Introduction to Fire Dynamics for Structural Engineers

by Dr Guillermo Rein

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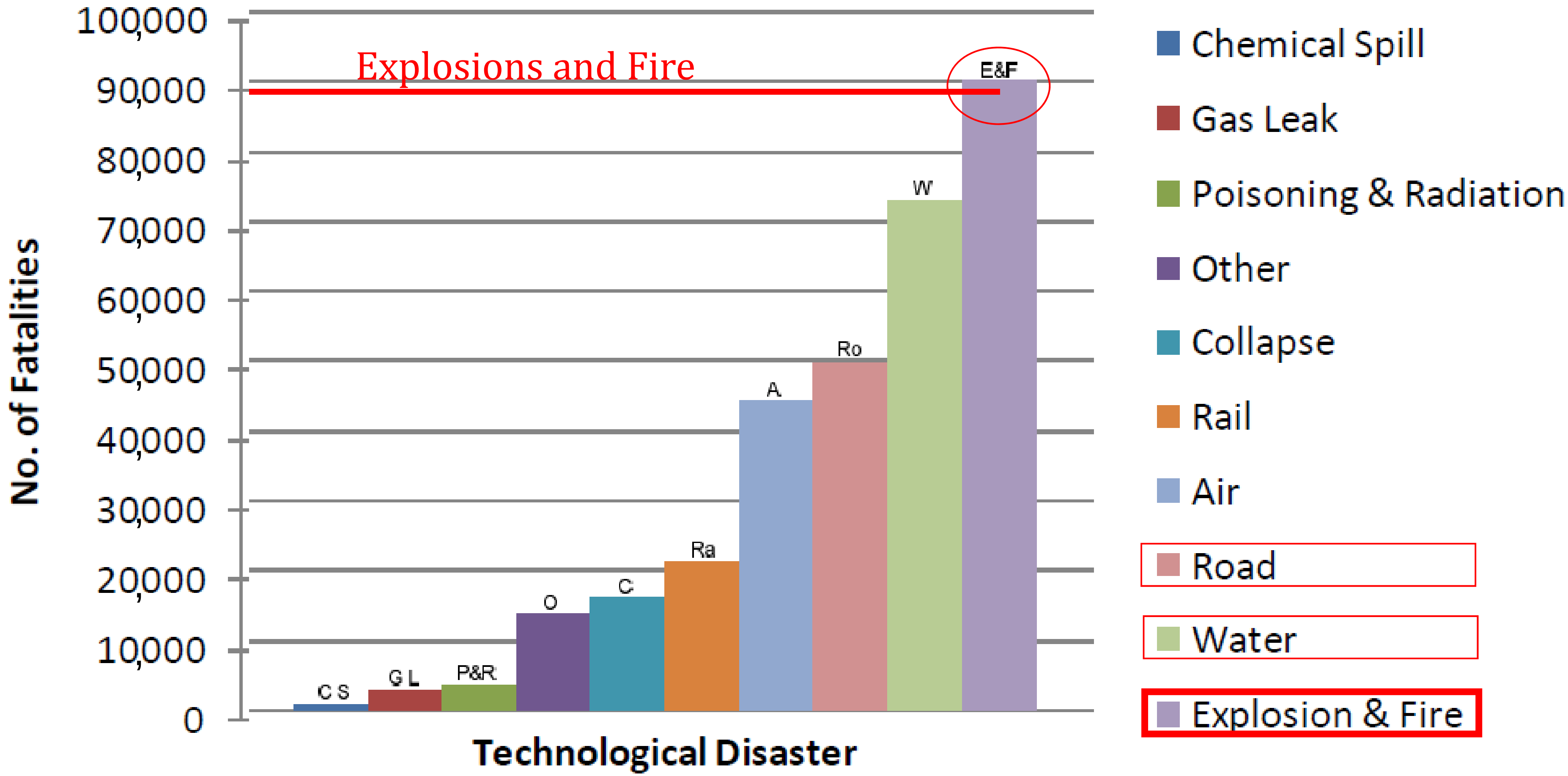
IMPERIAL HAZELAB

Training School for Young Researchers
COST TU0904, Naples, June 2013

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

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

bre
ARUP

190s

bre
ARUP

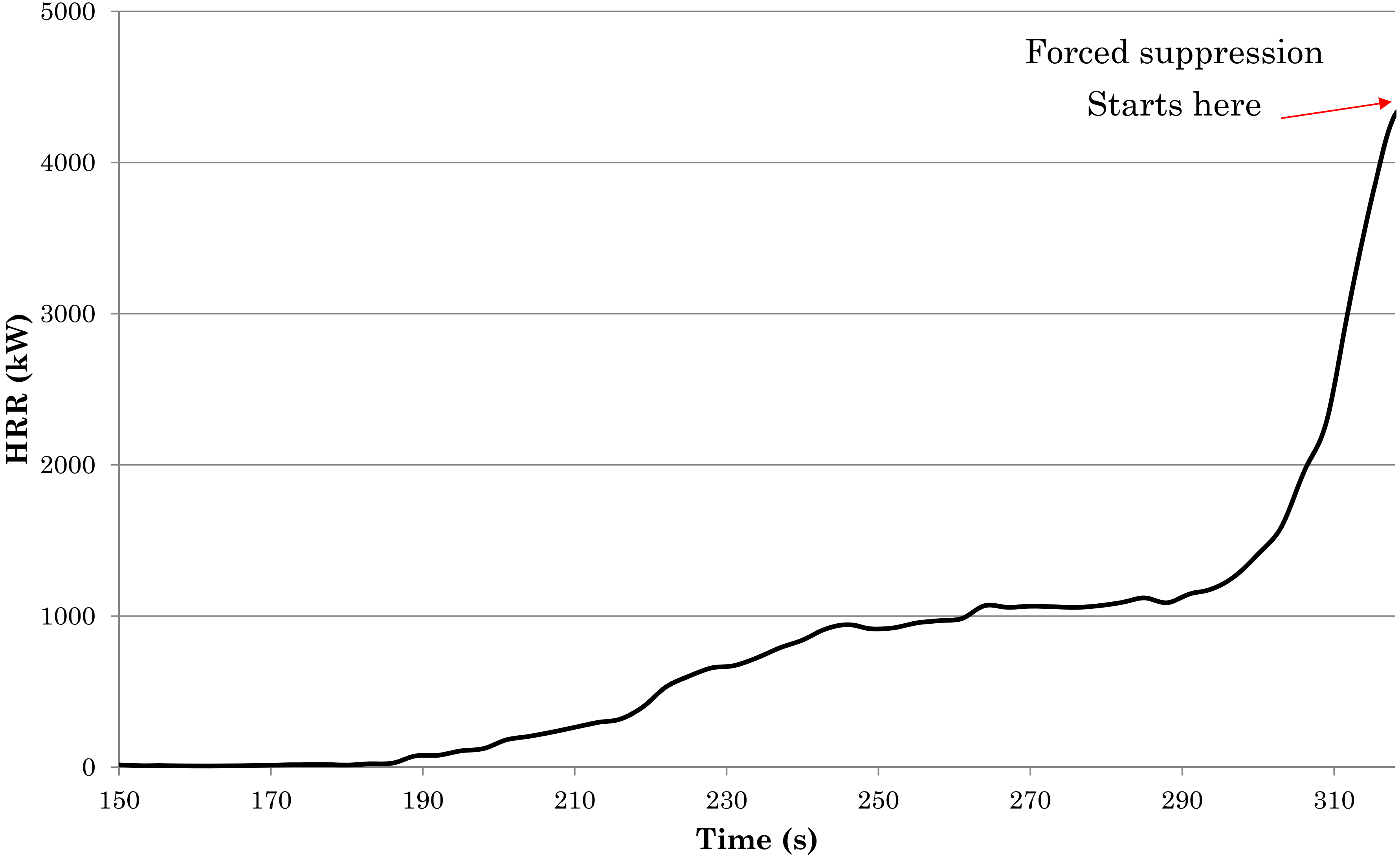
285s

bre
ARUP

316s

bre
ARUP

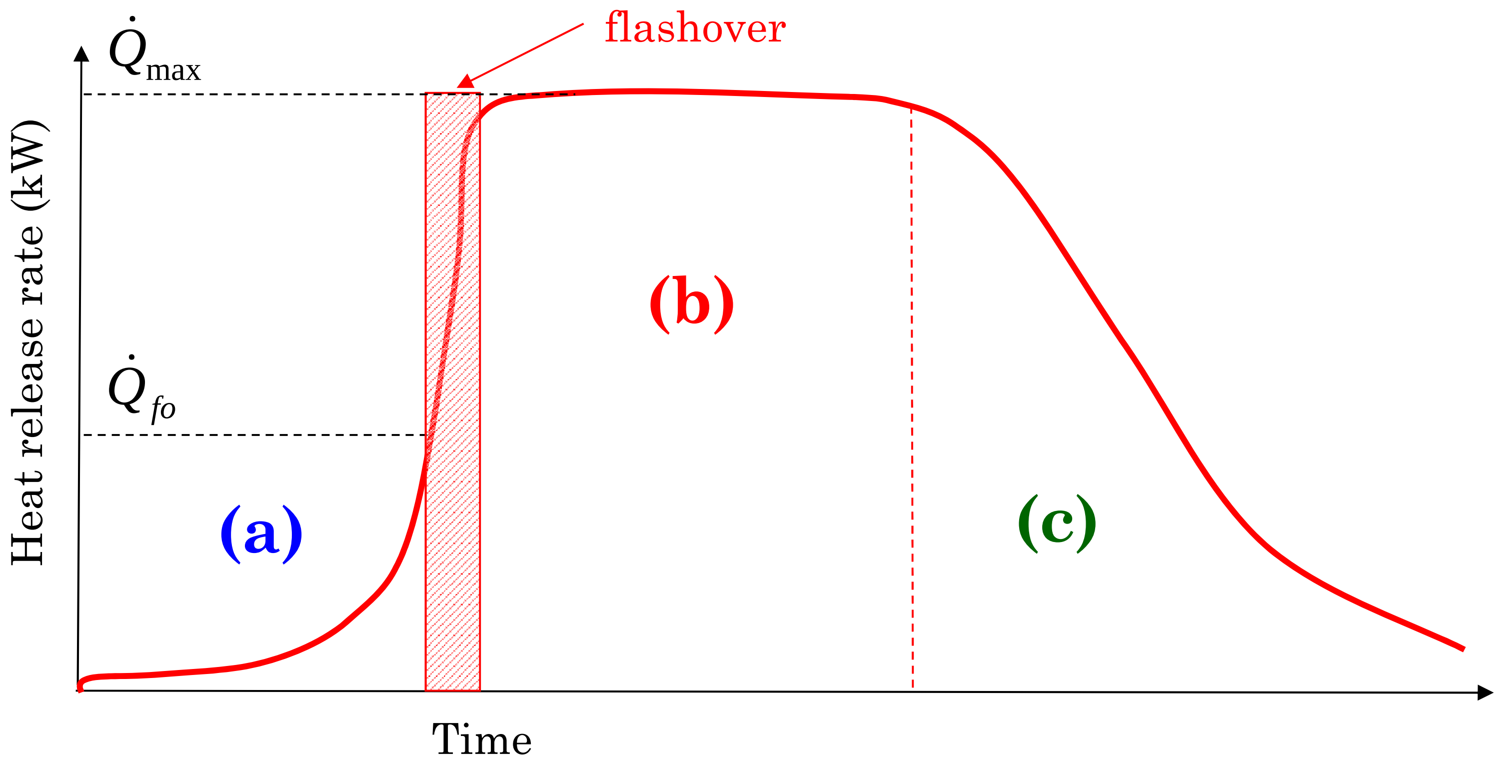
Fire Test in 4 x 4 x 2.4 m enclosure ~ small premise in shopping mall



