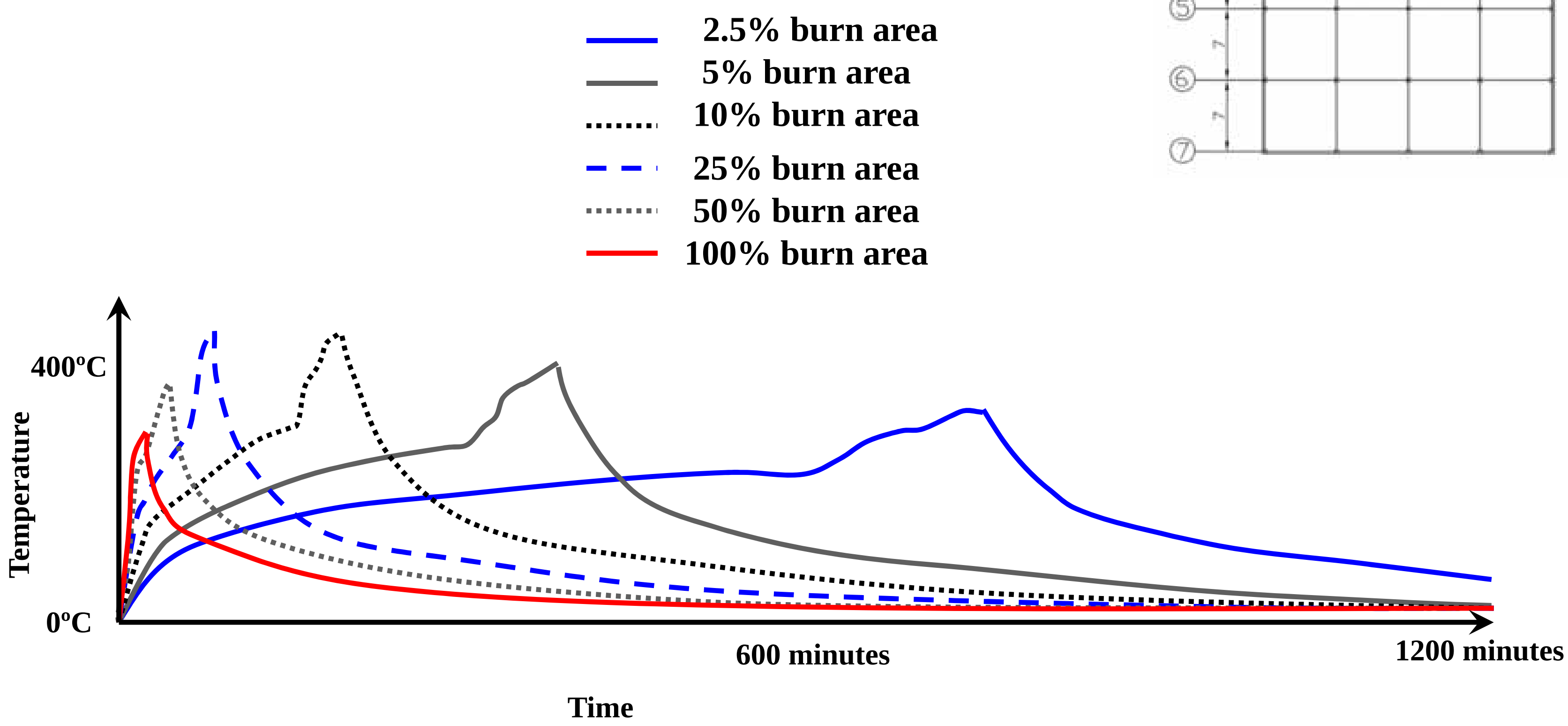
Rebar Temperature





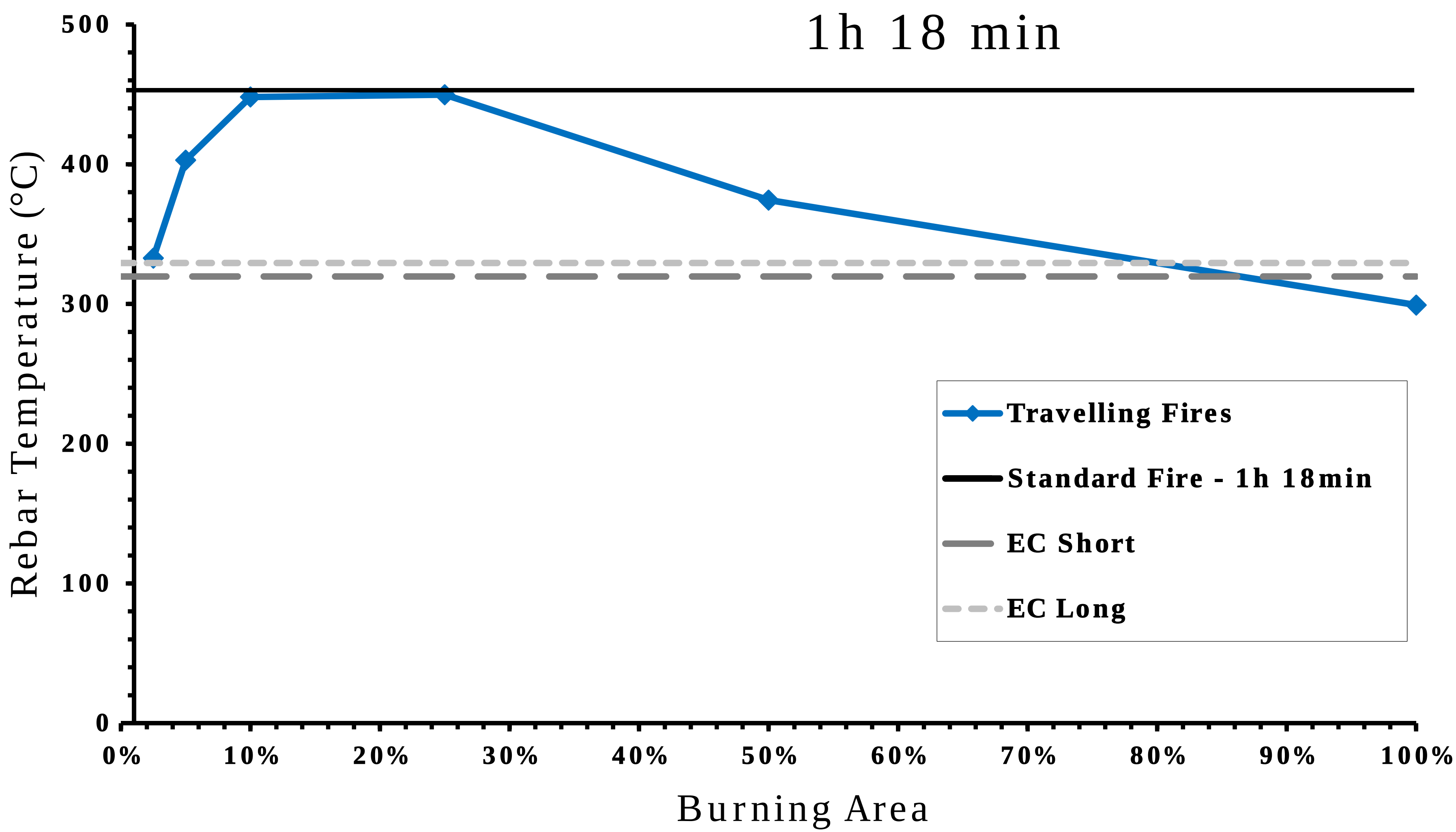
Rebar Temperature





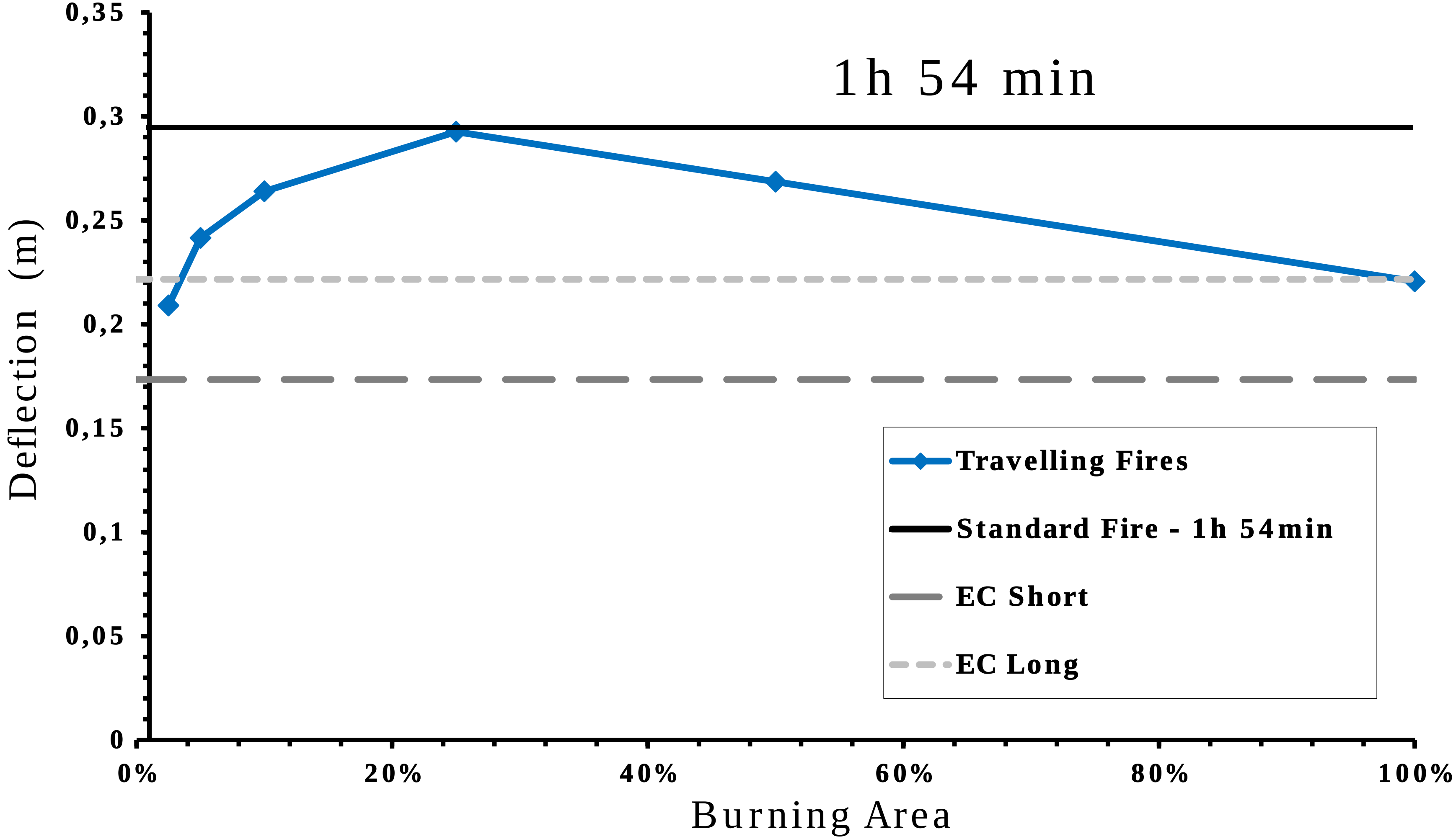
Law et al, *Engineering Structures* 2011

Max Rebar Temperatures vs. Fire Size



Law et al, *Engineering Structures* 2011

Max Deflection vs. Fire Size



Law et al, *Engineering Structures* 2011

Conclusions

- In large compartments, a post flashover fire is not likely to occur, but a travelling fire
- Provides **range of possible** fire dynamics
- Novel framework **complementing** traditional methods
- Travelling fires give more onerous conditions for the structure
- Strengthens collaboration between fire and structural fire engineers

Thanks

Sponsors:

THE UNIVERSITY OF EDINBURGH

ARUP

The Leverhulme Trust

The Royal Academy of Engineering

Collaborators:

J Stern-Gottfried

A Law

A Jonsdottir

M Gillie

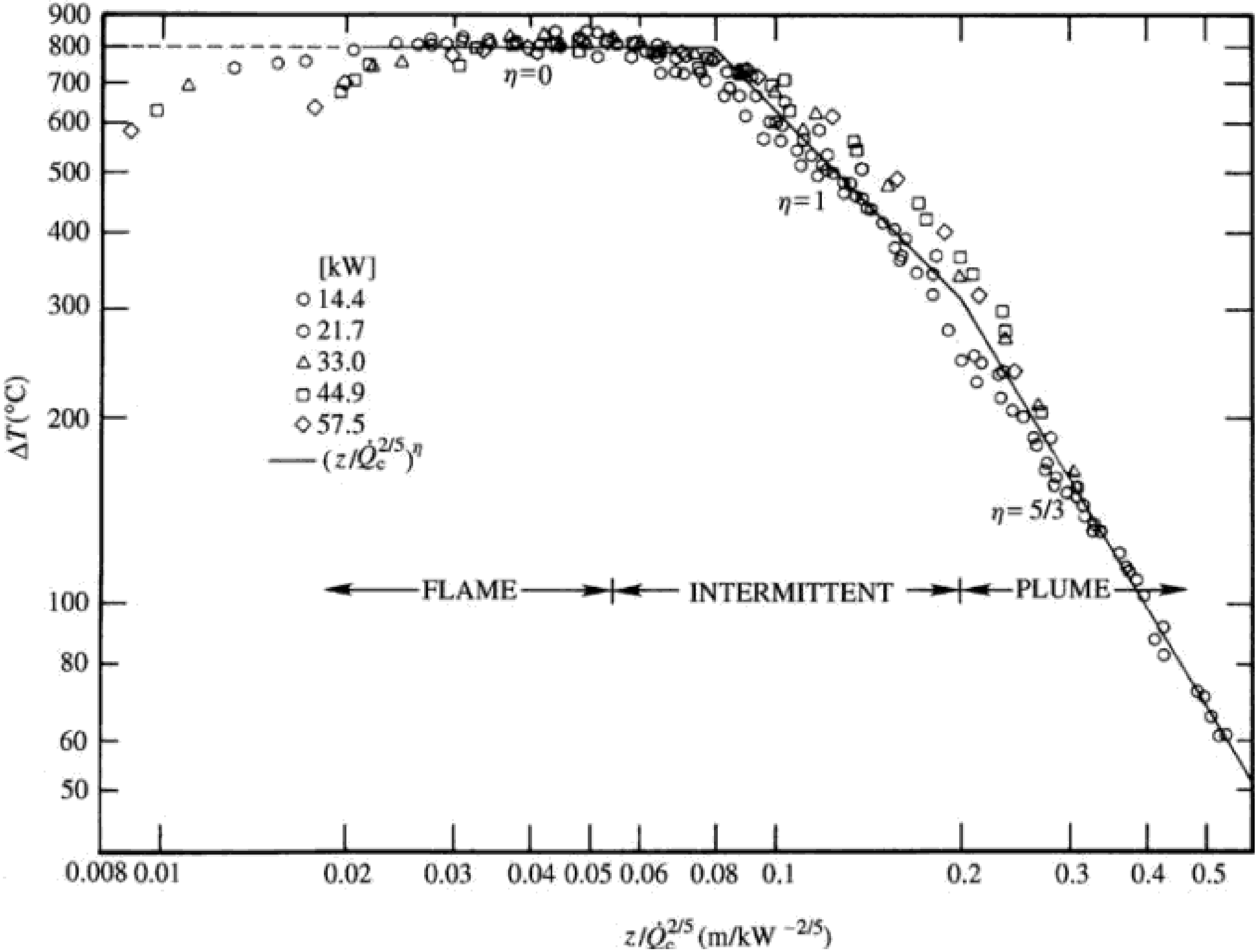
J Torero

- Law et al, *Engineering Structures* 2011
- Jonsdottir et al, *Interflam* 2010, Nottingham
- Stern-Gottfried et al, SPFE PBD, 2010, Lund
- Stern-Gottfried et al, *Fire Risk Management* 2009
- Jonsdottir et al, *Fire Risk Management* 2009
- Rein et al, *Interflam* 2007, London

Strengthening the bridges

Temperature of the plume

from **Introduction to fire Dynamics**, Drysdale, Wiley



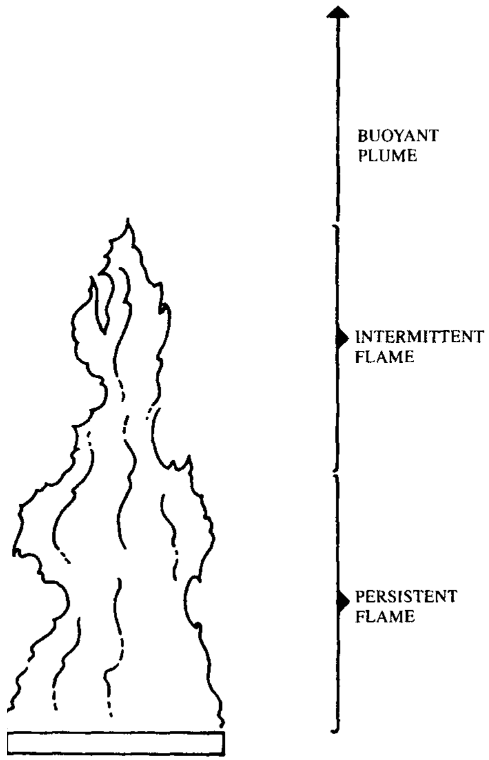


Figure 4.22 Variation of centreline temperature rise with height in a buoyant methane diffusion flame. Scales as $z/\dot{Q}_c^{2/5}$ (Table 4.2) (McCaffrey (1979), by permission). A similar correlation has been demonstrated for a range of hydrocarbon pool fires by Kung and Stavrianides (1982)

Conservation of Mass – burning time

- Burning at average heat release per unit area

$$t_b = \frac{m'' \Delta h_c}{\dot{Q}''}$$

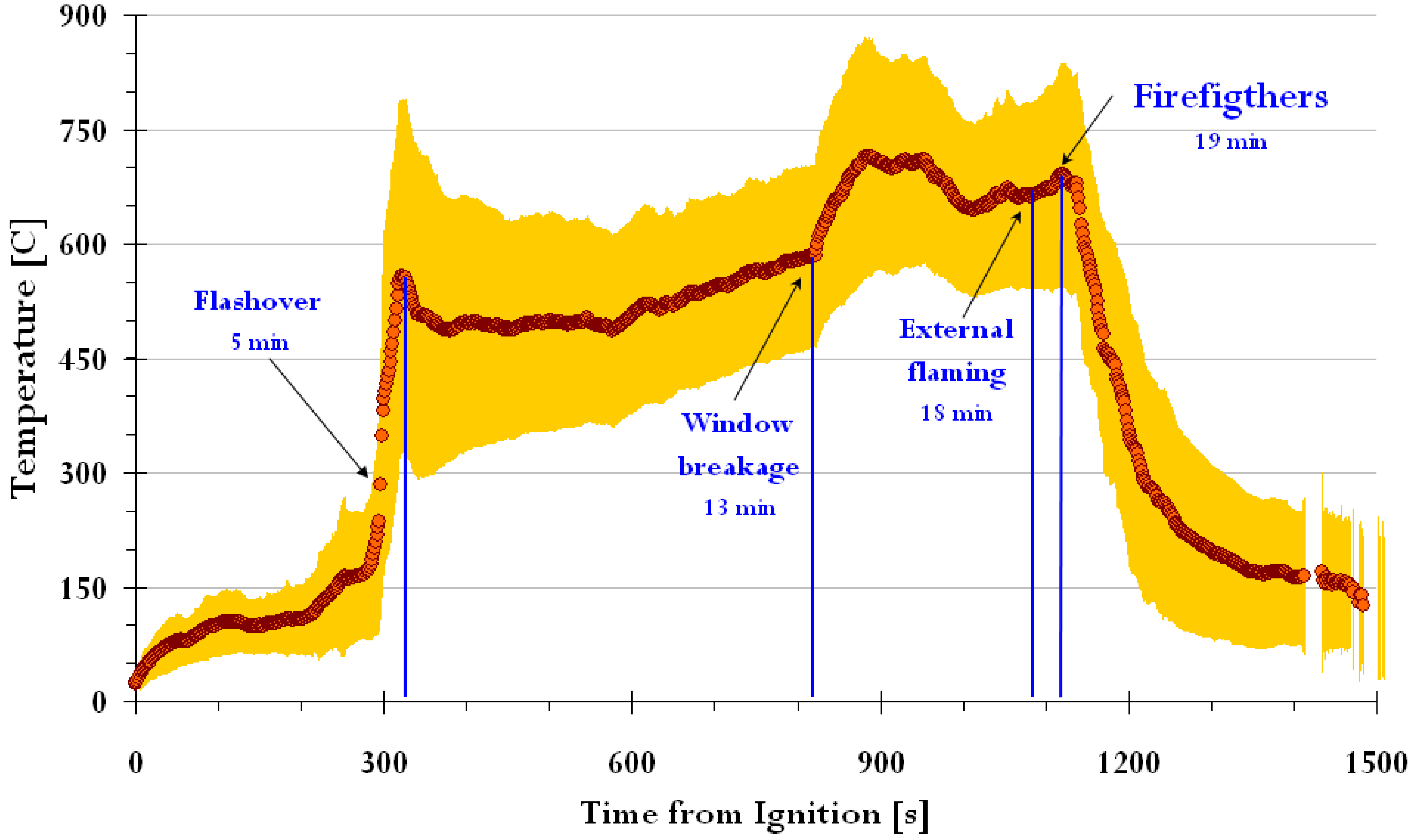
- ⌘ 50 MW fire on 200 m^2 burns for 30 **min**
- ⌘ 50 MW fire on 1000 m^2 burns for 15 **min**

where t_b is the burning time, *m*" is the fuel load density (kg/m^2), ΔH_c is the effective heat of combustion and Q" is the heat release rate per unit area (MW/m^2)