bre ARUP

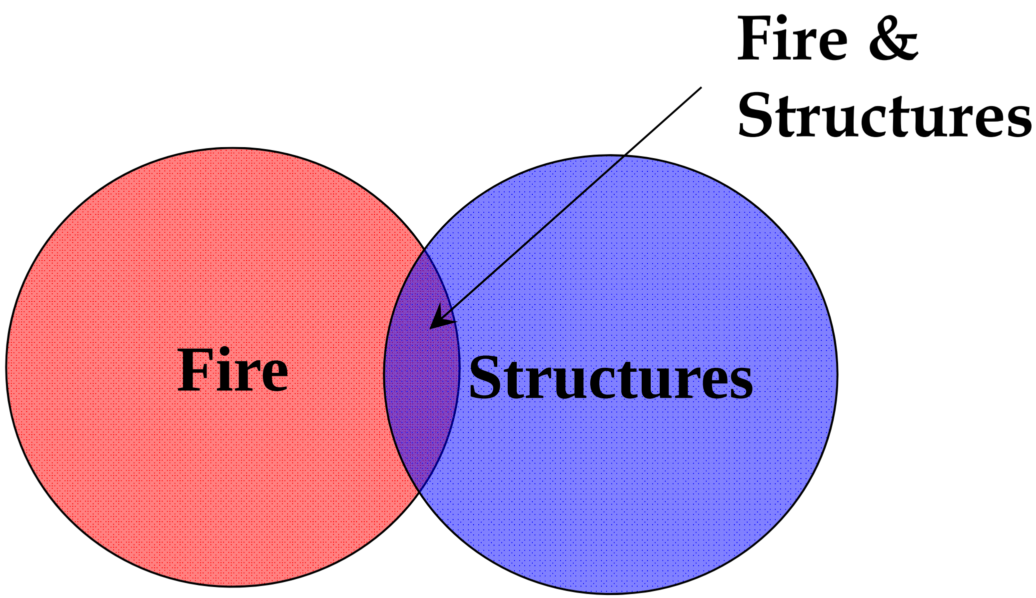
Compartment fires

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



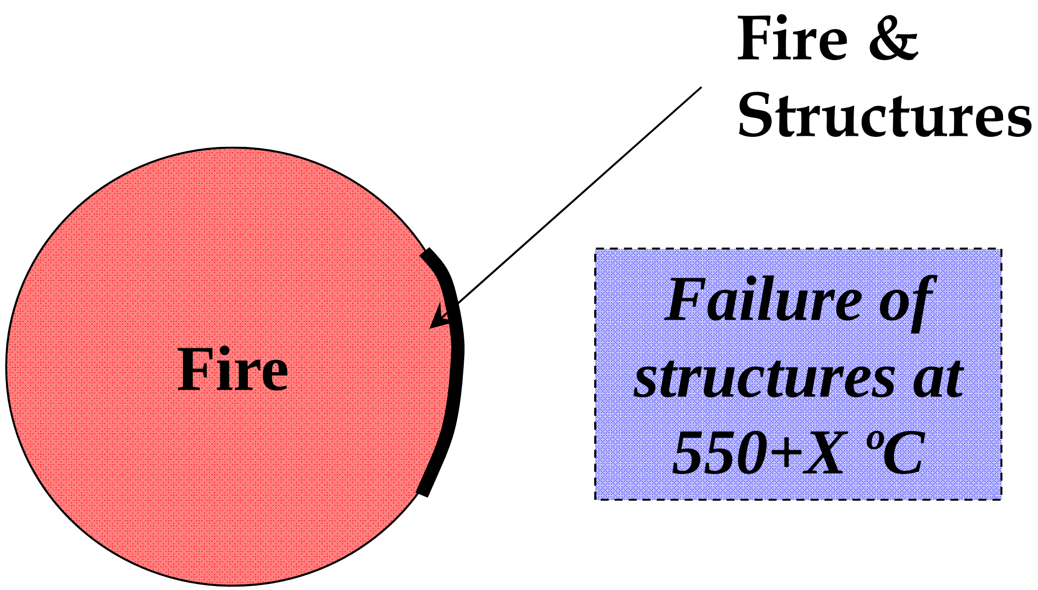
(a) growth period
(b) fully developed fire
(c) decay period

Discipline Boundaries



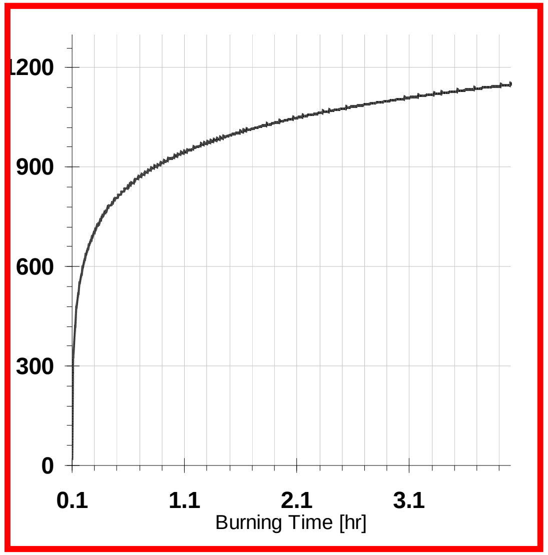
Boundary between fire and structures is the intersection of the two sets

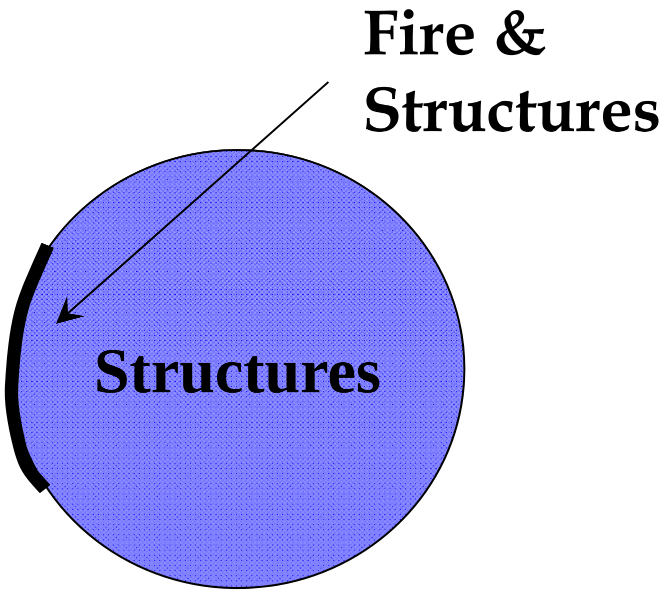
Lame Substitution of the 1st kind



When structural engineers are entirely replaced by pseudo-science.
It still survives in many standards

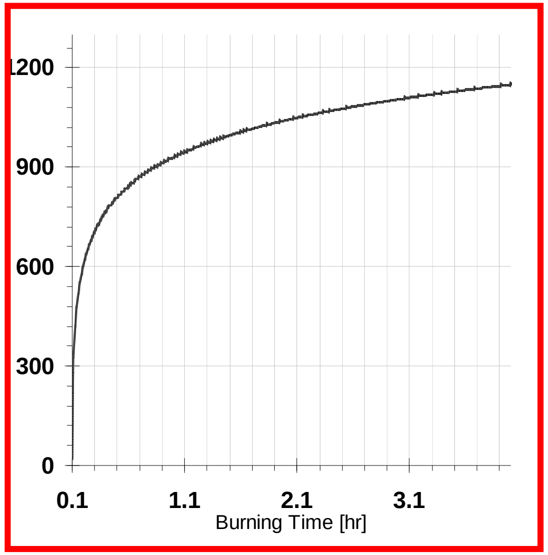
Lame Substitution of the 2nd kind

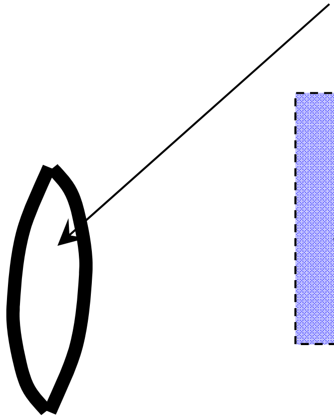




When fire engineers are entirely replaced by pseudo-science.
It is mainstream in structural engineering.

Lame Substitution of the 3rd kind





Fire & Structures

Failure of structures at 550+X °C

When both fire and structural engineers are simultaneously replaced by pseudo-science.
Any similarities with reality is a mere coincidence.

Objective of this talk

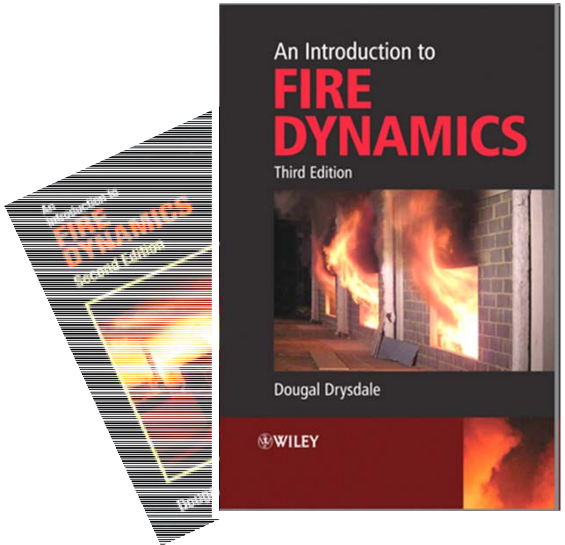
Provide an introduction to fire dynamics to the audience, a majority of structural engineers working on fire and structures

This introduction will make emphasis on the mechanism governing fire growth in compartments

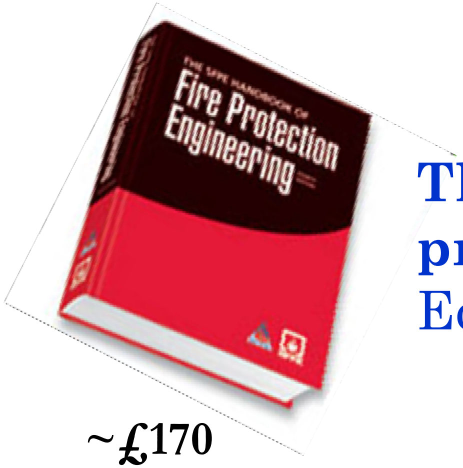
Then, two most fundamental flaws of current design fire methodologies will be reviewed

Textbooks

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



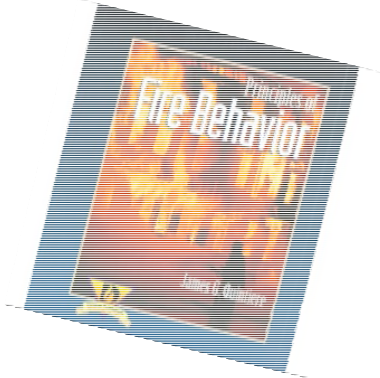
~£46



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

~£170

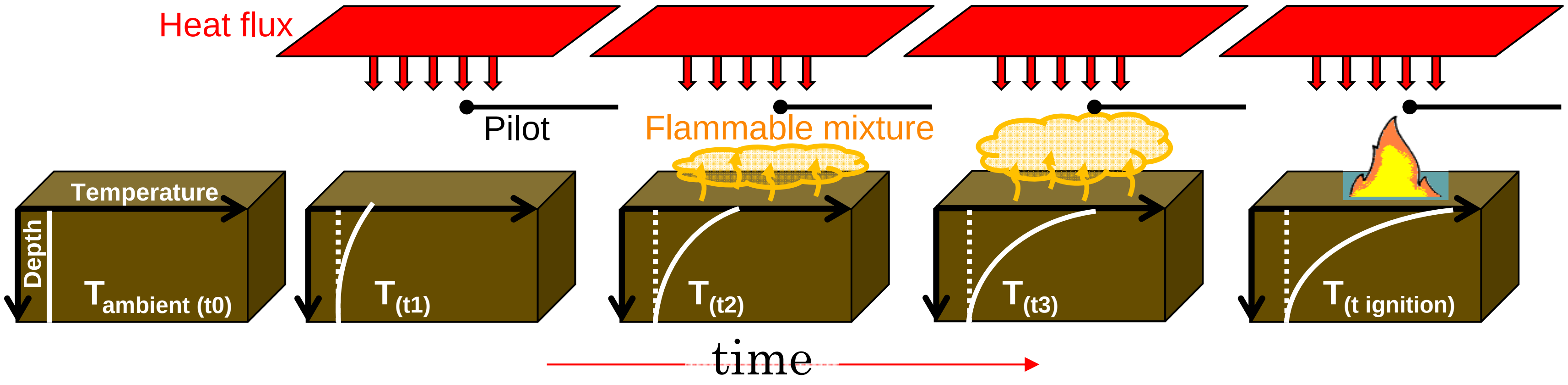
Principles of Fire Behavior
by James G. Quintiere

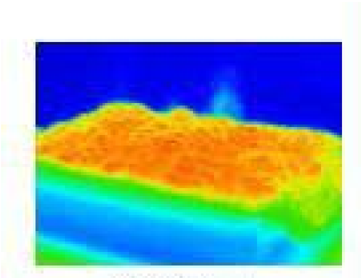


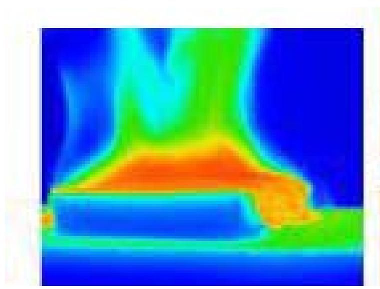
~£65

Ignition – fuel exposed to heat

- Upon receiving sufficient heat, a solid/liquid fuel starts to decompose giving off gasses: pyrolysis
- Ignition takes place when a flammable mixture of fuel vapours is formed over the fuel surface