Rein et al, *Interflam* 2007, London

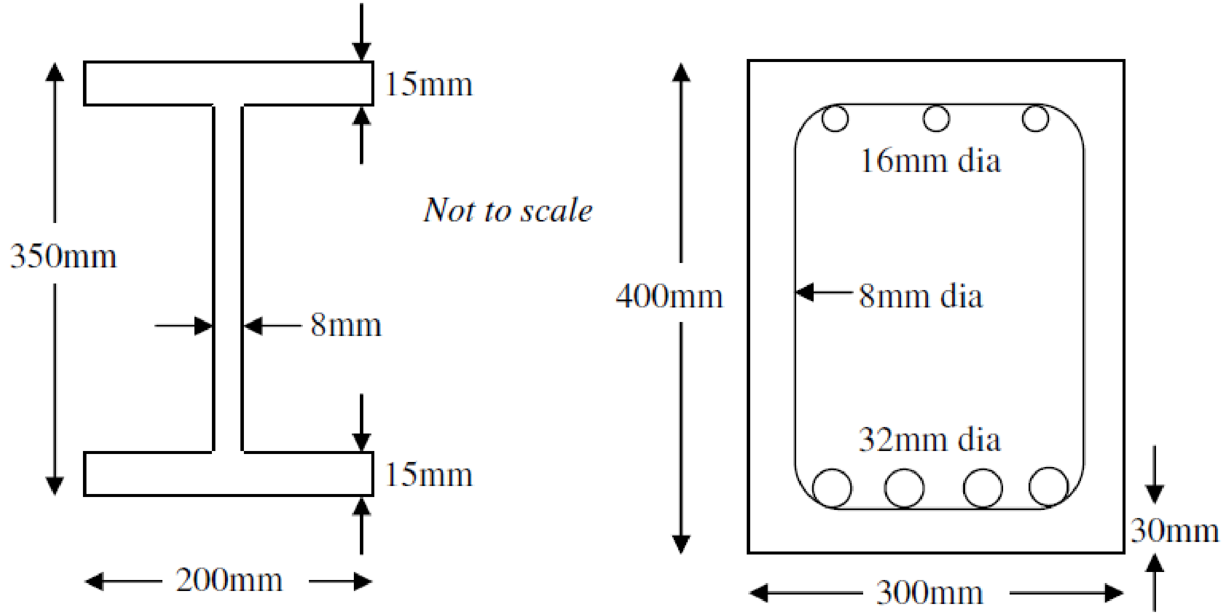
Aftermath

Average Compartment Temperature

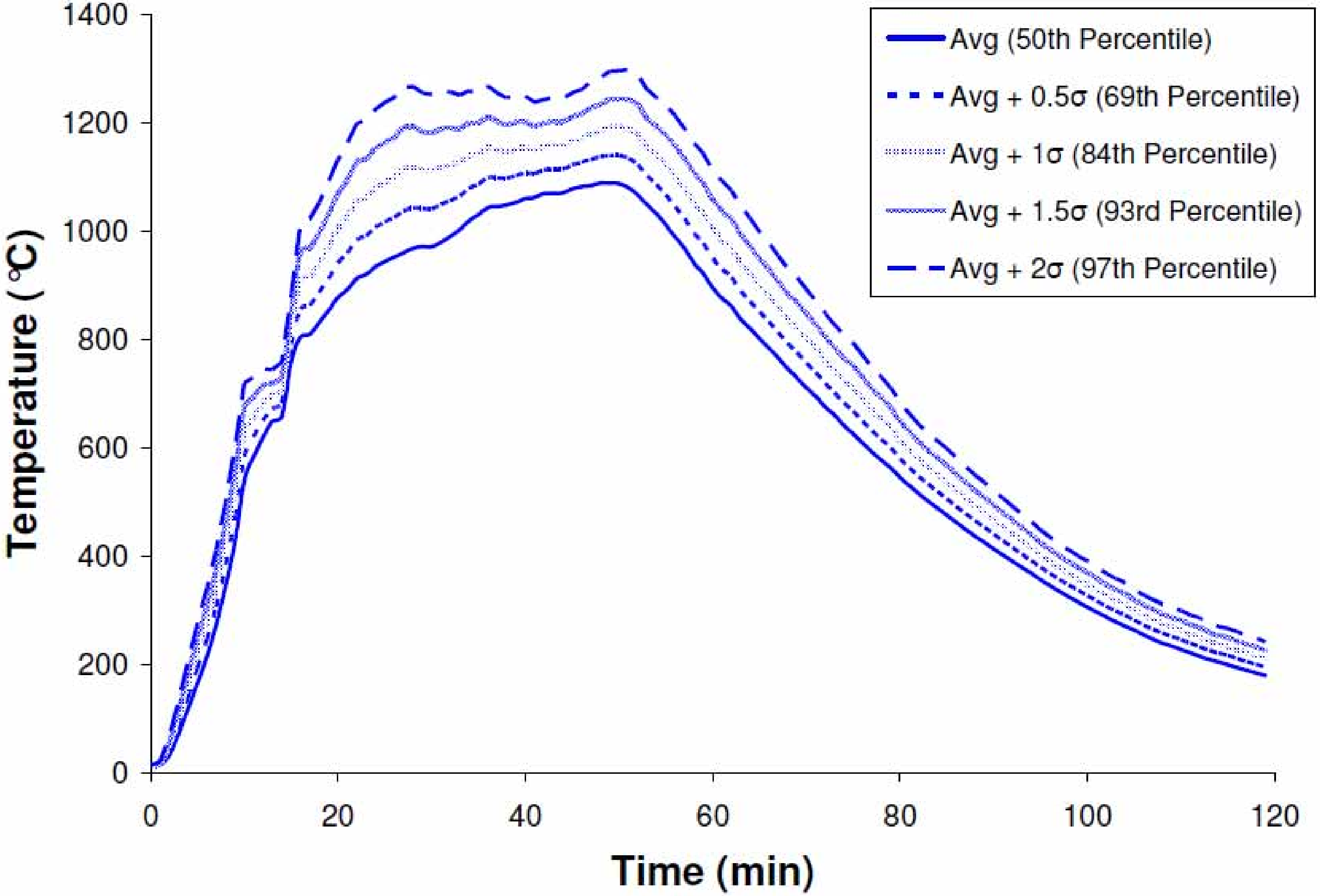


Three different beams used

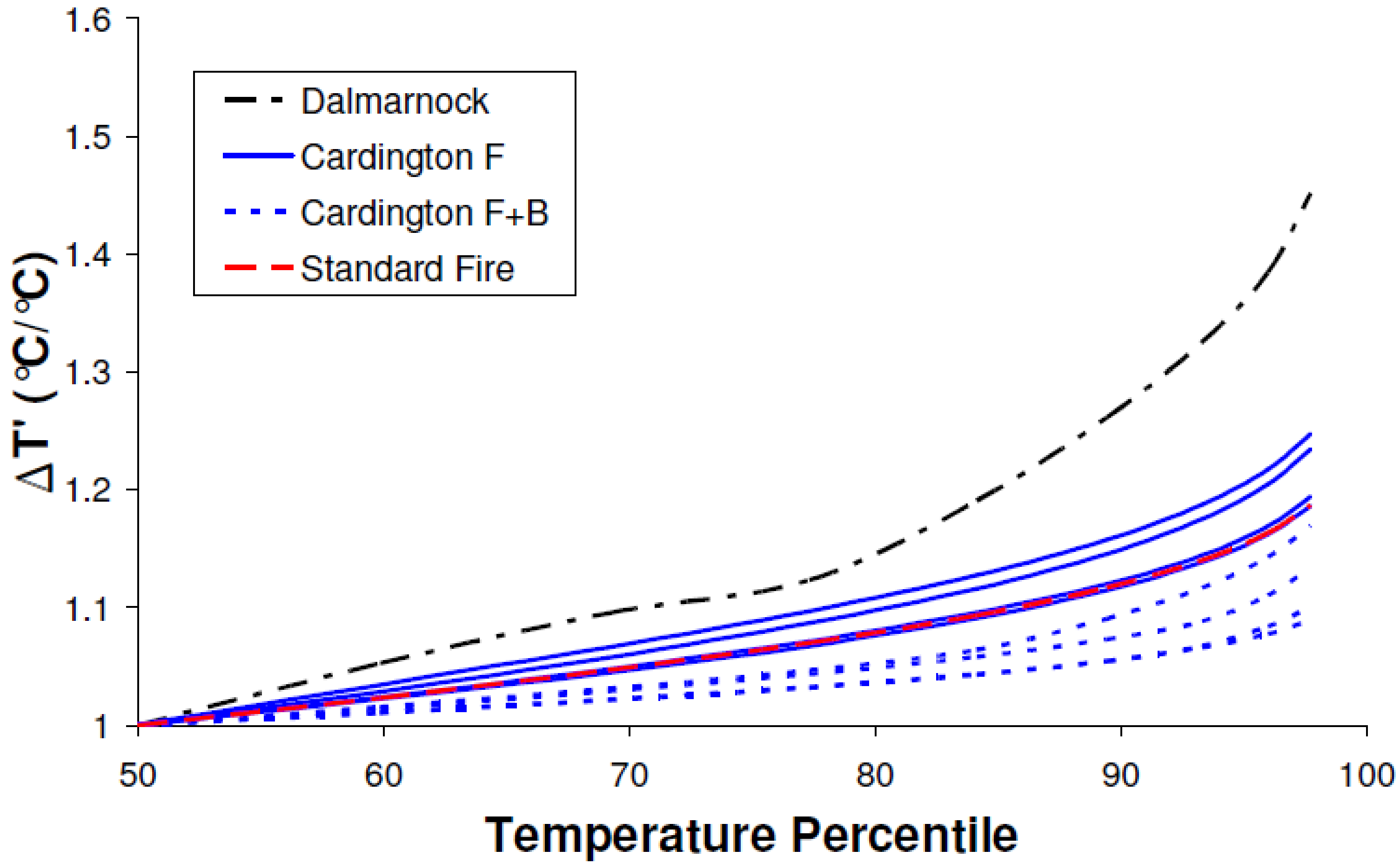
- Unprotected steel I-beam
- Protected steel I-beam to 60 min (12mm high density perlite)
- (



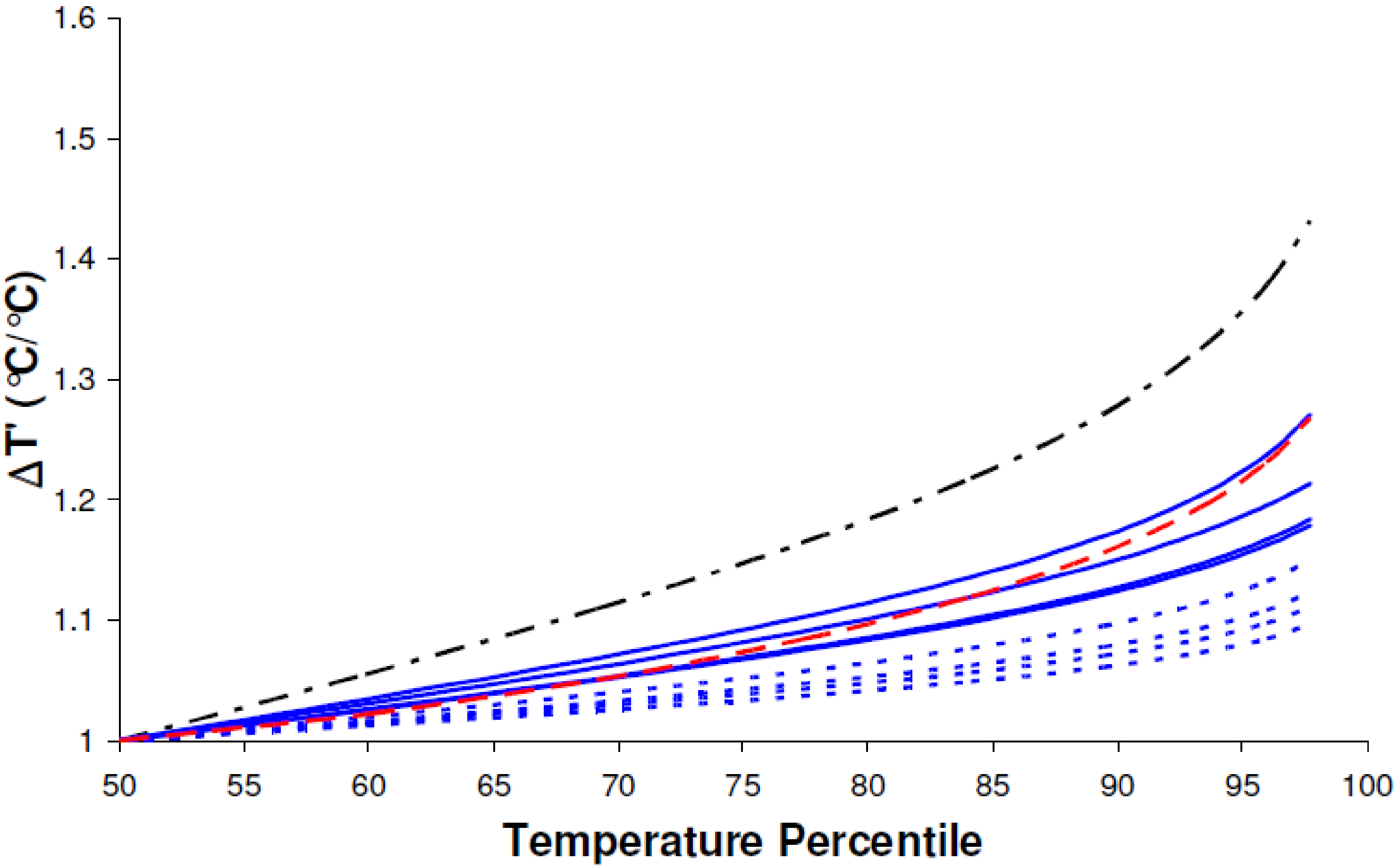
Example: Cardington



Unprotected Steel

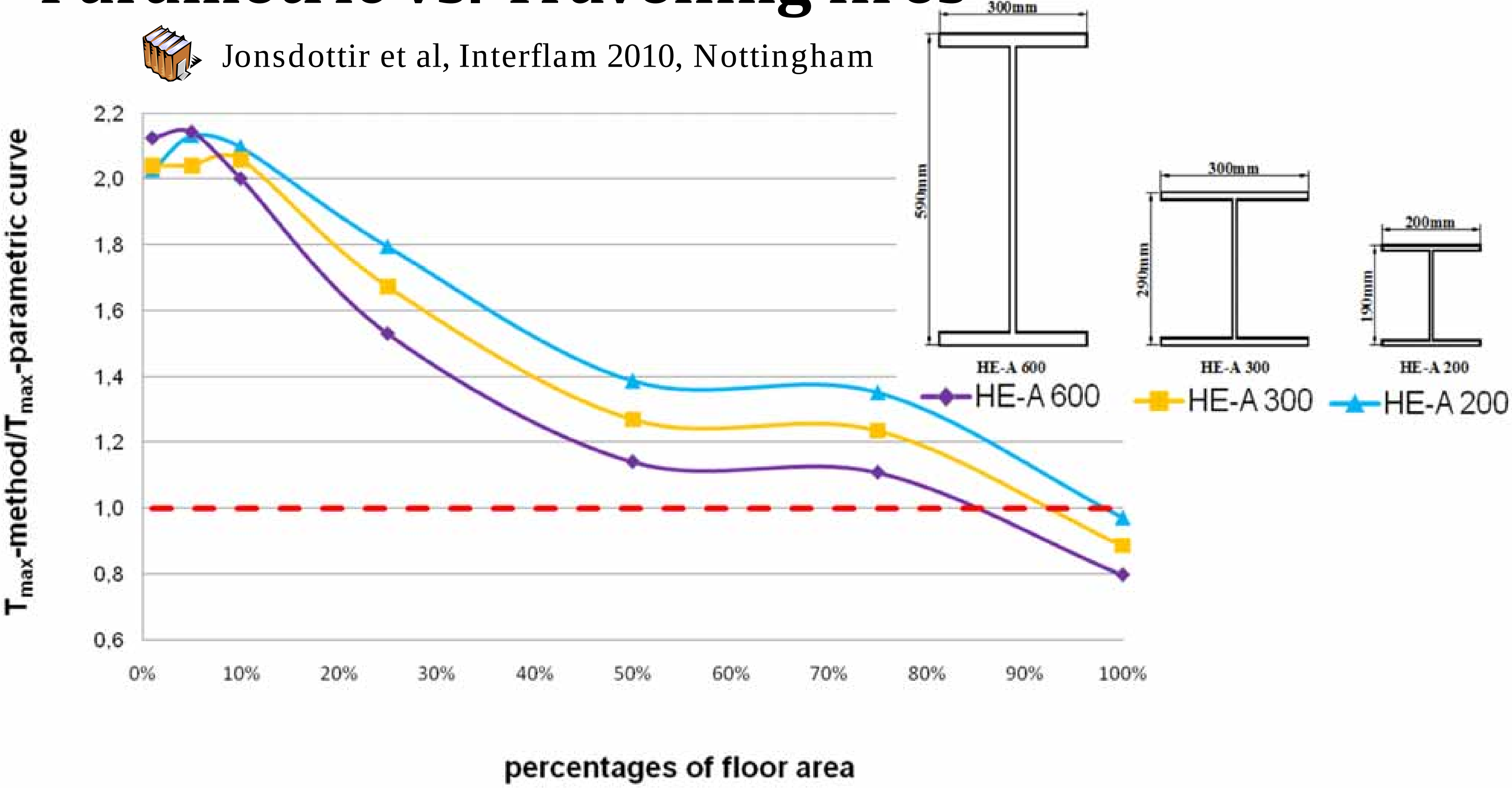


Protected Steel



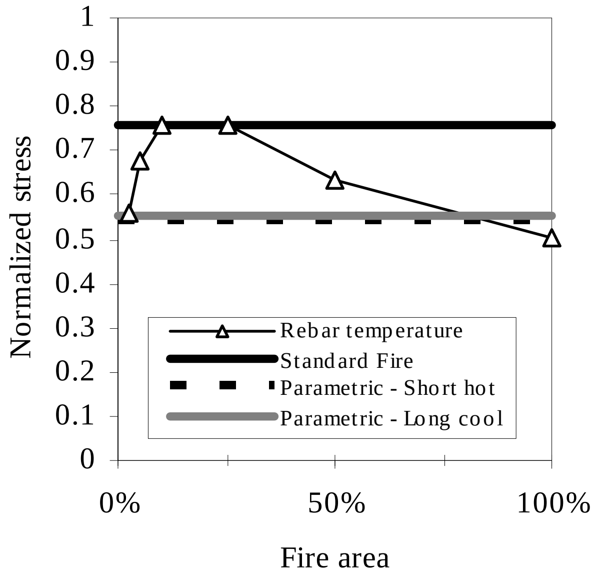
Results for Insulated Steel: Parametric vs. Travelling fires

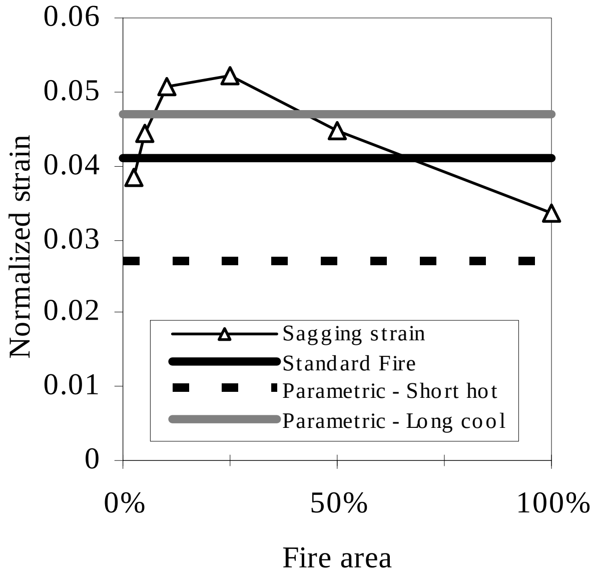
Jonsdottir et al, Interflam 2010, Nottingham

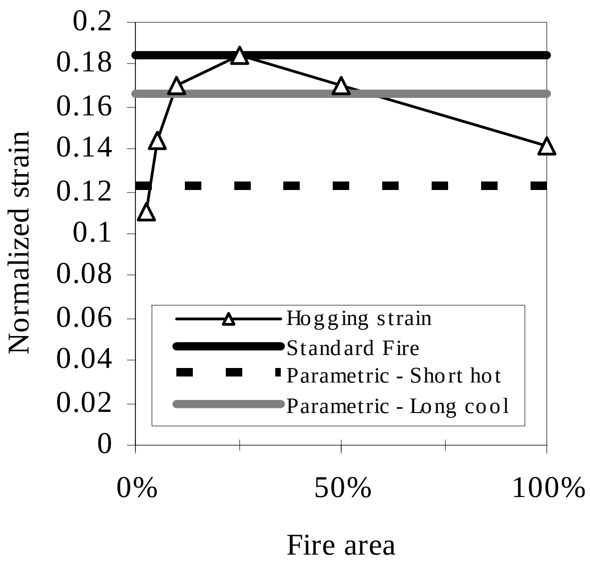


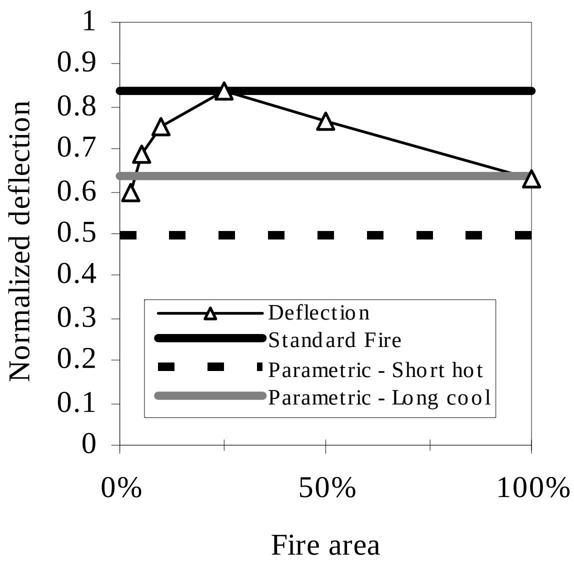
- Compared to parametric fire, 110% higher temperatures for a protected steel with 39 mm-gypsum

Structural Behaviour

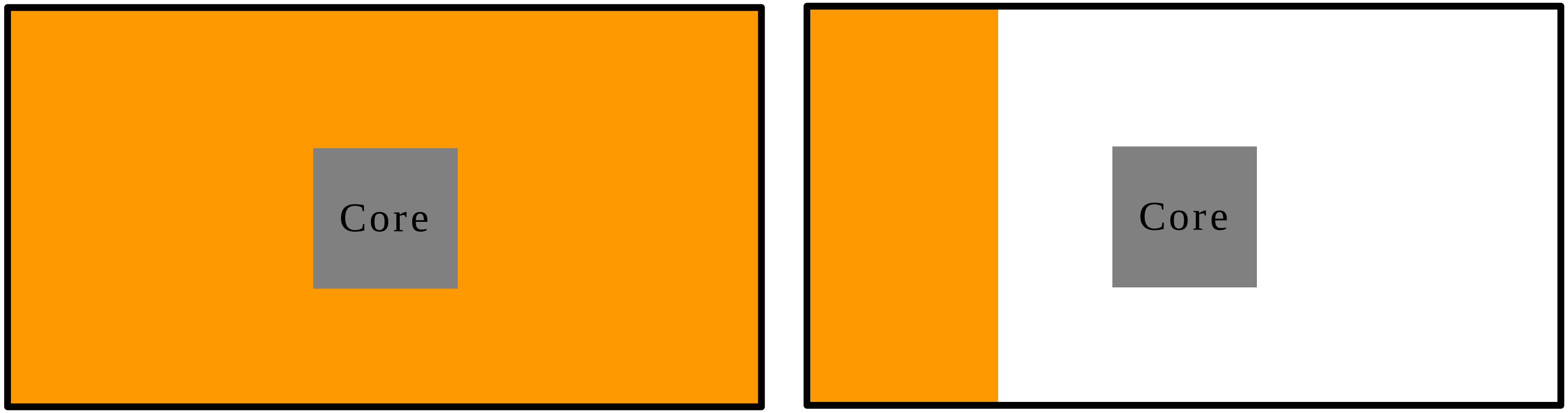




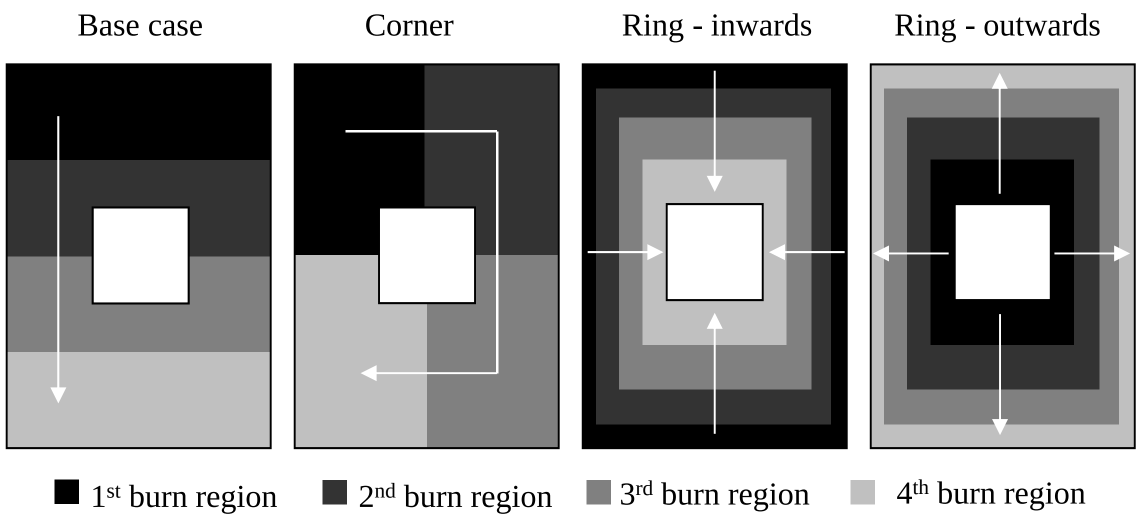




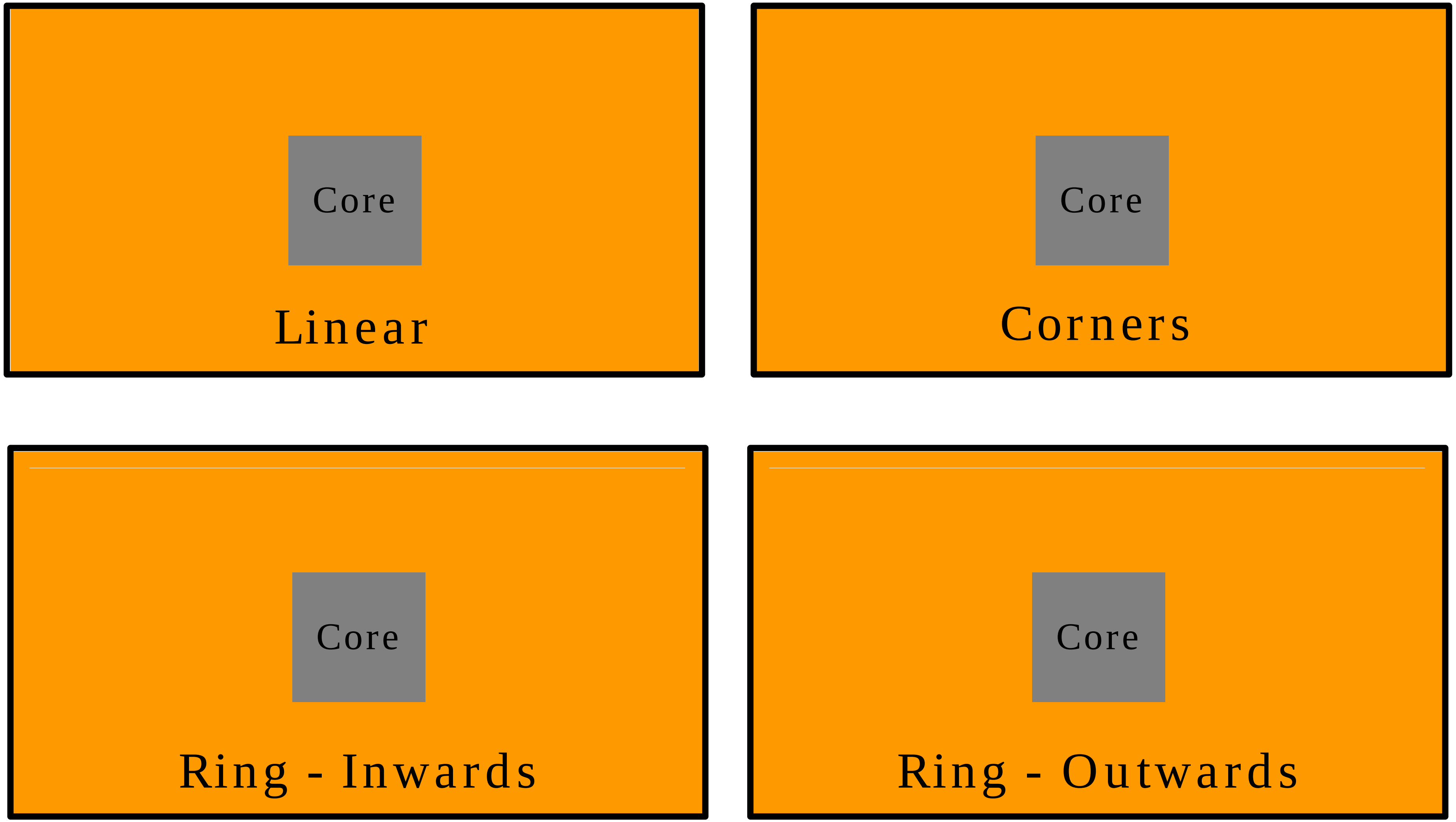
Fire Progression



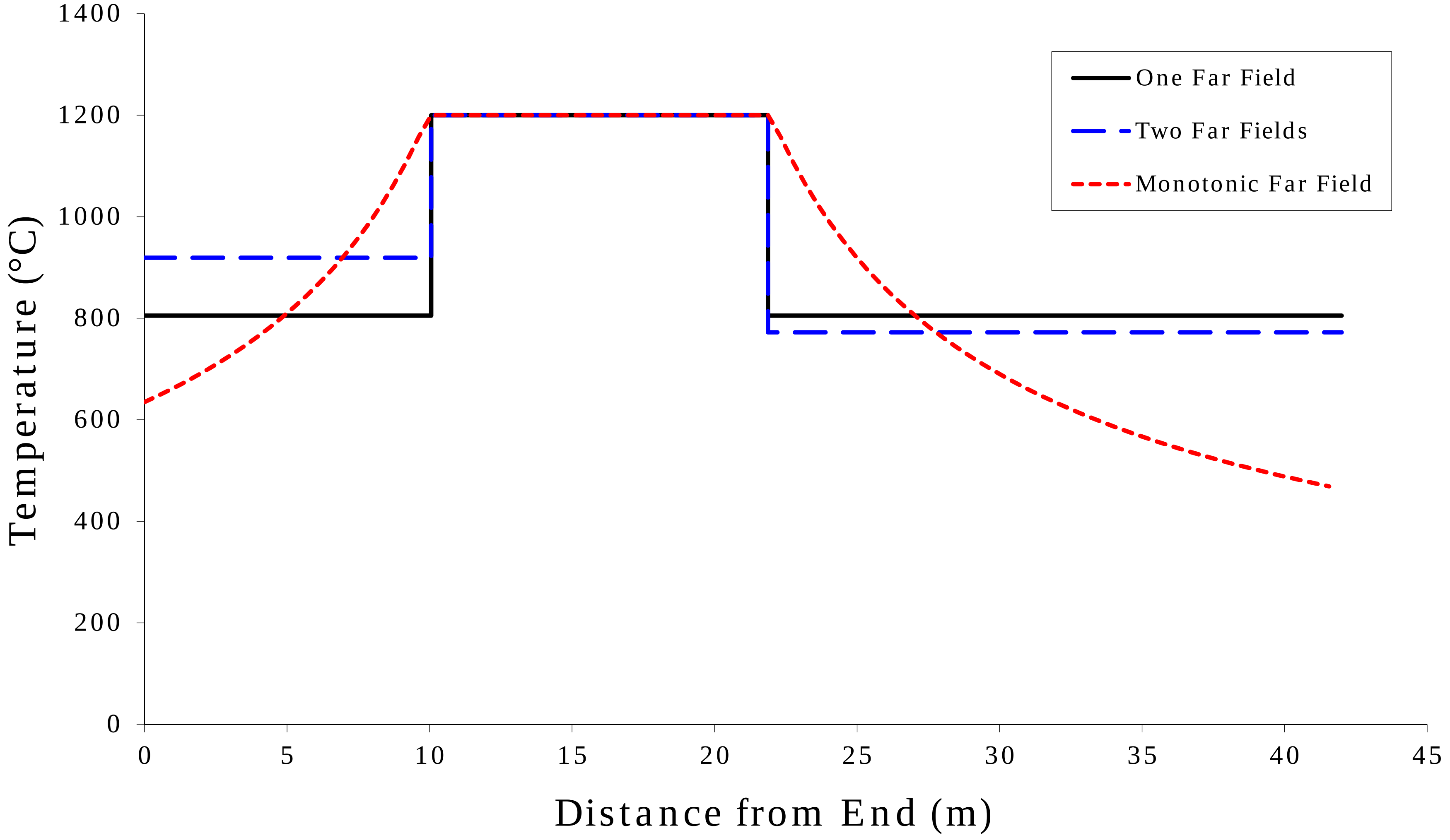
Sudden **Gradual**


Base case
Corner
Ring - inwards
Ring - outwards
1st burn region
2nd burn region
3rd burn region
4th burn region