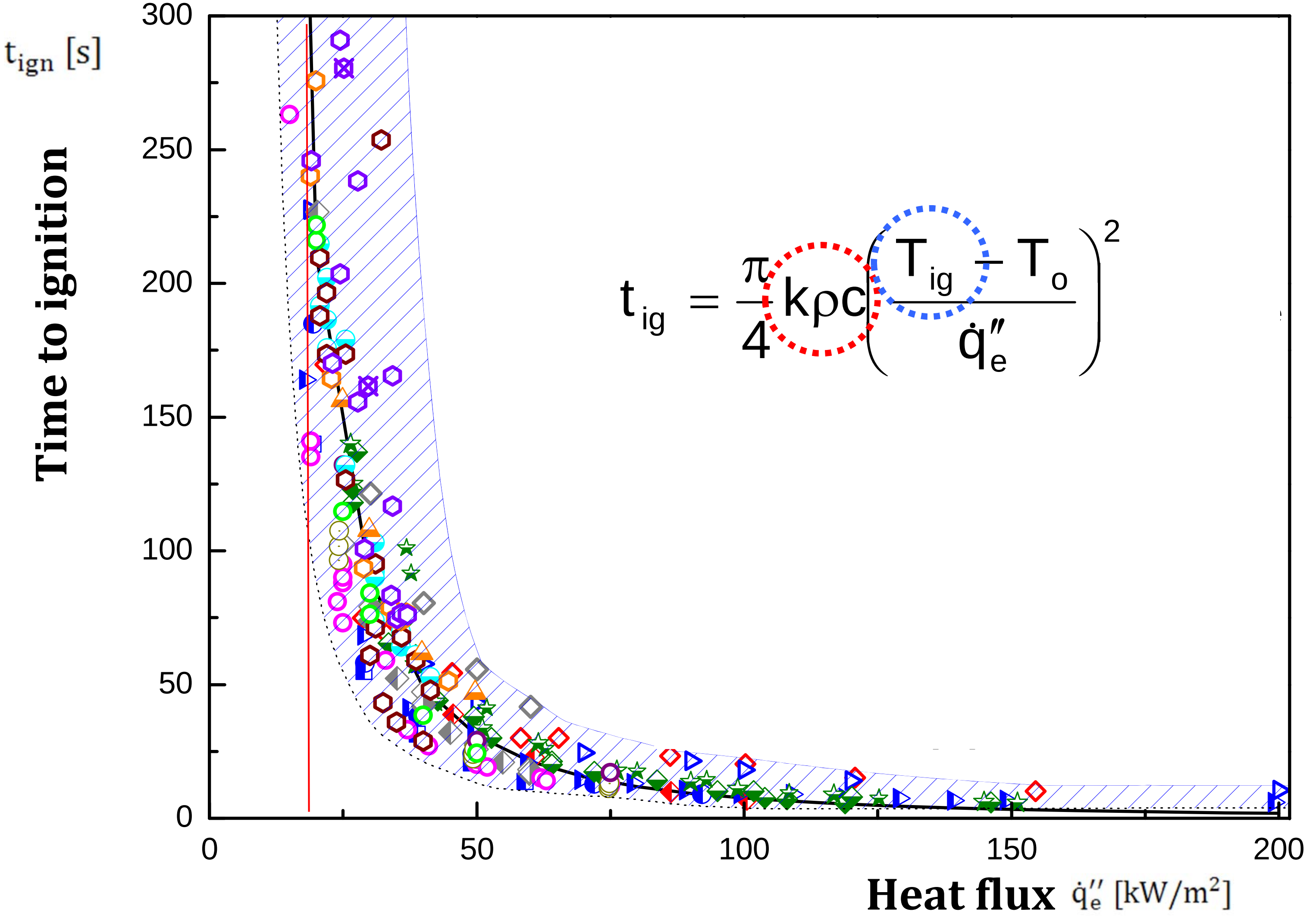
Pyrolysis video

Pyrolysis of clear PMMA slab 25mm thick

htttp://www.youtube.com/watch?v=UusEwufhWaw

Time to ignition – Thick Samples

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

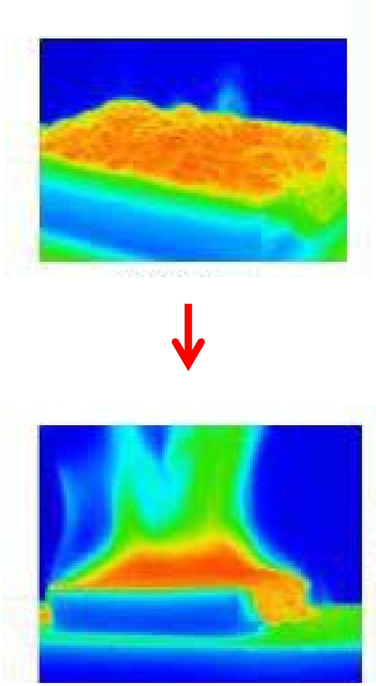


from Bal and Rein, **Combustion and Flame 2011**

Flammability
~ material property

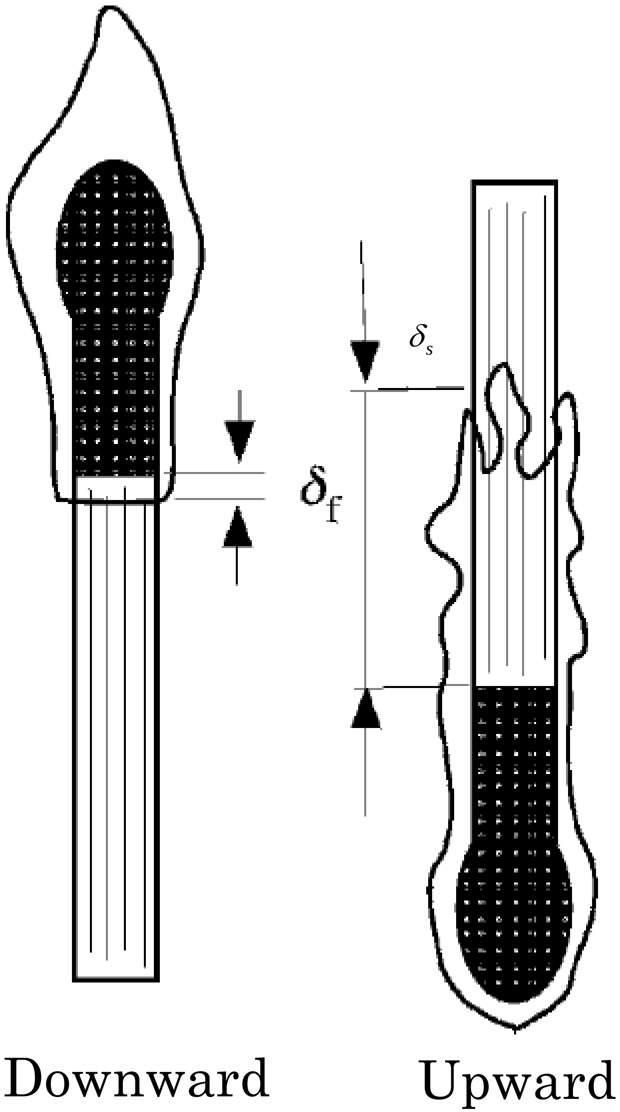
Ignition Data from ASTM E-1321 per Quintiere

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.

Flame Spread Rate



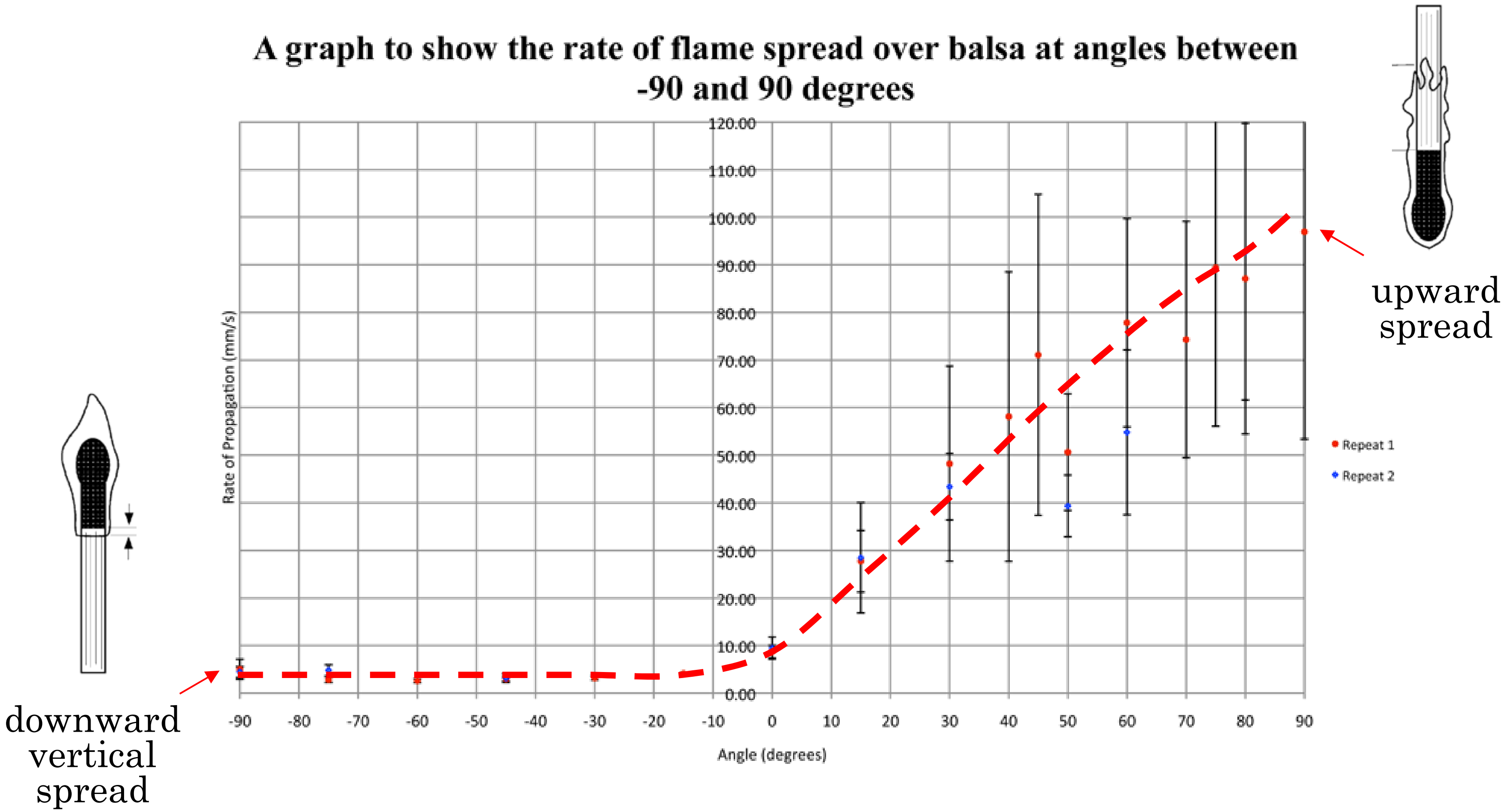
$$S \propto \frac{\delta_s}{t_{ig}}$$

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

Flame Spread vs. Angle



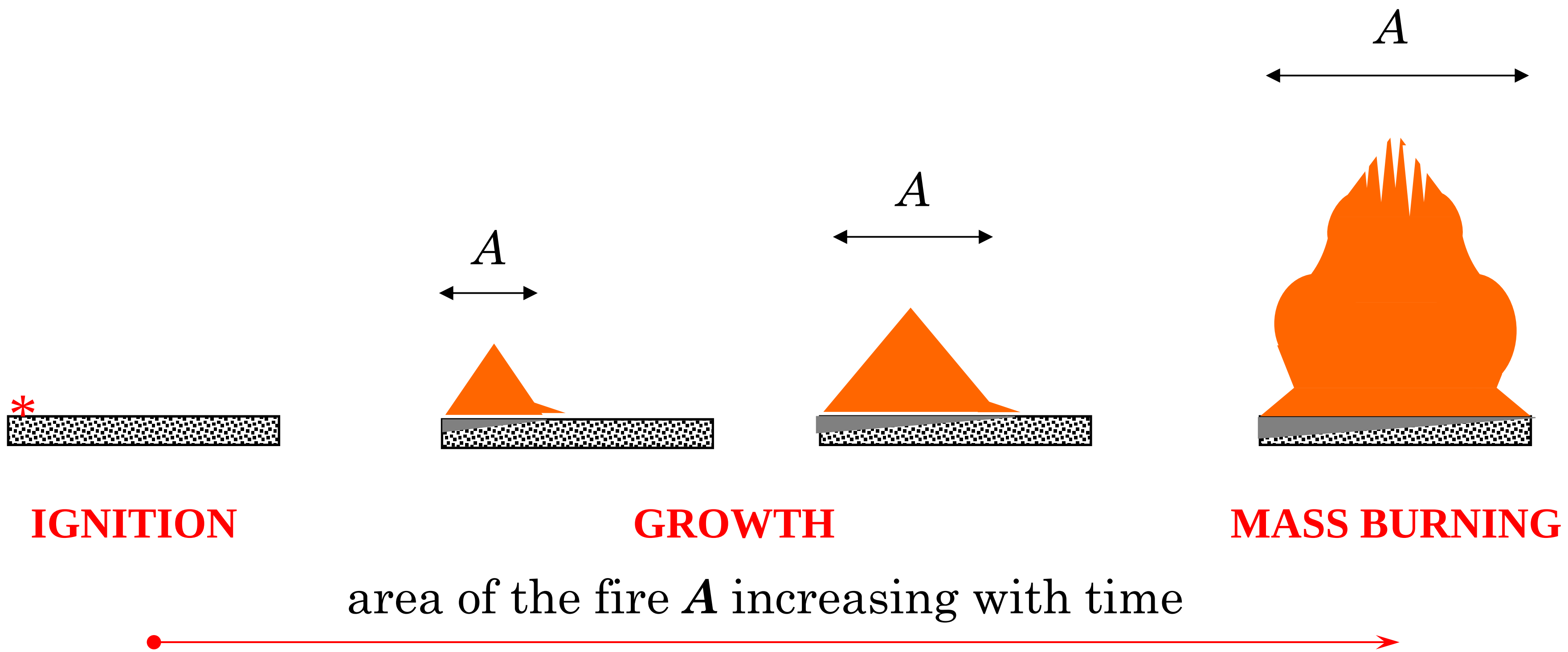
Upward spread is 20 times faster than downward spread

Test conducted by Aled Beswick BEng 2009

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


A
A
A
IGNITION
GROWTH
MASS BURNING
area of the fire A increasing with time

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

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
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

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**

In general, it is a material and scenario dependant. In open fires it can be approximated as a material property only.

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

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_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

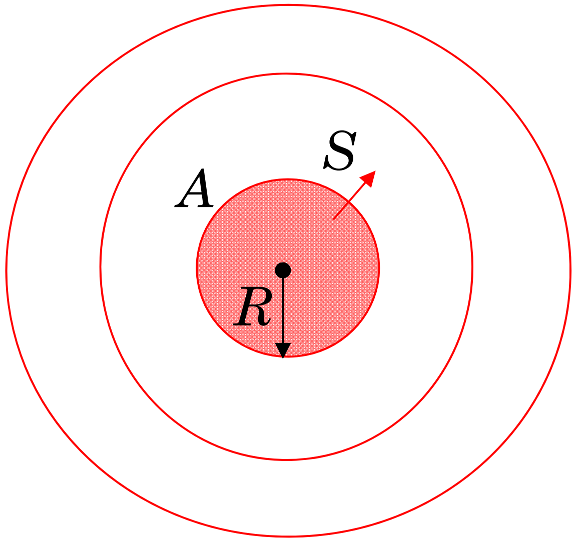
[a] The initial states of the fuels correspond to their natural states at normal temperature and pressure (298°C and 1 atm pressure). All products are taken to be in their gaseous state—thus these are the net heats of combustion.

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

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

Flame spread

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



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

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

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

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

~ material property in well ventilated fires

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

when flame spread is ~constant, the fire grows as t²

t-square growth fires

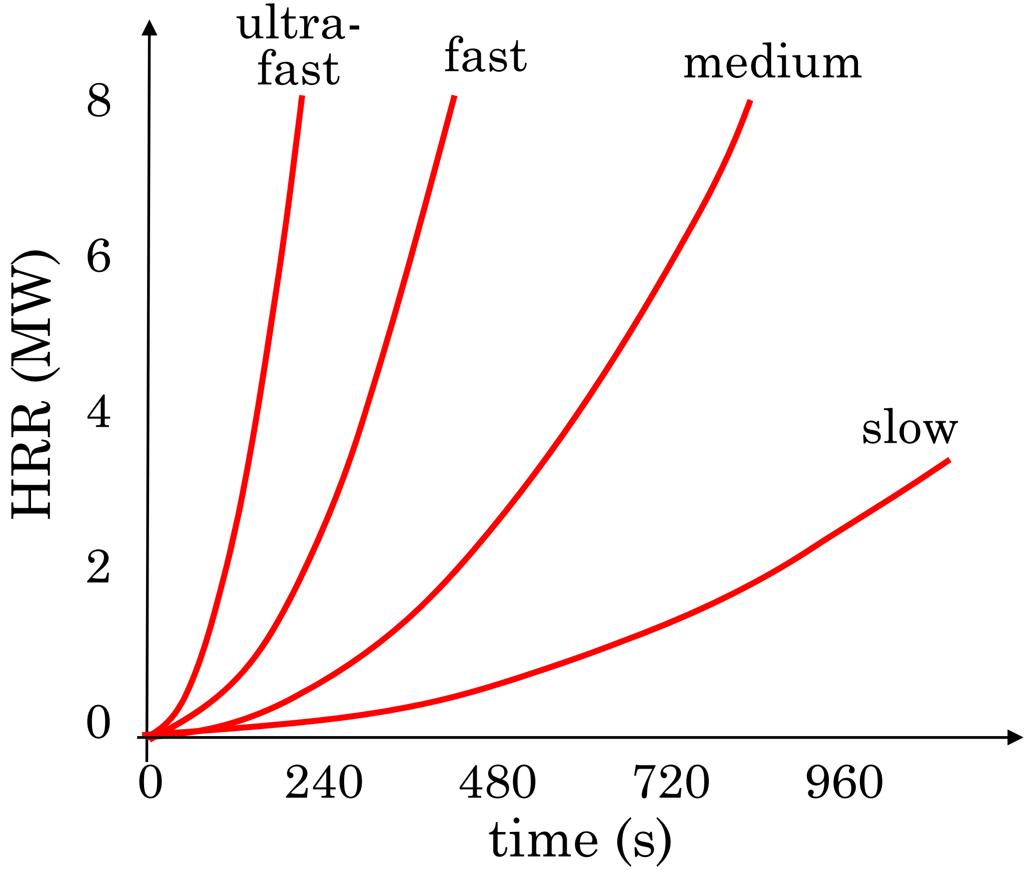
Tabulated fire-growths of different fire types

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

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

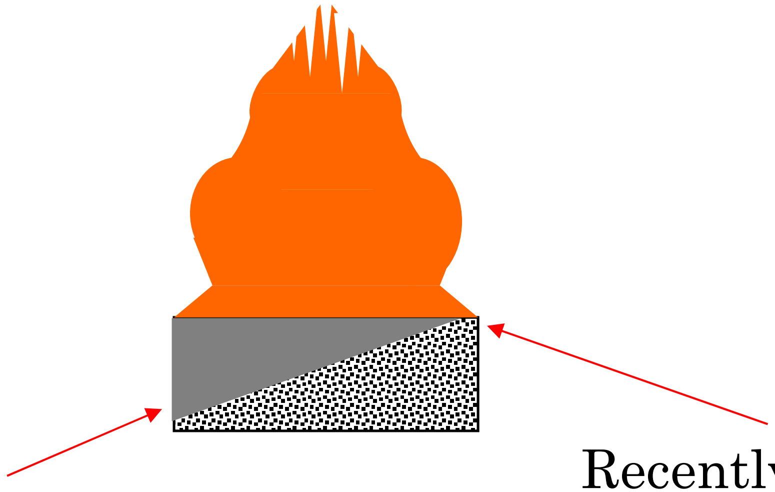
Description	Typical scenario	α_f kW/s^2
Slow	Densely packed paper products[a]	0.00293
Medium	Traditional mattress/boxspring[a] Traditional armchair	0.01172
Fast	PU mattress (horizontal)[a] PE pallets, stacked 1 m high	0.0469
Ultrafast	High-rack storage PE rigid foam stacked 5 m high	0.1876

[a] National Fire Protection Association (1993a).



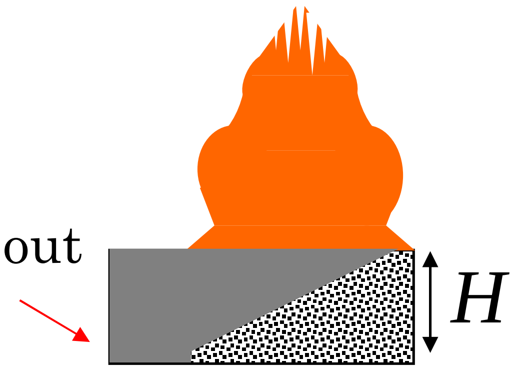
Burn-out

At some point:

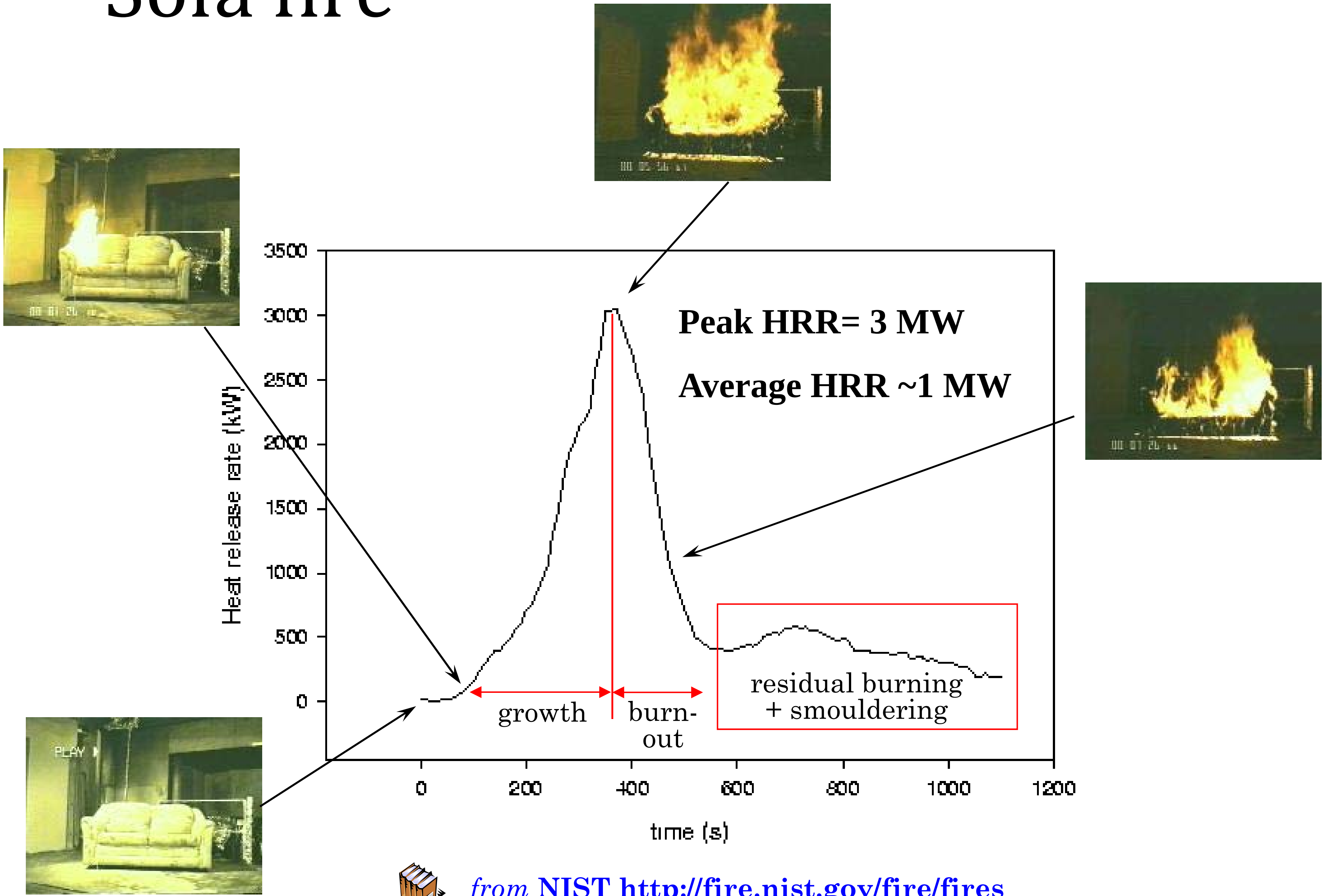


Later on:

$$t_{out} = \frac{H\rho}{\dot{m}''}$$



Sofa fire



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

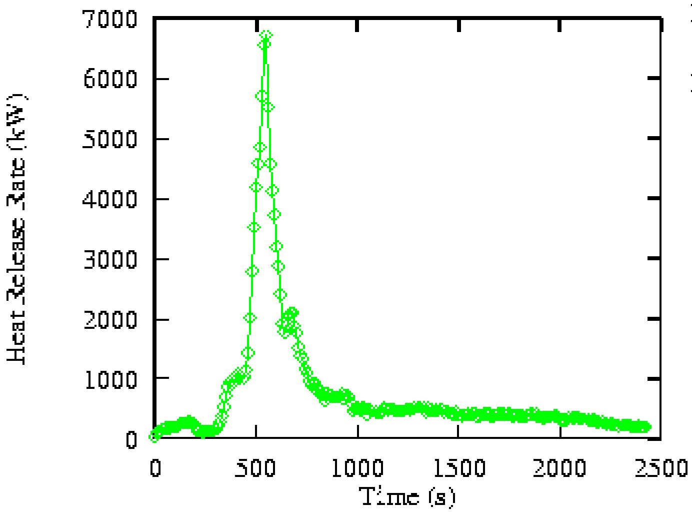
Examples of HRR

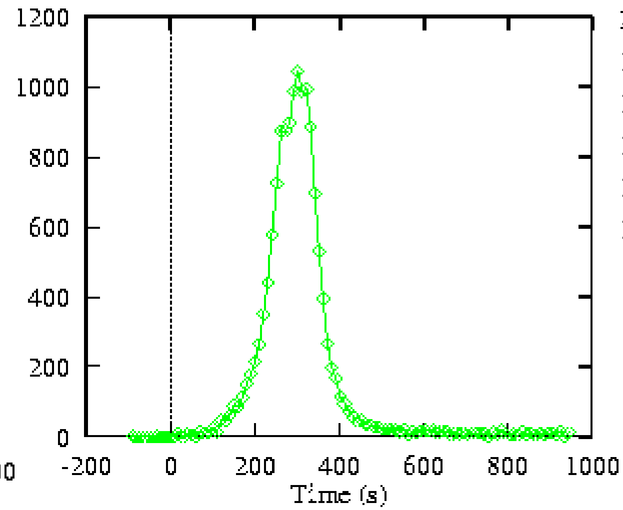
from **NIST http://fire.nist.gov/fire/fires**

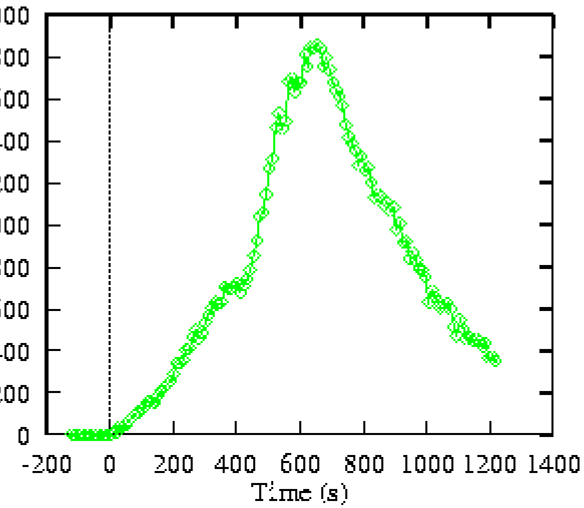
workstation

mattress

wood crib







190s

285s

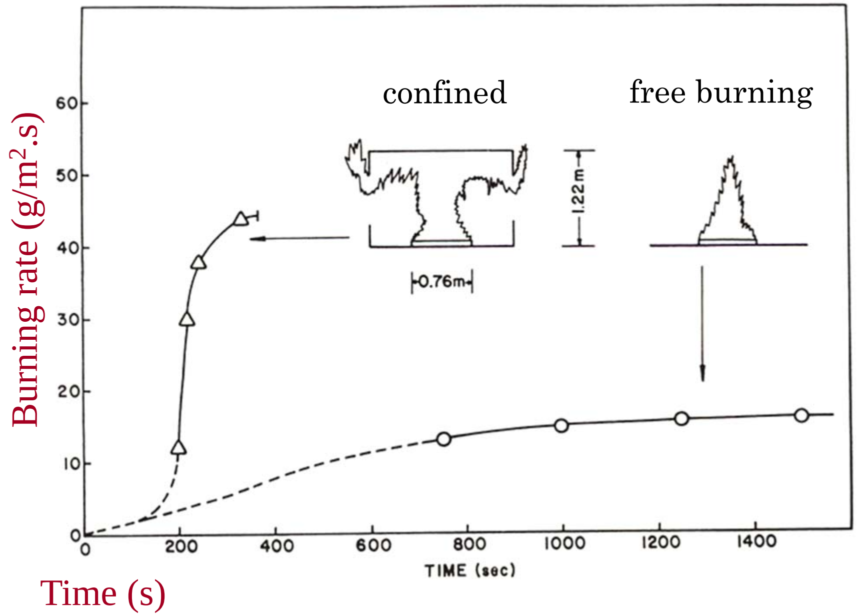
316s

bre
ARUP

Free burning vs. Confined burning

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

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



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

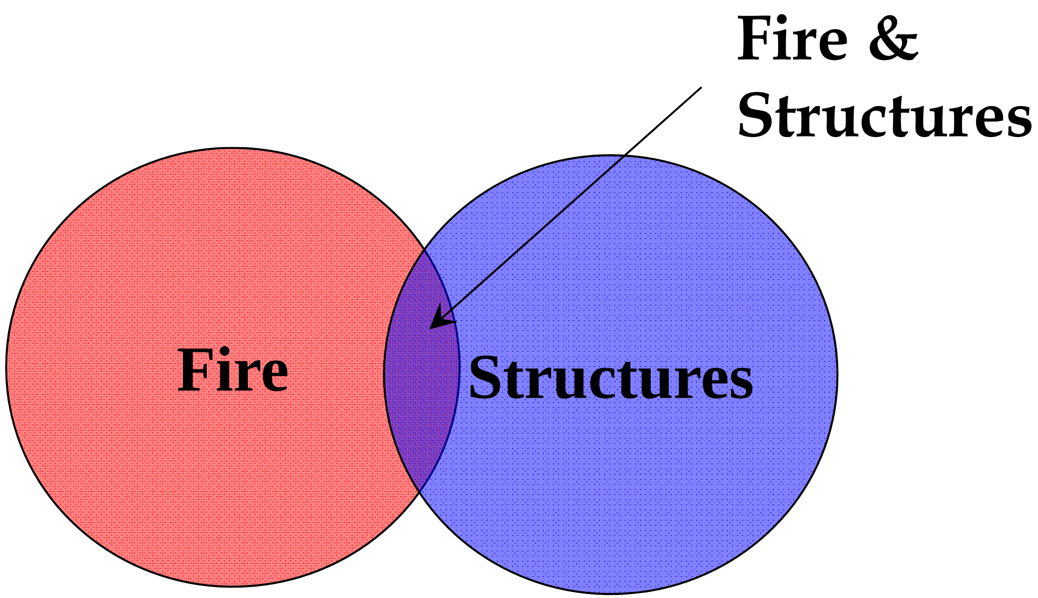
NOTE: Average temperate of 600°C implies that the room space is occupied mostly by interment flames

I believe in human rights,

therefore:

Break of 5 min

Discipline Boundaries



GI $\Rightarrow$ GO

- When problems arise at the interface between fire and structures, most consequences travel downstream, ie. towards the structural engineer

- **If the input is incomplete or wrong, the subsequent analysis is flawed and cannot be trusted**

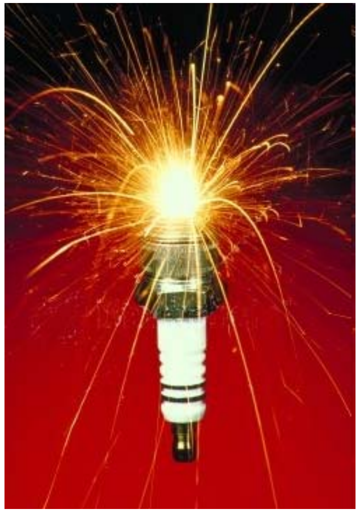
- Fire is the input (boundary condition) to subsequent structures analysis.

Views of fire

Artist

Geoscientist

Forester



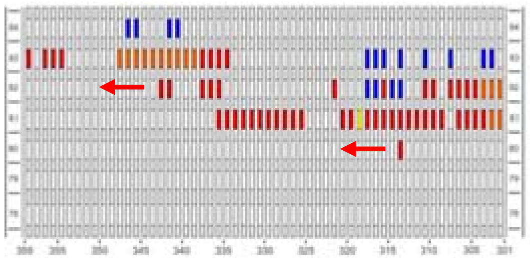
Mechanical engineer

Structural engineer

Rest of the world

WTC 2 - East face

9:05 am



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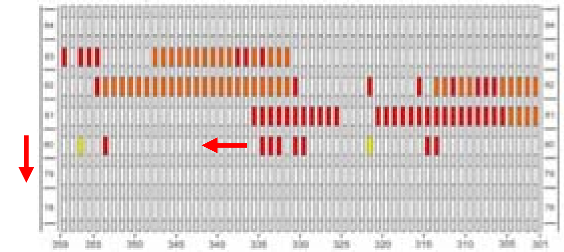
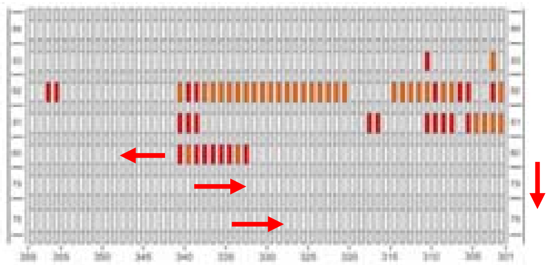
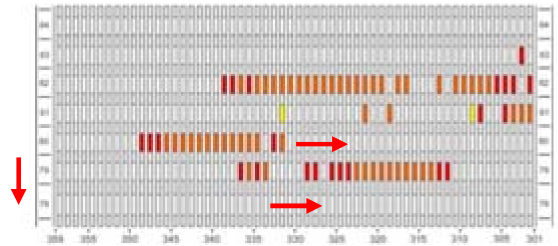


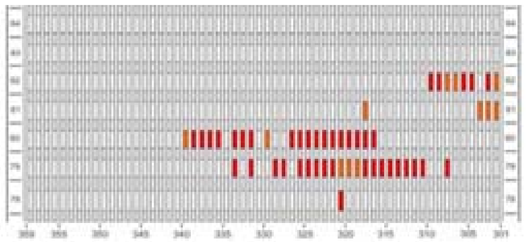
9:30 am



9:45 am



10:00 am



White = no fire

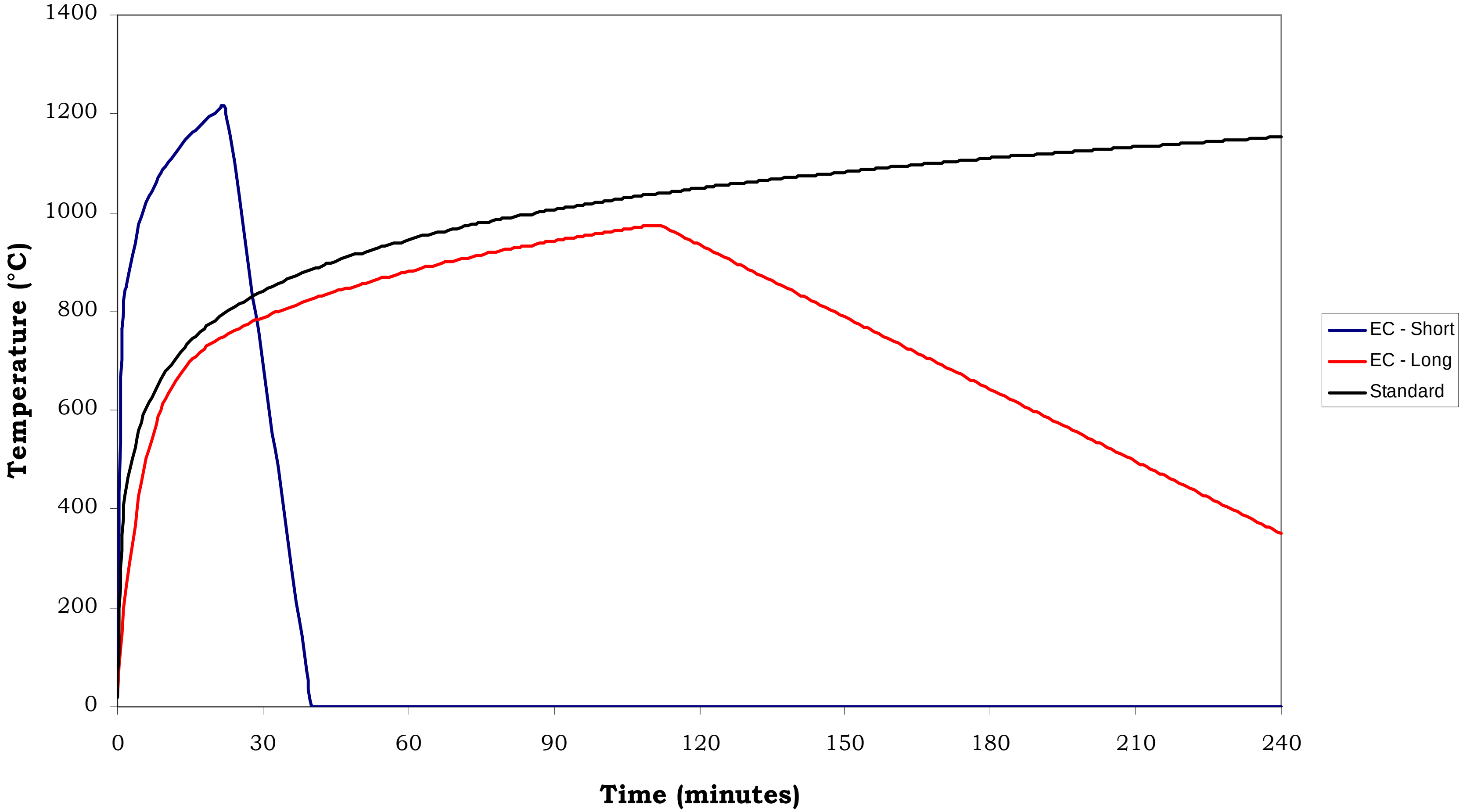
Red = fire visible inside, Orange = external flaming, Yellow = spot fire