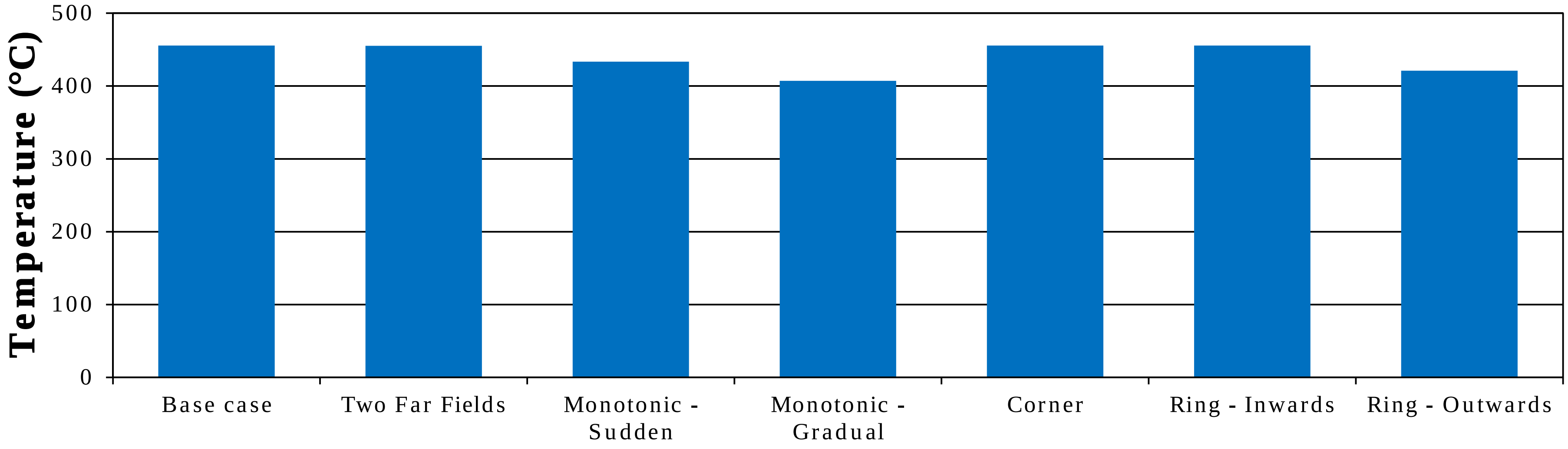
Fire Shape/Path

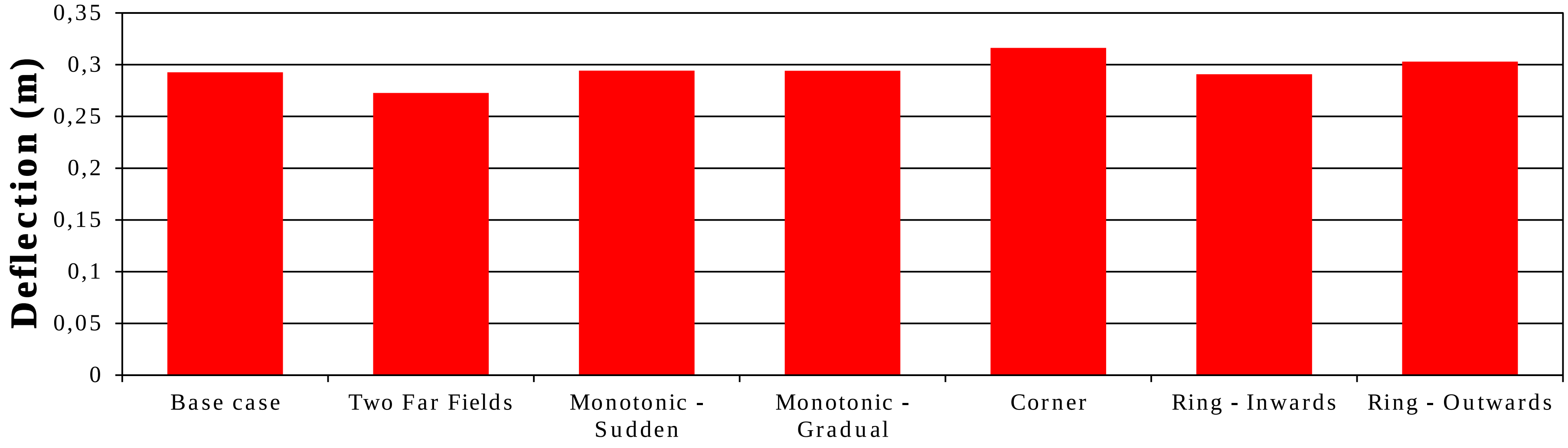


Far Field Temperature Discretization



Sensitivity Results





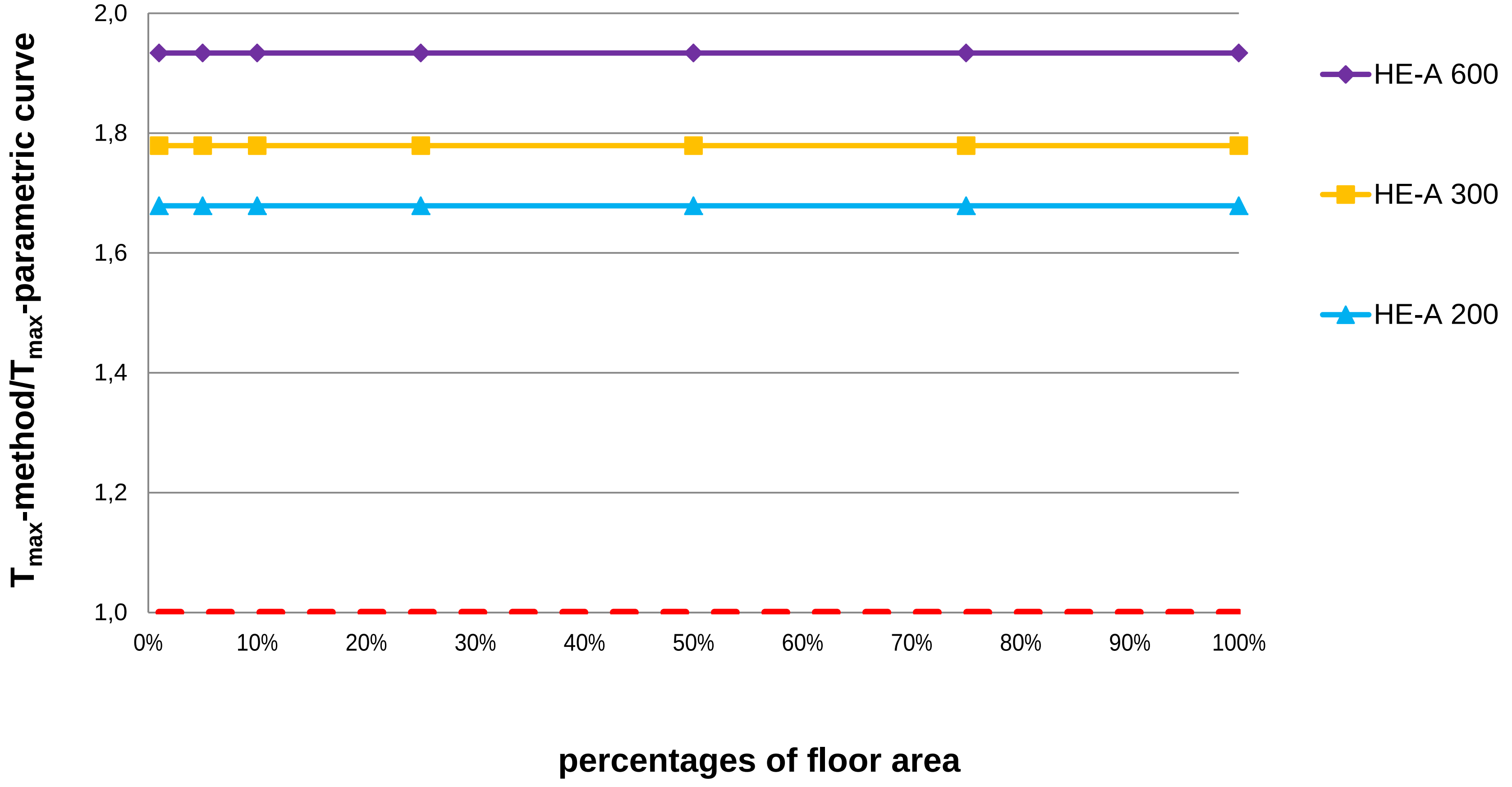
- Unprotected steel – up to 10% higher steel temperature (independent of fire size)
- Protected steel – from **65%-95%** higher steel temperature
  - Maximum over prediction (110%) at fire areas of 5-10%
  - Maximum under prediction (20%) at fire areas over 85%

The case study

The above methodology was applied to a real building, The Informatics Forum Building of the University of Edinburgh

Results

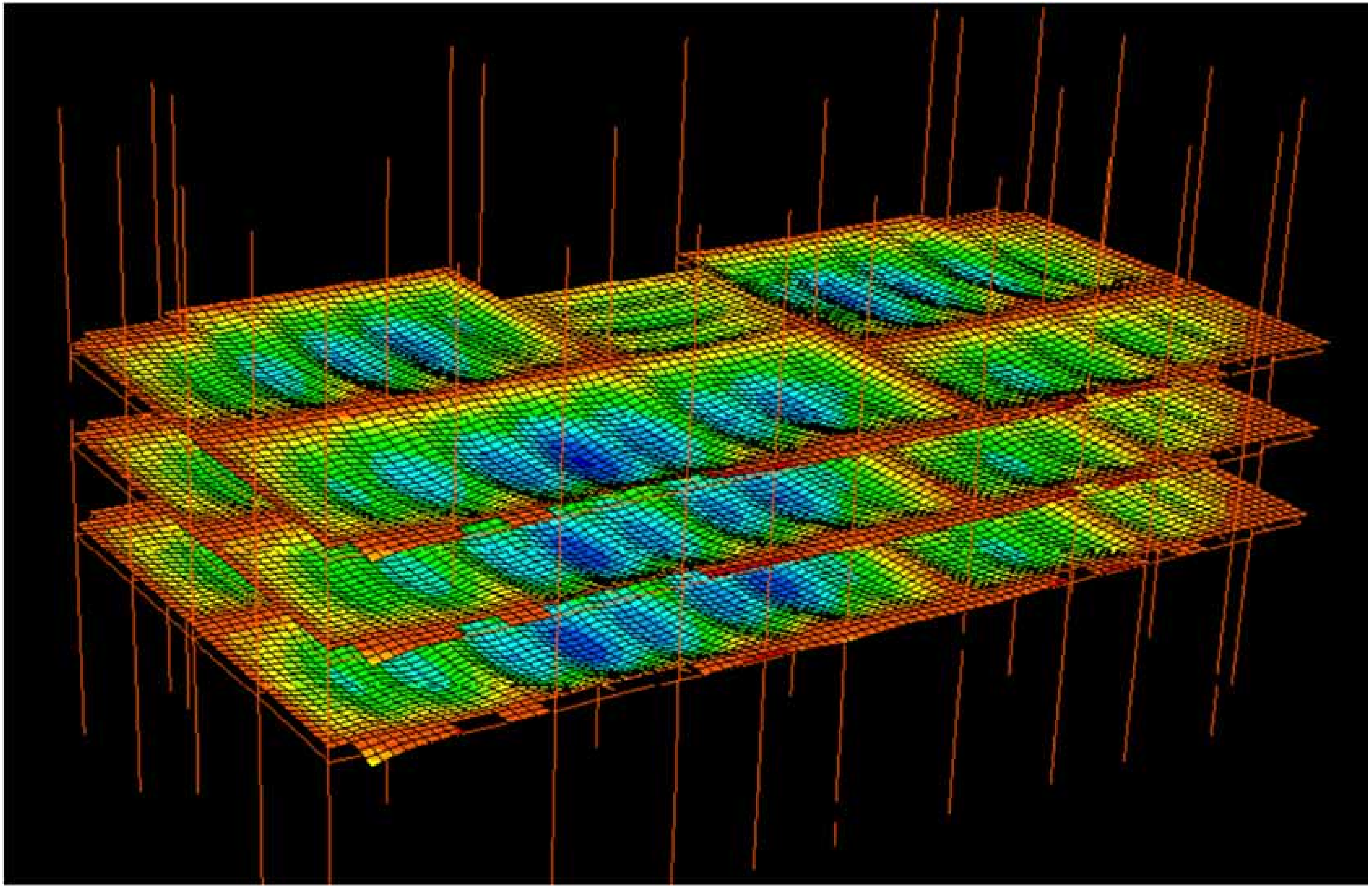
T_{max}-method / T_{max}-parametric curve - for unprotected steel:



Heron Tower

- 46 Storey Office Building in City of London
- 3-storey atriums forming 'villages'
- First ever project to consider the robustness of a structure in a multi-storey fire.

Heron Tower



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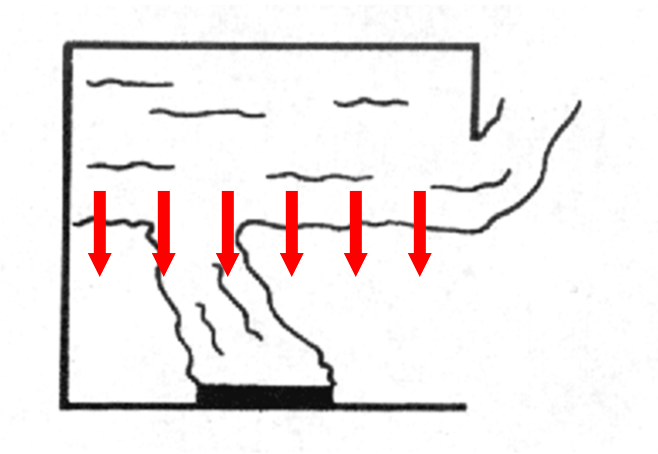
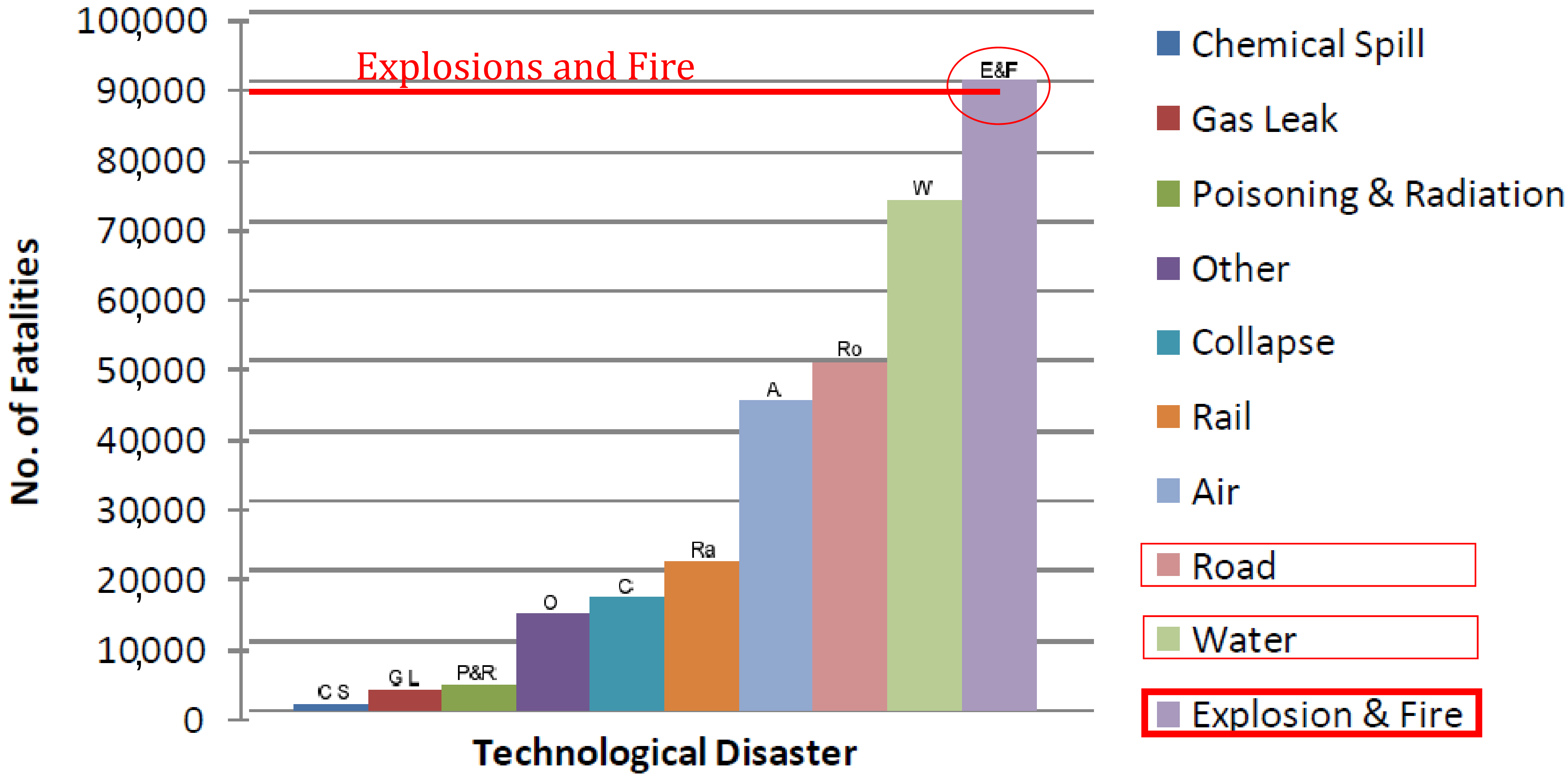
Sudden and generalized ignition (*flashover*)



$$q'' \sim \sigma T^4$$

- When feedback heat flux is ~20 kW/m^2 (above the critical ignition for most known fuels) enhanced flame spread and fast secondary ignition take places in the compartment → **onset of flashover**

Technological Disasters 1900-2000

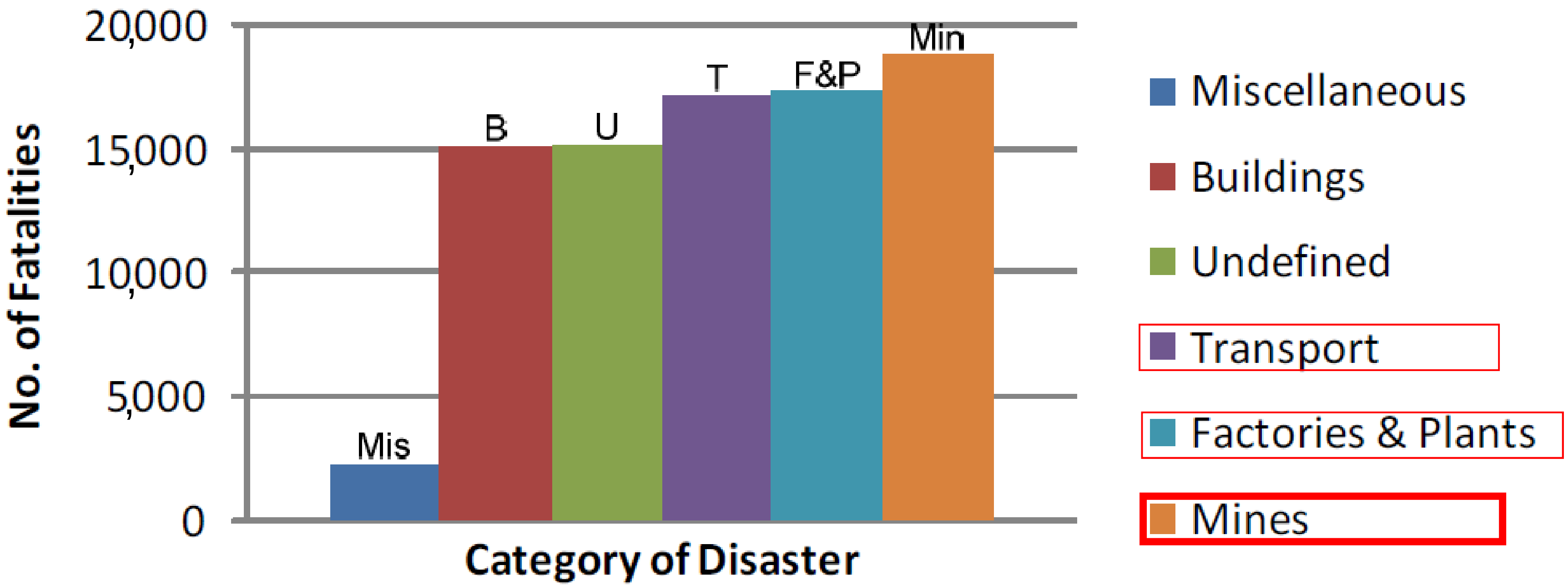


NOTE: Immediate fatalities as a proxy to overall damage. Disaster defined as >10 fatalities, >100 people affected, state of emergency or call for international assistance.

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

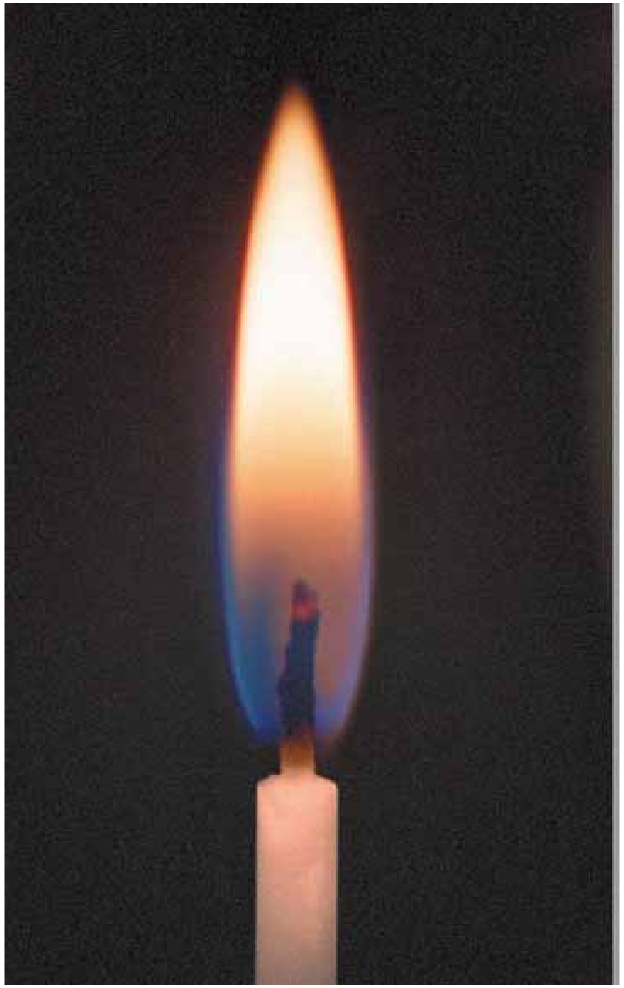
Technological Disasters 1900-2000
Fire and Explosions



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

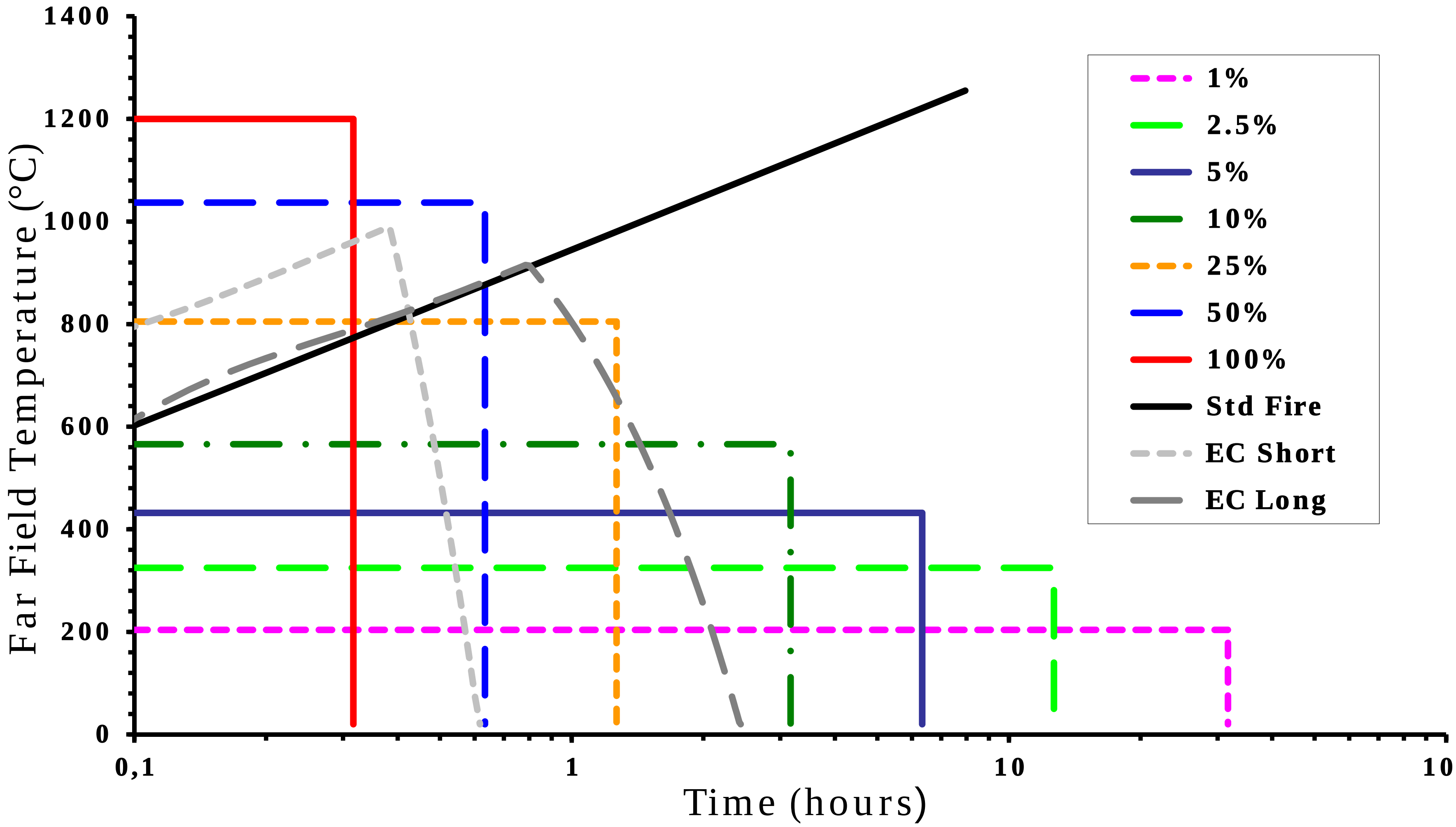
Jocelyn Hofman, Fire Safety Engineering in Coal Mines MSc Dissertation, University of Edinburgh, 2010

Buoyancy



Candle burning on Earth (1g) and
in microgravity inside the ISS (~0g)