Blue = observation not possible

figures/data from NIST

Ancient Design Fires
Traditional Design Fires

- Standard Fire ~1880 (on paper in ~1912)
- Swedish Curves ~1972
- Eurocode Parametric Curve ~1995



Blind extrapolation from limited experience

Fire in Small compartment

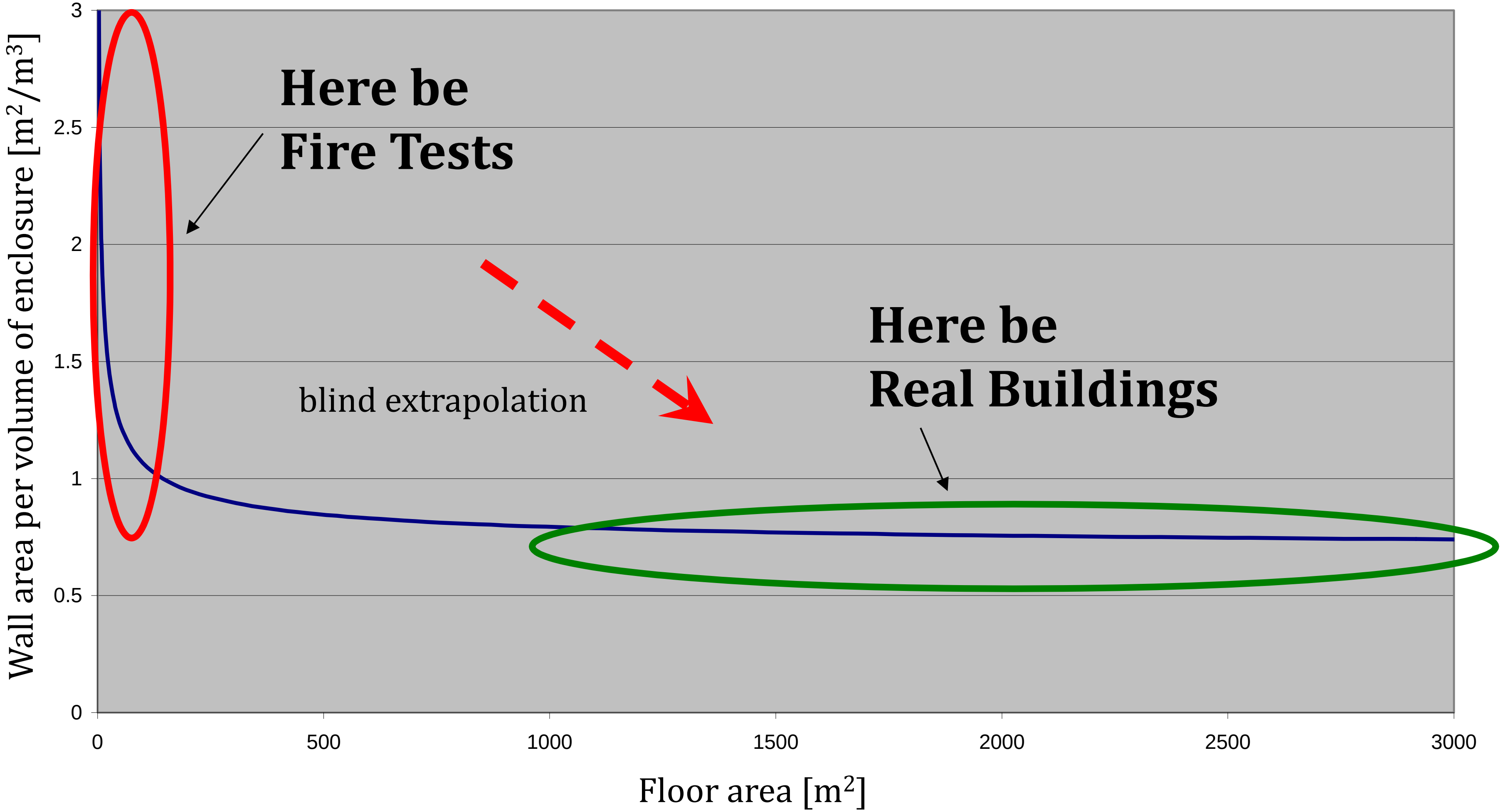
blind extrapolation

Fire in Normal compartment

Fire in Large compartment

Fire in Multi-storey compartment

Scaling effects



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

What follows is a review of the current state of the art on design fires in fire and structures.

I believe in human rights,

therefore:

Break of 5 min

Traditional Methods

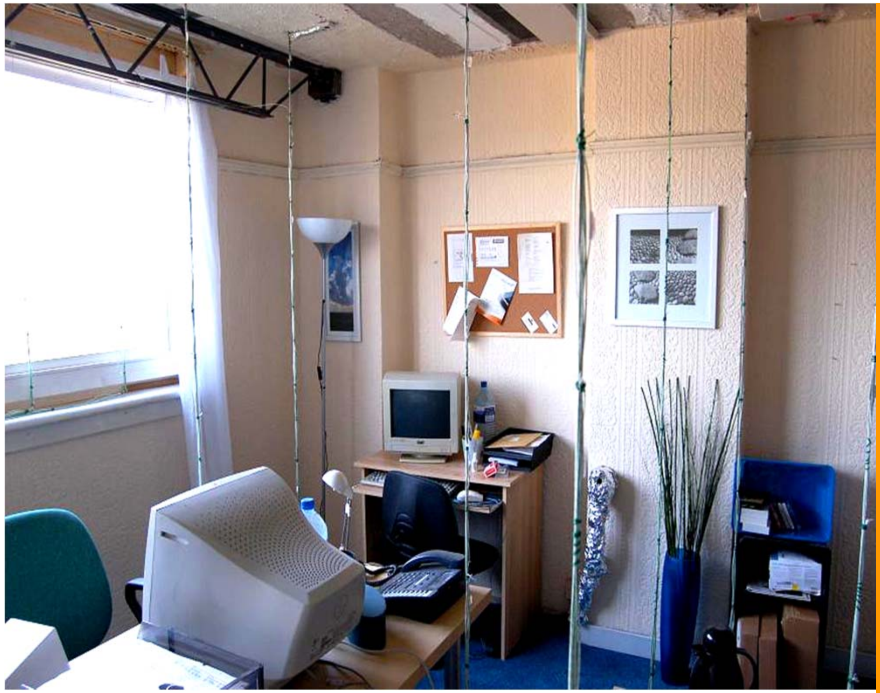
- Traditional methods are based on experiments conducted in **small compartment** (~3 m^3)

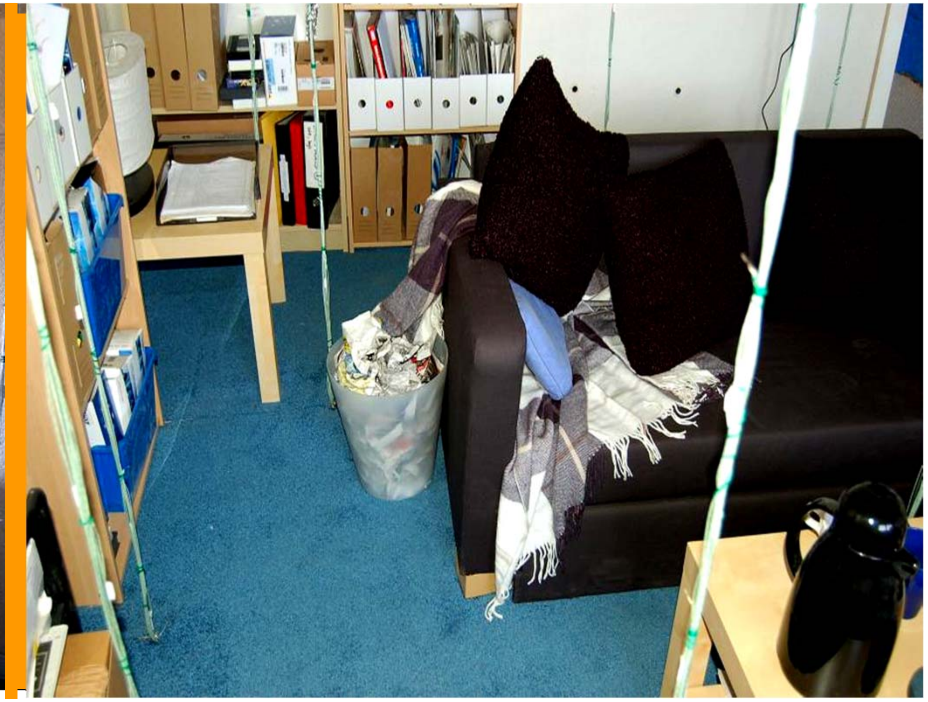
1. Traditional methods assume **uniform fires** that lead to uniform fire temperatures (?)

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

Stern-Gottfried, PhD thesis, *University of Edinburgh* 2011.