Family of possible fires



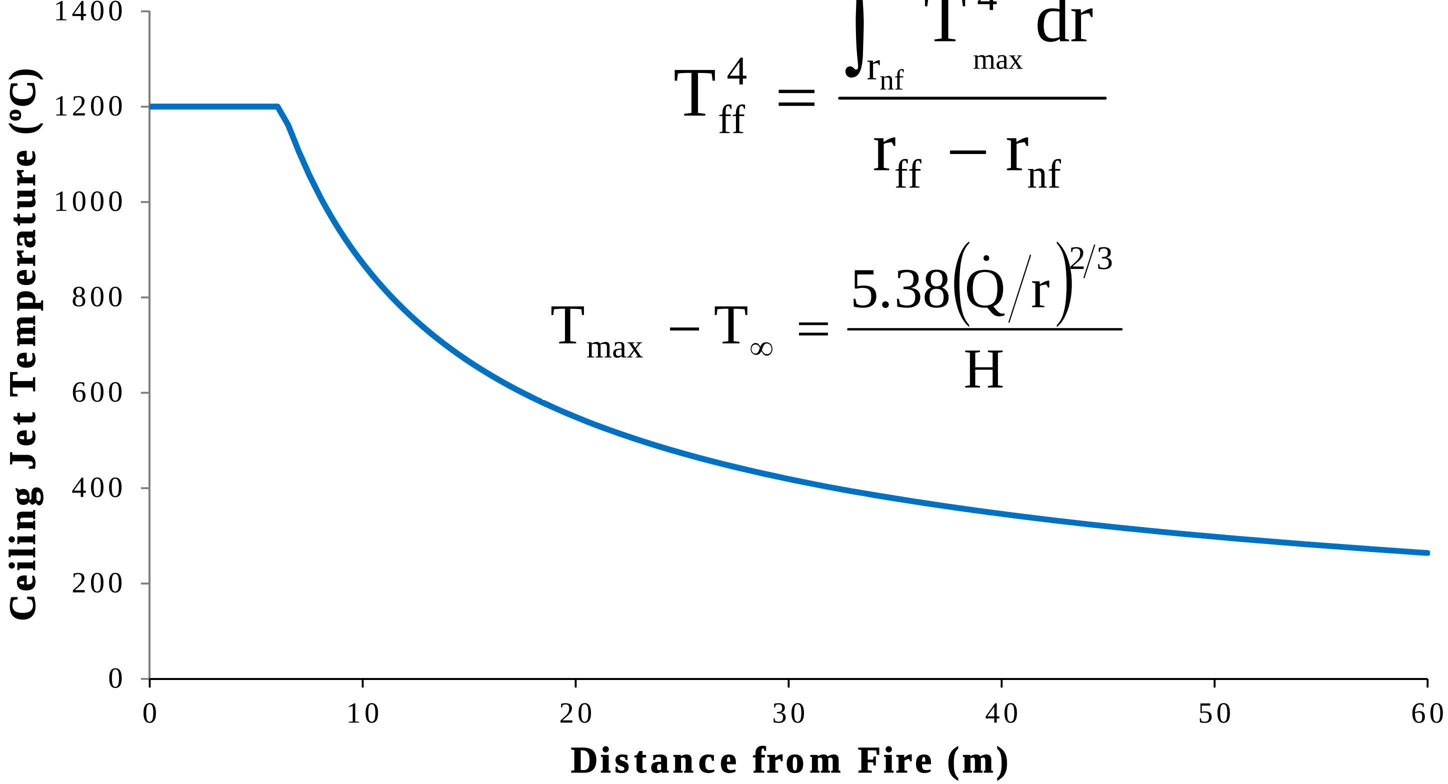
Stern-Gottfried et al, SPFE PBD, 2010, Lund

Far Field Temperature

- Maximum temperature at ceiling jet. Average calculated over the correlation with the distance from the fire (Alpert's correlation)

$$T_{ff}^4 = \frac{\int_{r_{nf}}^{r_{ff}} T_{max}^4 \, dr}{r_{ff} - r_{nf}}$$

$$T_{max} - T_{\infty} = \frac{5.38\left(\dot{Q}/r\right)^{2/3}}{H}$$



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

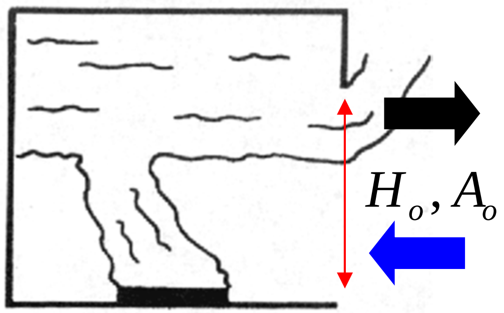
flow of stoichiometric air

eg, value for propane

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

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

Ventilation flows



Flows in and out of the compartment are controlled by buoyancy which scales with the density differences and the size of the opening.

$$\rho v^2 = \Delta \rho g H_0 \leftarrow \text{for buoyant flows}$$

$$\dot{m} = vA_0 \Rightarrow \dot{m} \propto \underbrace{A_0\sqrt{H_0}}_{\text{ventilation factor}}$$

$$\dot{m}_{a,\max} = 0.5 A_0 \sqrt{H_0}$$

$$\dot{m}_{a,\max} \geq \dot{m}_a$$

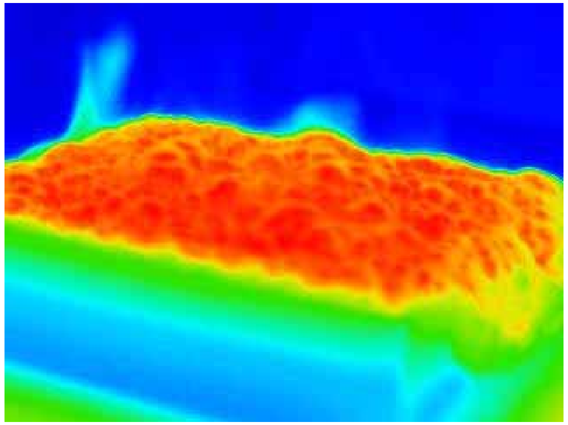
- The flow through openings has a maximum possible limit.
- At steady state, flow of smoke out is approximately equal to the flow of air in.

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

A_o Opening area (m^2)

H_o Height of opening (m)

Pyrolysis



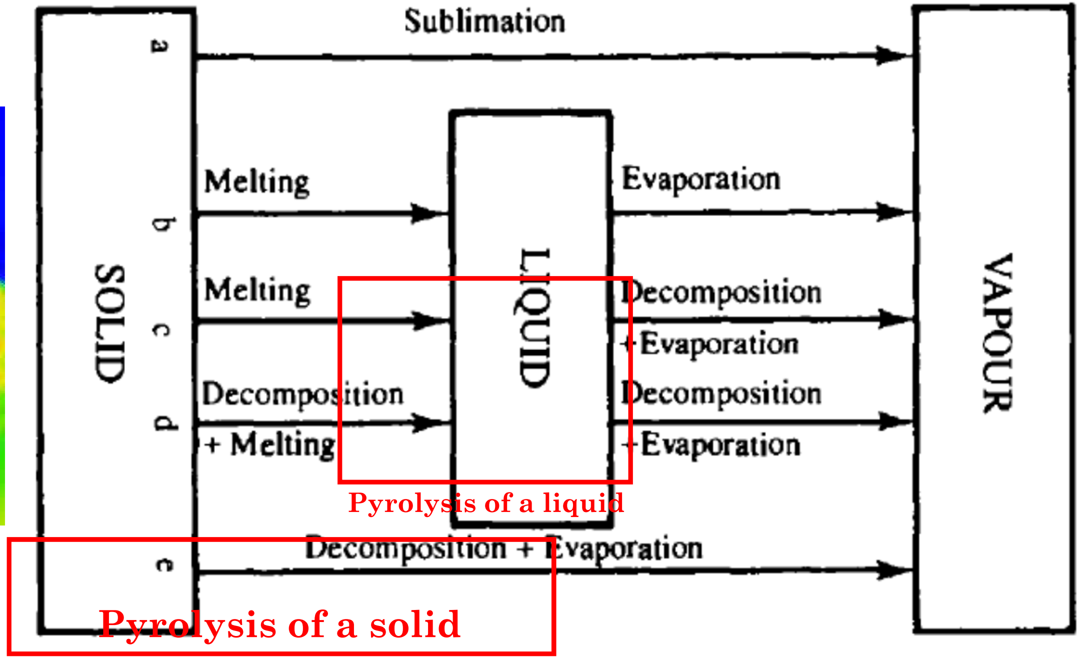
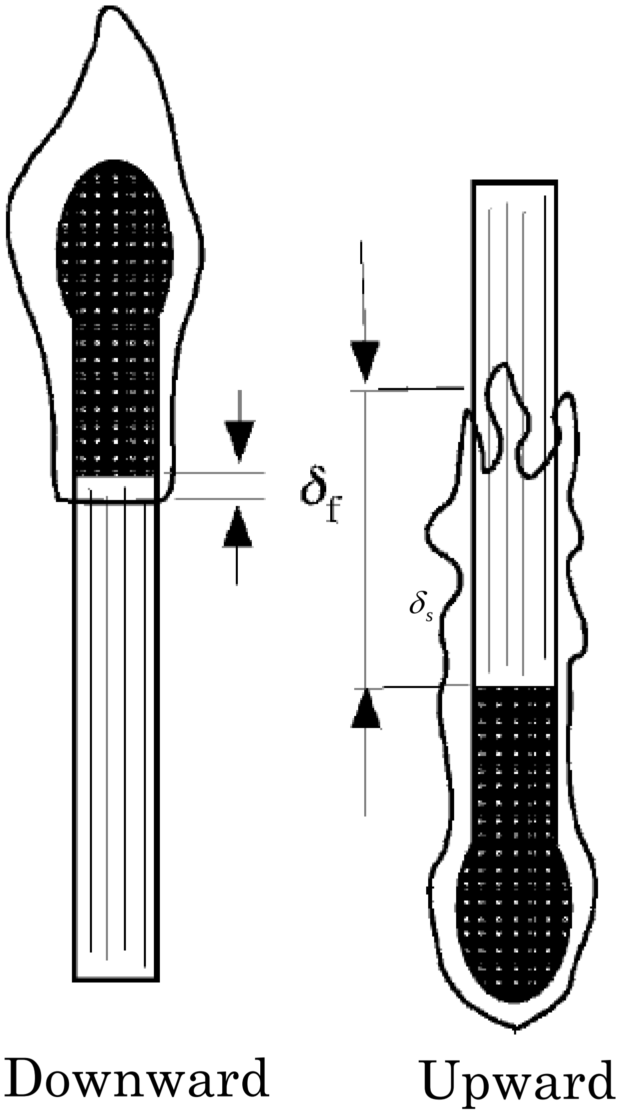


Figure 1.3 Different modes in which fuel vapour is generated from a solid (Table 1.3)

When a solid material heats up, it eventually reaches a temperature threshold where it begins to chemically break down. This process is called pyrolysis and is similar to gasification but with one key difference – pyrolysis is the simultaneous change of chemical composition (eg, long hydrocarbon chains to shorter chains) and physical phase (ie, solid or liquid to vapour) and is irreversible. When a solid is burning with a flame, it is actually the pyrolysis vapours (aka *pyrolyzate*) directly above it that is burning, not the solid itself.

Flame Spread – rate of area growth



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

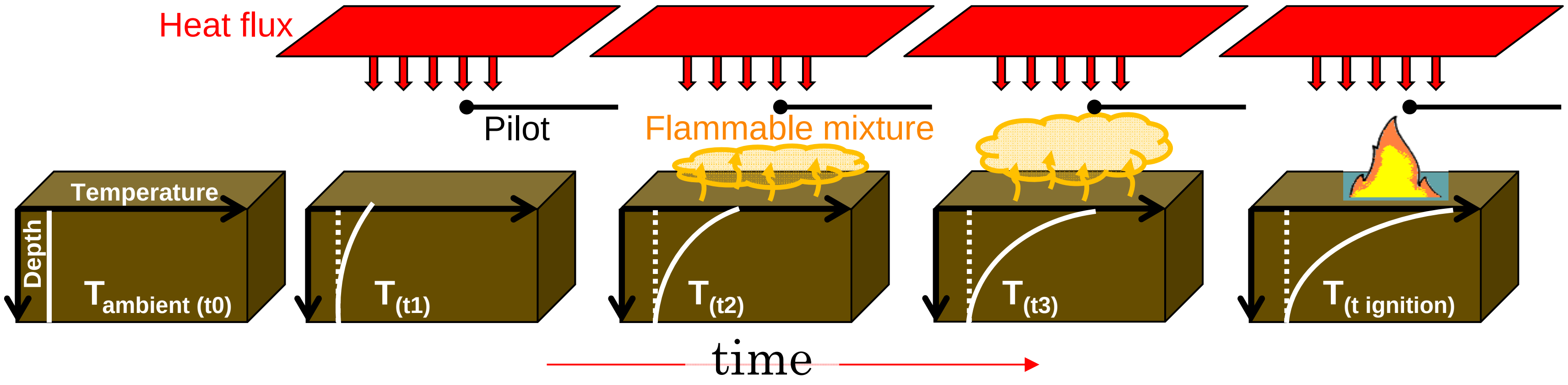
Flame spread is inversely proportional to the time to ignition