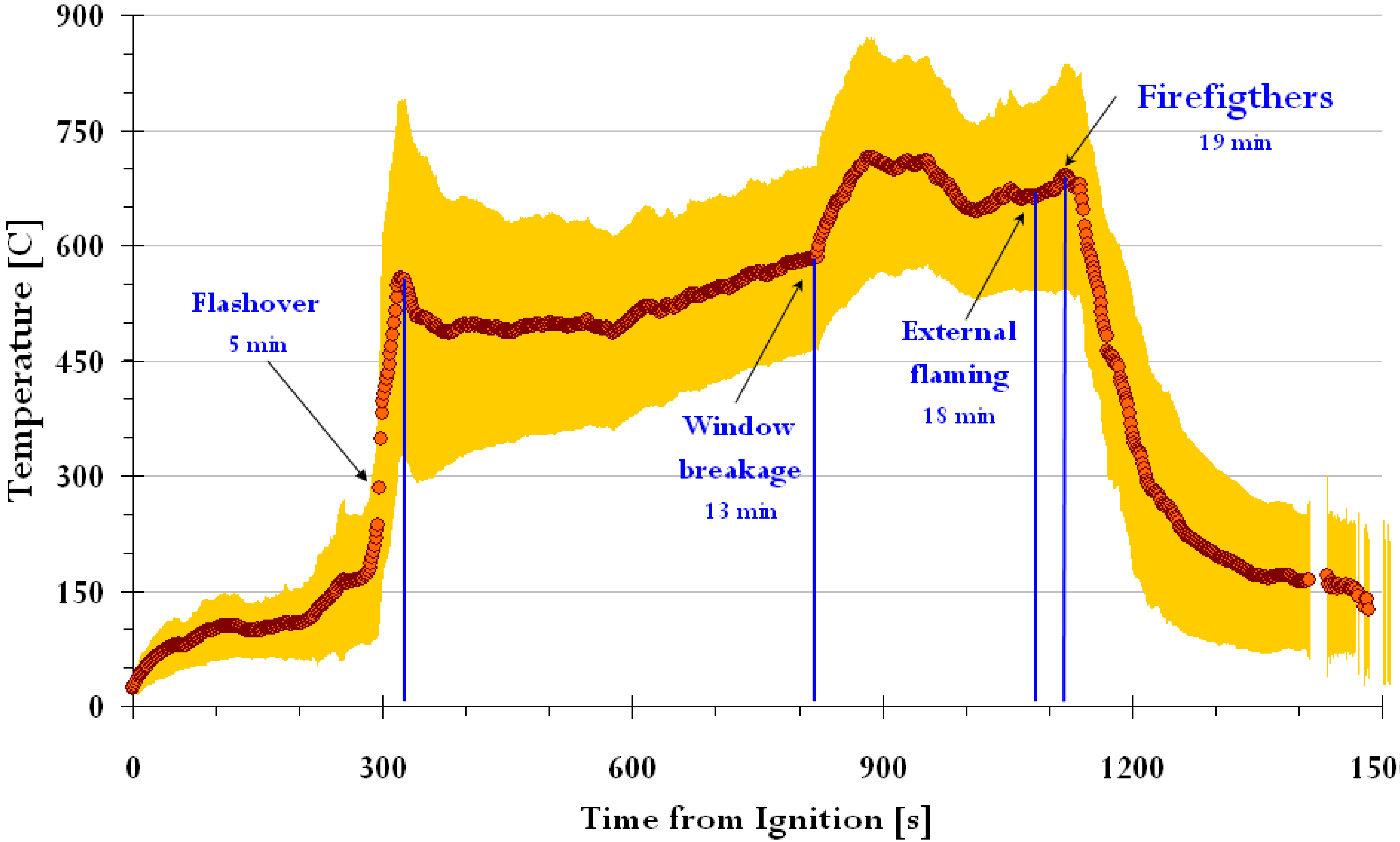
Fuel Load





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

Average Compartment Temperature



Compartment Temperature

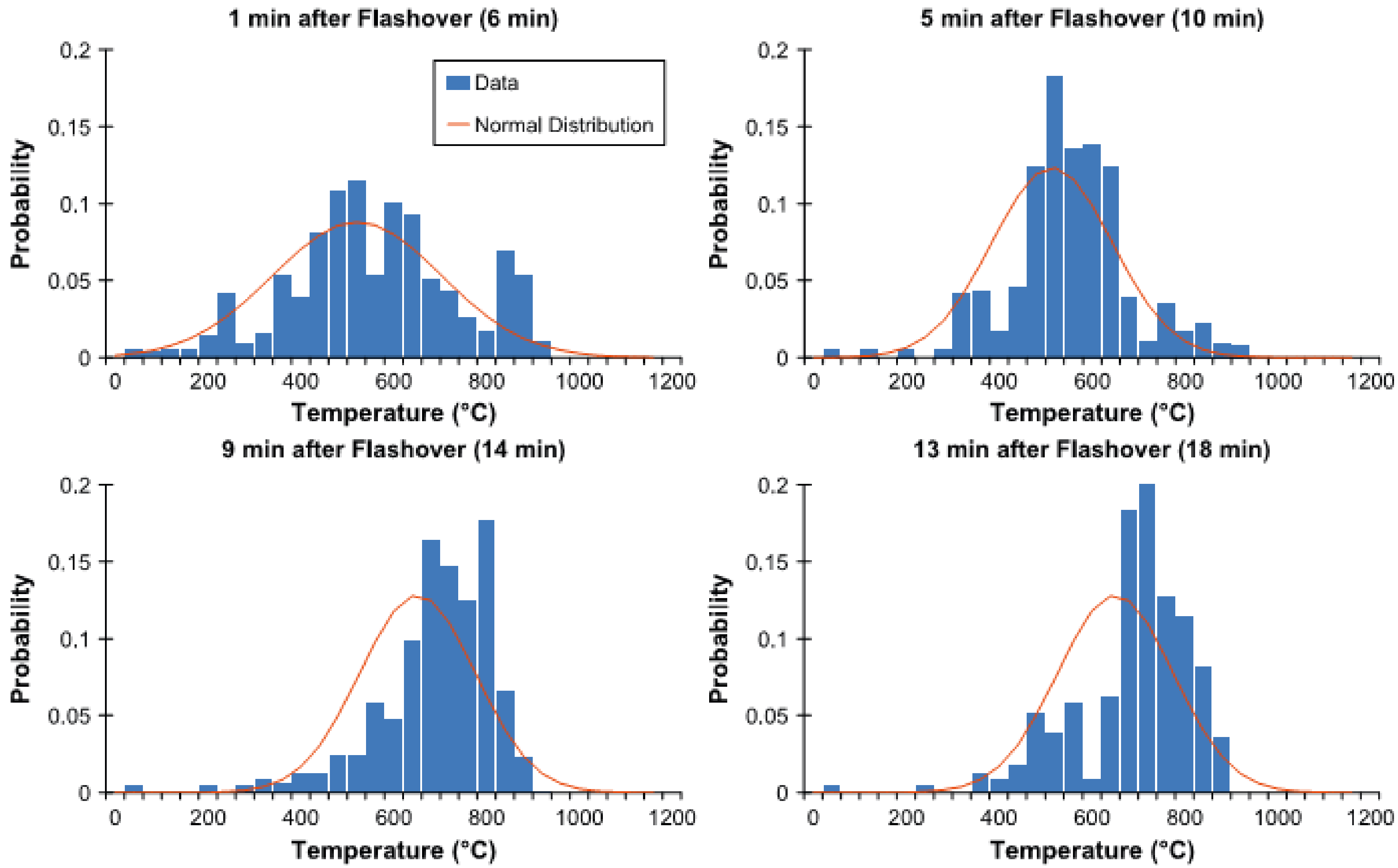
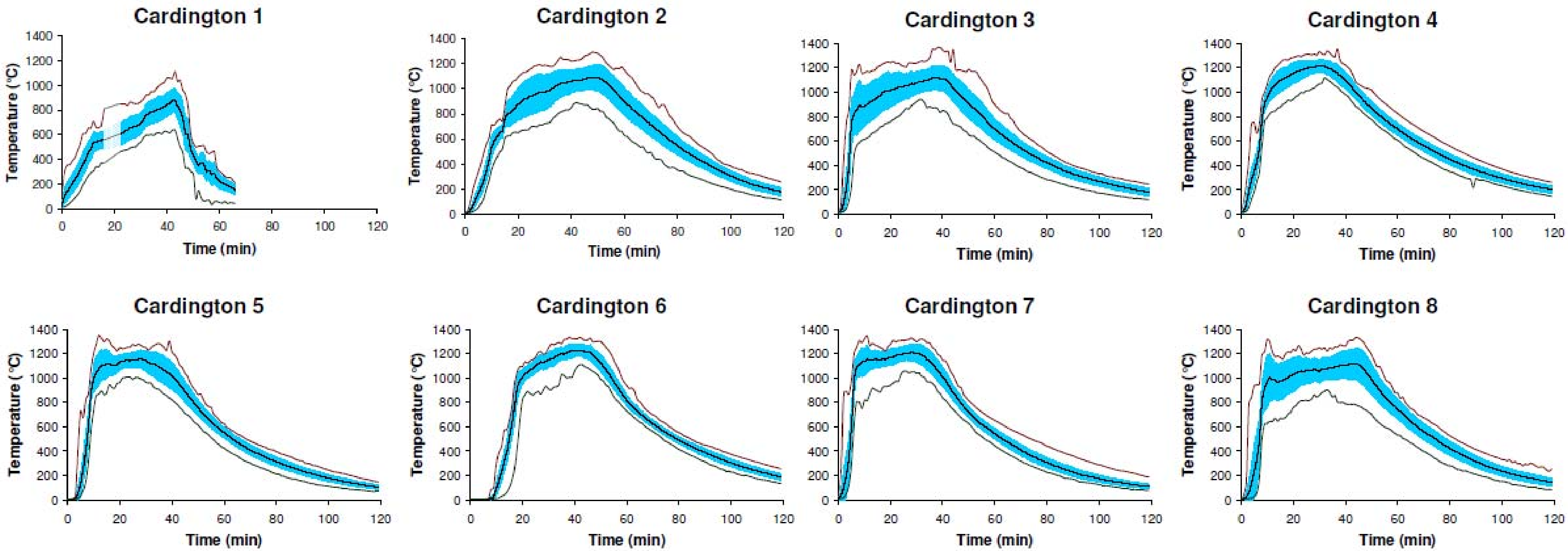


Fig. 6. Comparisons of the measured temperature distributions against the associated normal distributions at 4 min intervals after flashover for Dalmarnock Test One.

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

Cardington Results



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

Conclusions on homogeneity

- Decently instrumented fire tests show considerable non-uniformity in the temperature field
- When exposed to 80% percentile temperatures instead of average, the time to failure decreases to 15% in Protected Steel and to 22% for Concrete.
- **One single temperature for a whole compartment is not correct nor safe assumption**
- Heterogeneity has significant impact on structural fire response
- Fire tests with crude spatial resolution have led to erroneous conclusions
- Future tests should be instrumented as densely as possible

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

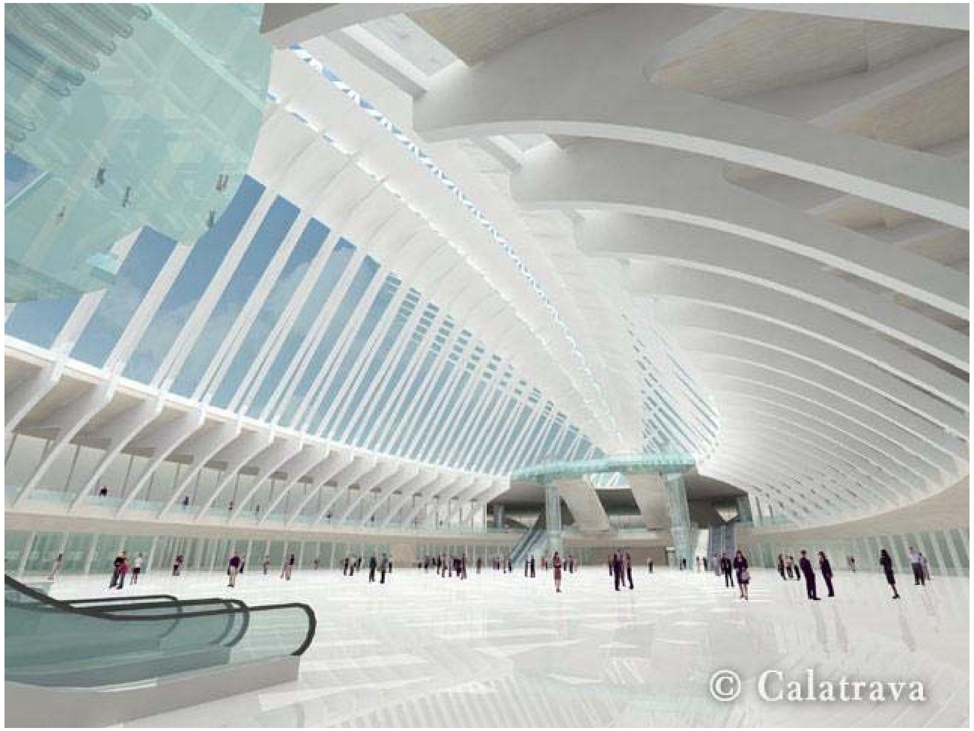
Limitations

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

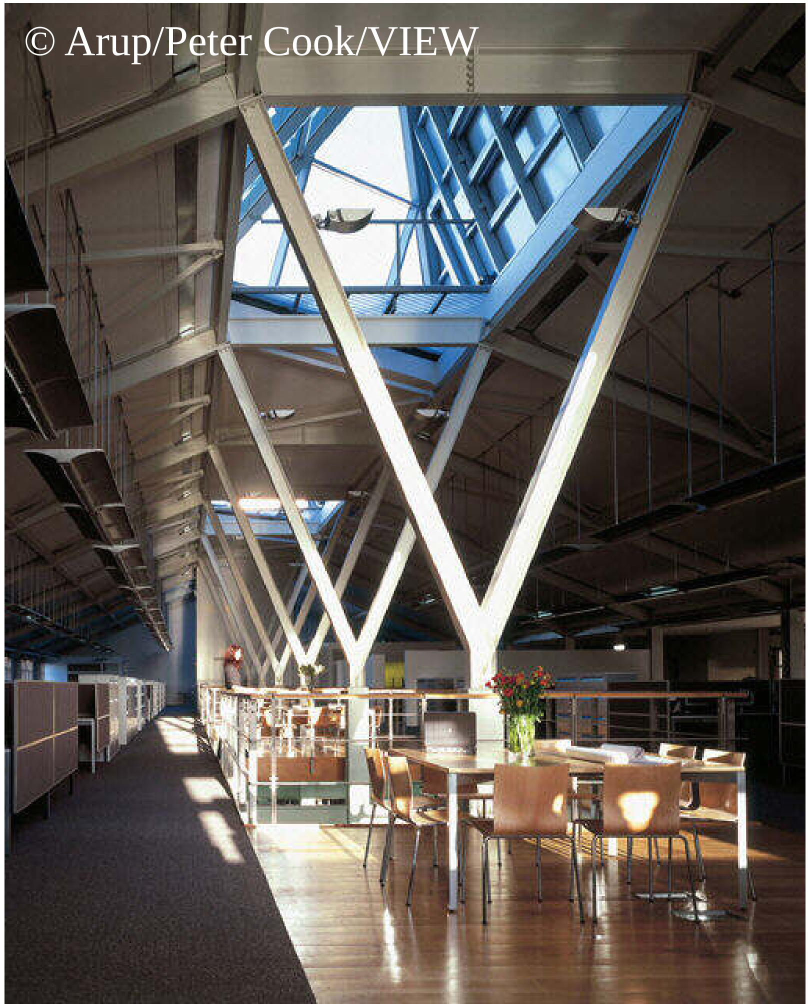


Proposed WTC Transit Hub

Insulating lining?