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

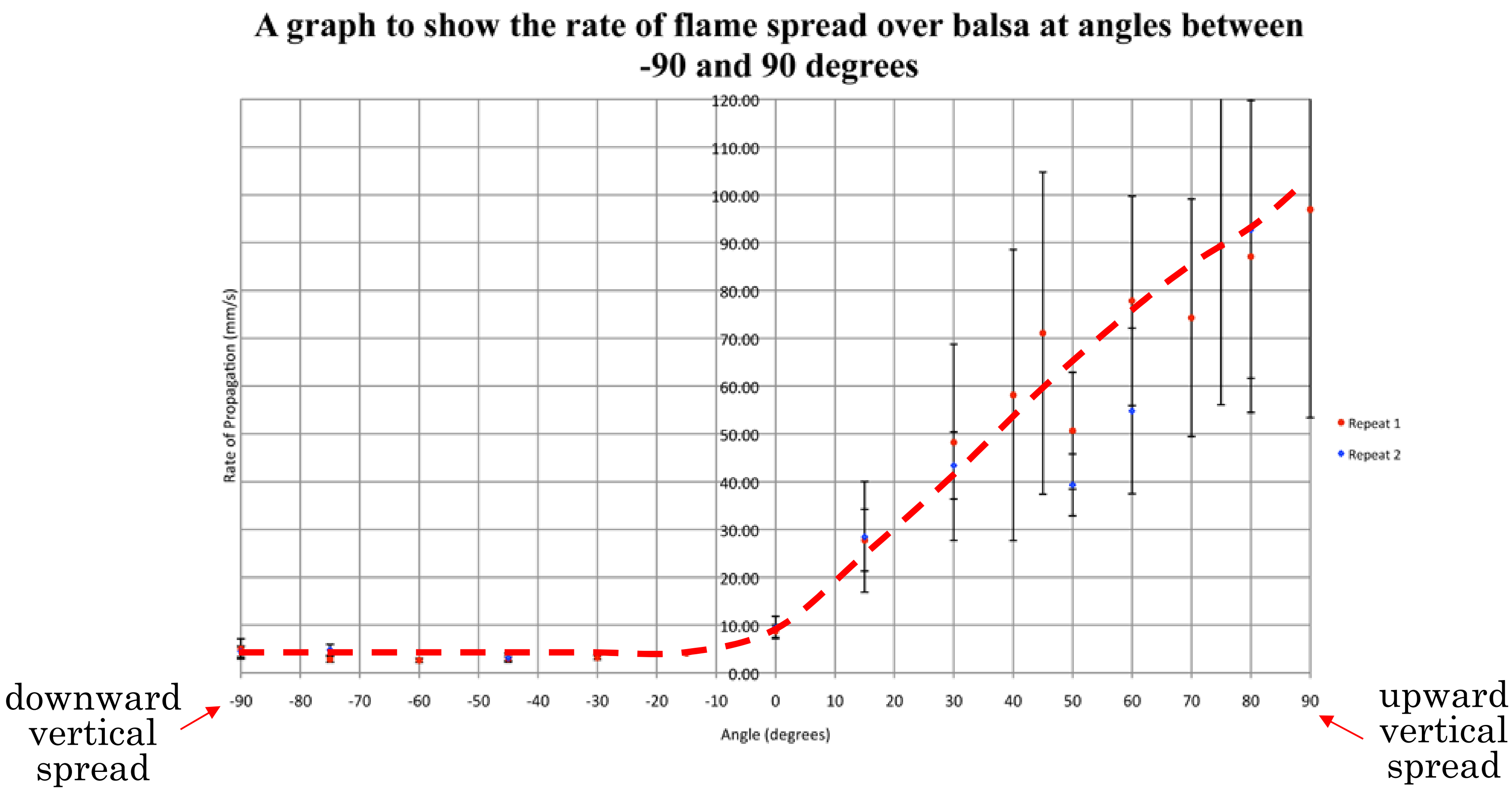
Ignition – fuel exposed to heat

- Material start to decompose giving off gasses: pyrolysis

- Ignition takes place when a flammable mixture of fuel vapours is formed over the fuel surface



Flame Spread vs. Angle



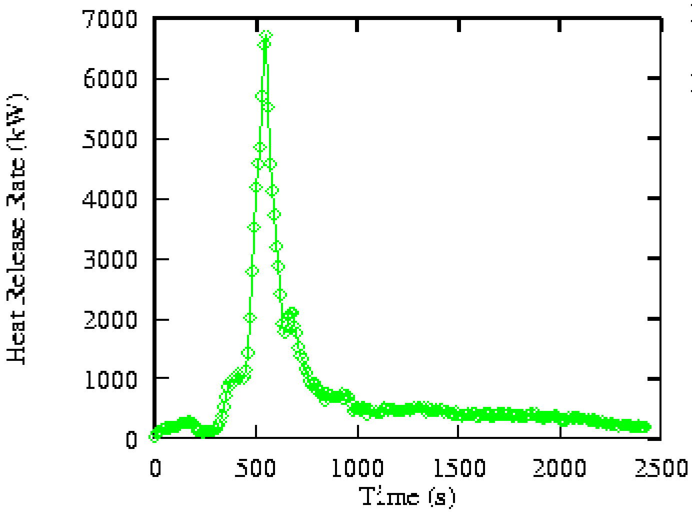
Upward spread up to 20 times faster than downward spread

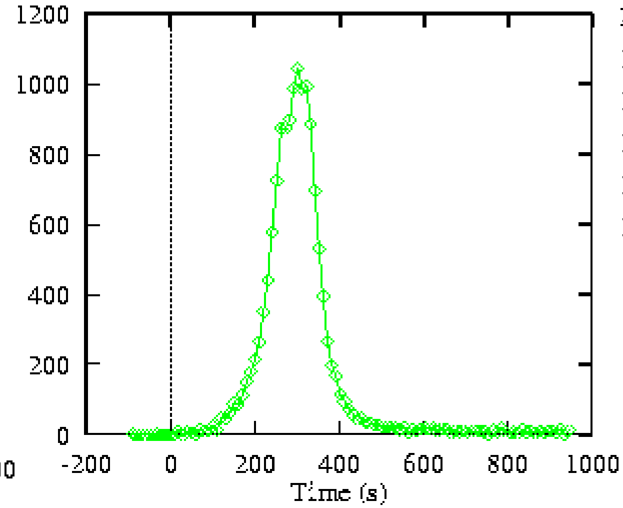
Examples of HRR

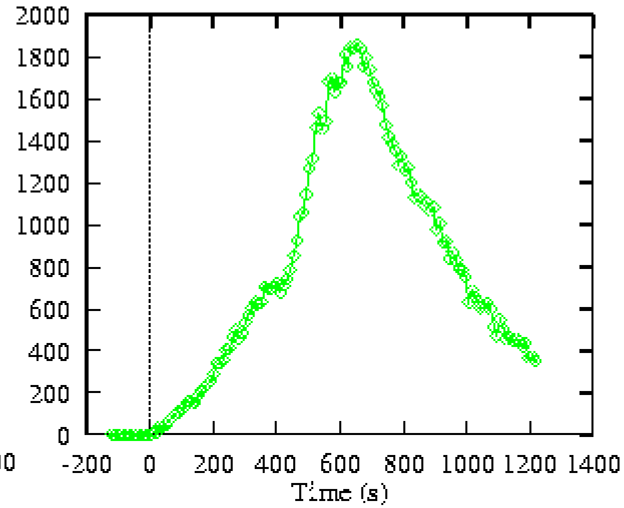
workstation

mattress

wood crib







Under Ventilated fires and External flaming

0:00 min 4:15 min 5:00 min

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

Ceiling Jet

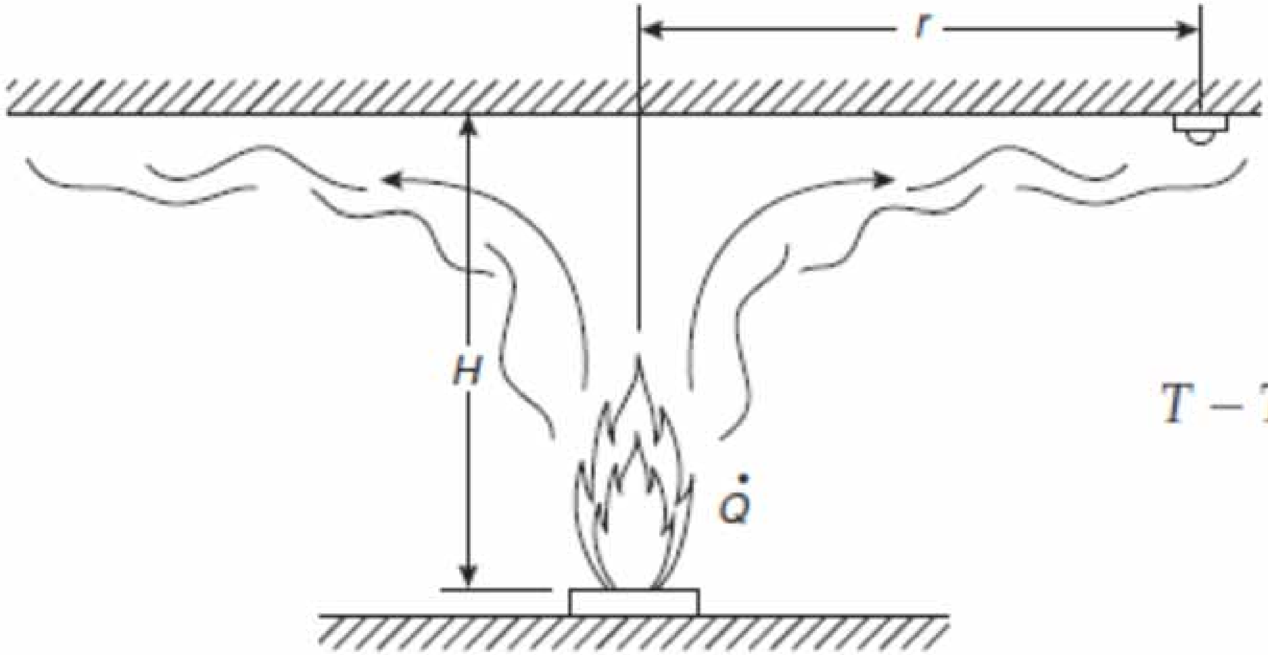
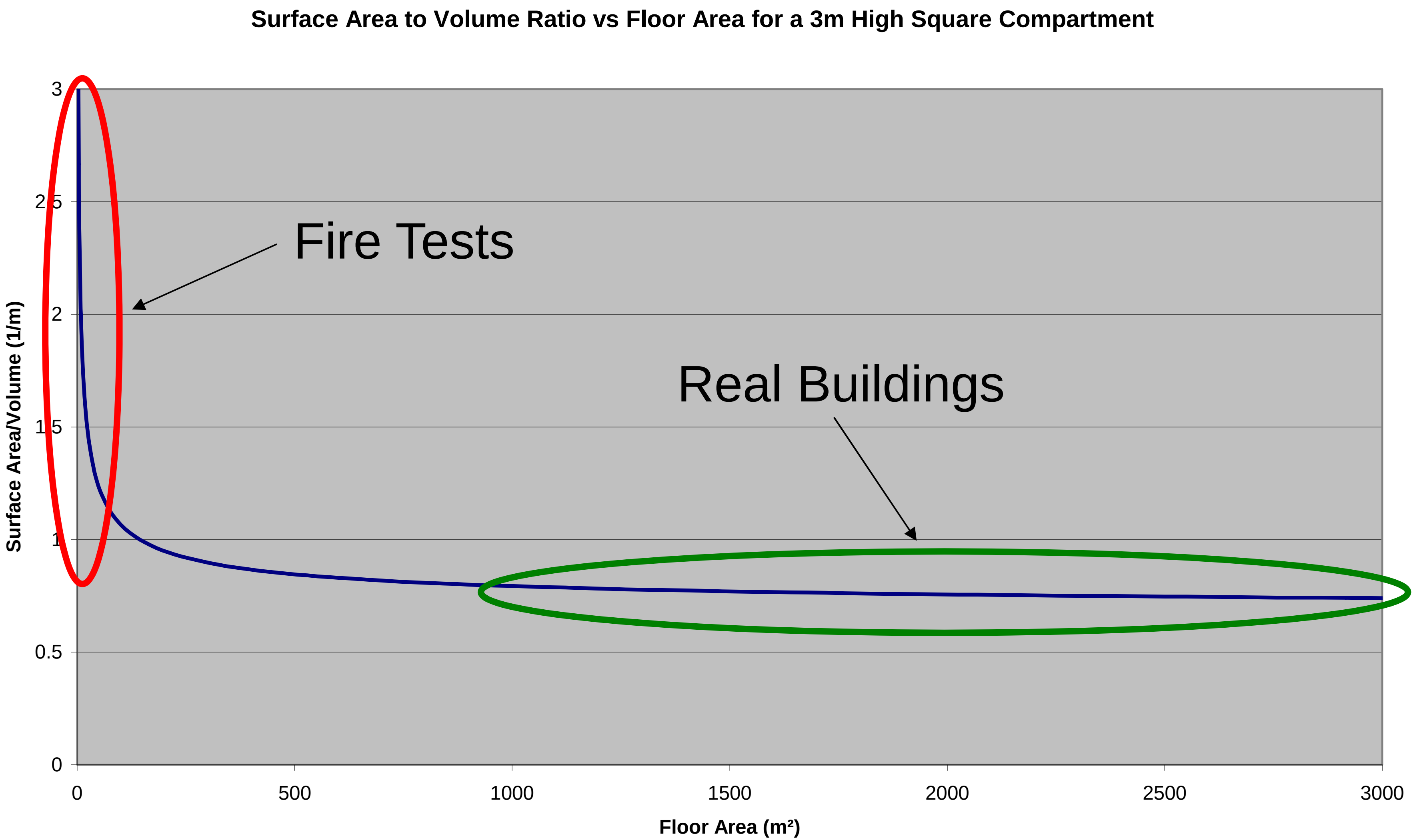


Figure 2-2.1. *Ceiling jet flow beneath an unconfined ceiling.*

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

from Alpert, **Ceiling jet flows**, SFPE handbook

Size Matters



Stern-Gottfried et al, *Fire Risk Management* 2009

Encouraging initial reactions to this work

- Abstract submitted in 2007 to Structures in Fire (SiF)
- Title: "ON THE STRUCTURAL DESIGN FIRES FOR VERY LARGE ENCLOSURES"
- Reviewer #1: *This abstract does not it fit with [conference] theme.*
- Reviewer #2: *This paper is outside the scope of the conference*
- Reviewer #3: *The authors are encouraged to submit their paper somewhere else*

- Abstract submitted in 2011 to Structures in Fire (SiF)
- Title: "TRAVELLING FIRES IN LARGE COMPARTMENTS: MOST SEVERE POSSIBLE SCENARIOS FOR STRUCTURAL DESIGN"
- *Reviewer 1: Several works has been done and published*
- *Reviewer 2: No significant input*
- *Reviewer 3: Authors must provide examples for typical case studies*

Thanks

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