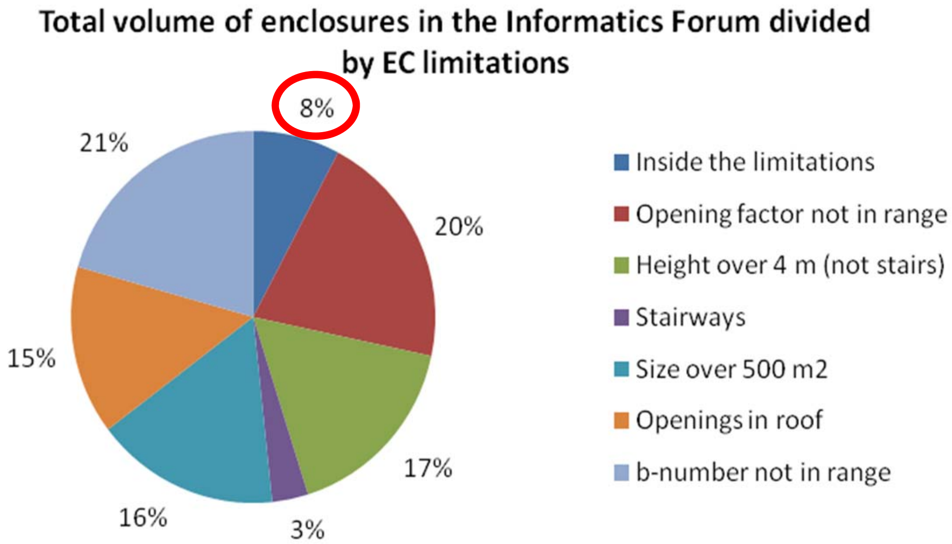
London Bridge Tower

No ceiling opening?



Arup Campus

3000 compartments



We surveyed most of the enclosures in the Kings Buildings campus of the University of Edinburgh.

- Buildings from 1850-1990: ~66% of volume within limitations
- Buildings from 2000: ~8% of volume within limitations (figure)

Modern architecture increasingly produces buildings out of range

Jonsdottir et al, Out of range, *Fire Risk Management* 2009

Traditional Methods

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

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

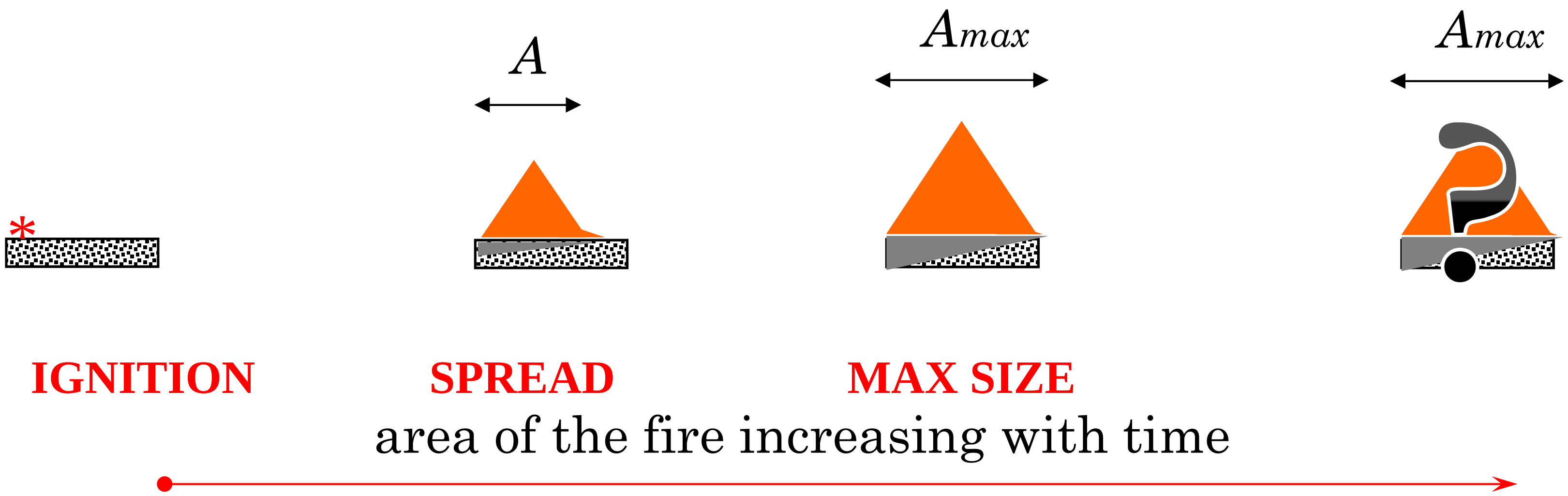
2. Traditional methods have been said to be **conservative** (?)

Stern-Gottfried, PhD thesis, *University of Edinburgh* 2011.

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

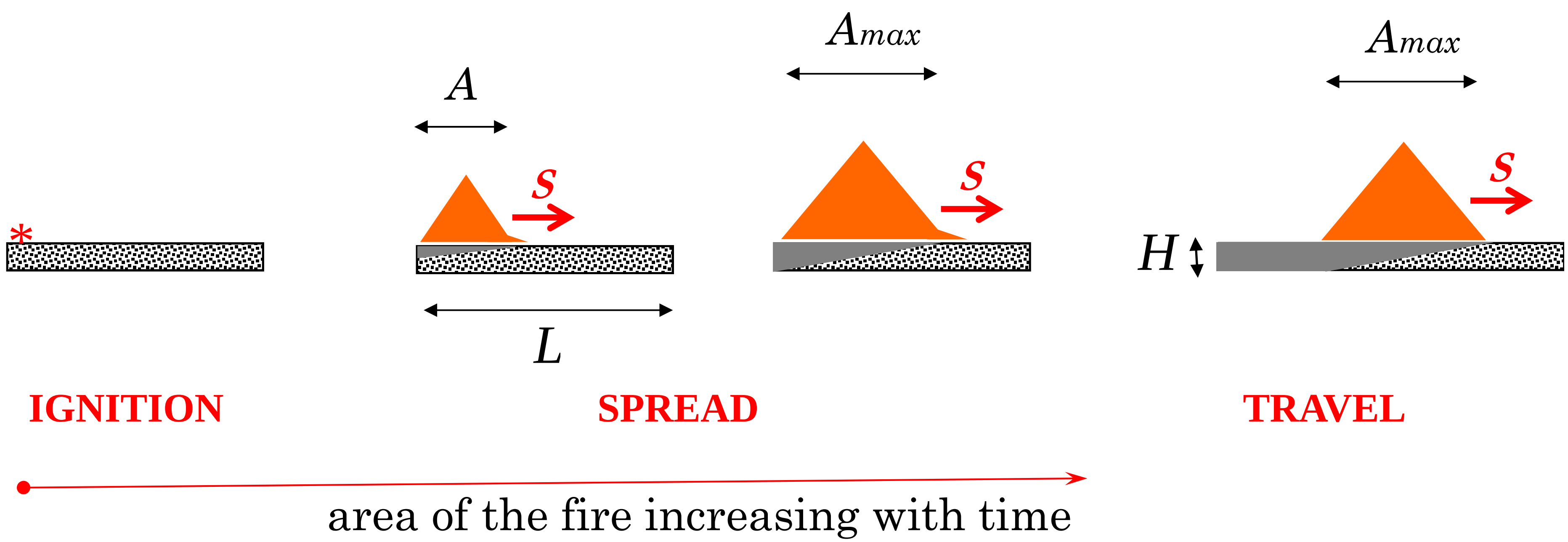
Attributed to A Einstein

Fire spread in small vs. large room – Extrapolation of Maximum Size



Because all knowledge on fire behaviour came from tests in small rooms, the implicit assumption was to extrapolate the maximum size

The fire travels in large floors



Condition for travelling behaviour:

$$t_{spread} = \frac{L}{S} > t_{out} = \frac{H\rho}{\dot{m}''}$$

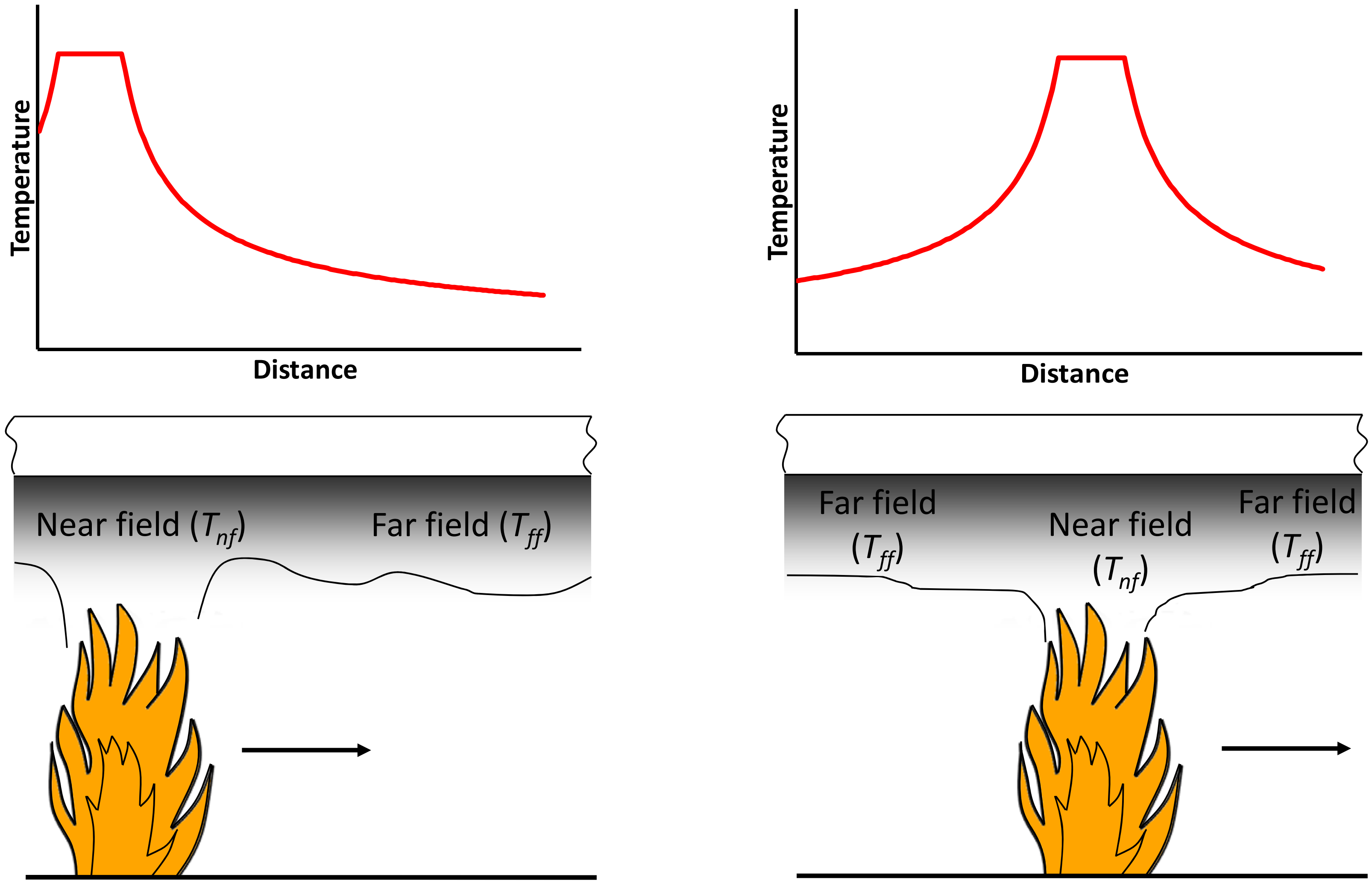
NOTE: The name *Travelling Fires* was incidentally given by Barbara Lane in an email in 2007. Chances are high she does not know this.

I believe in human rights,

therefore:

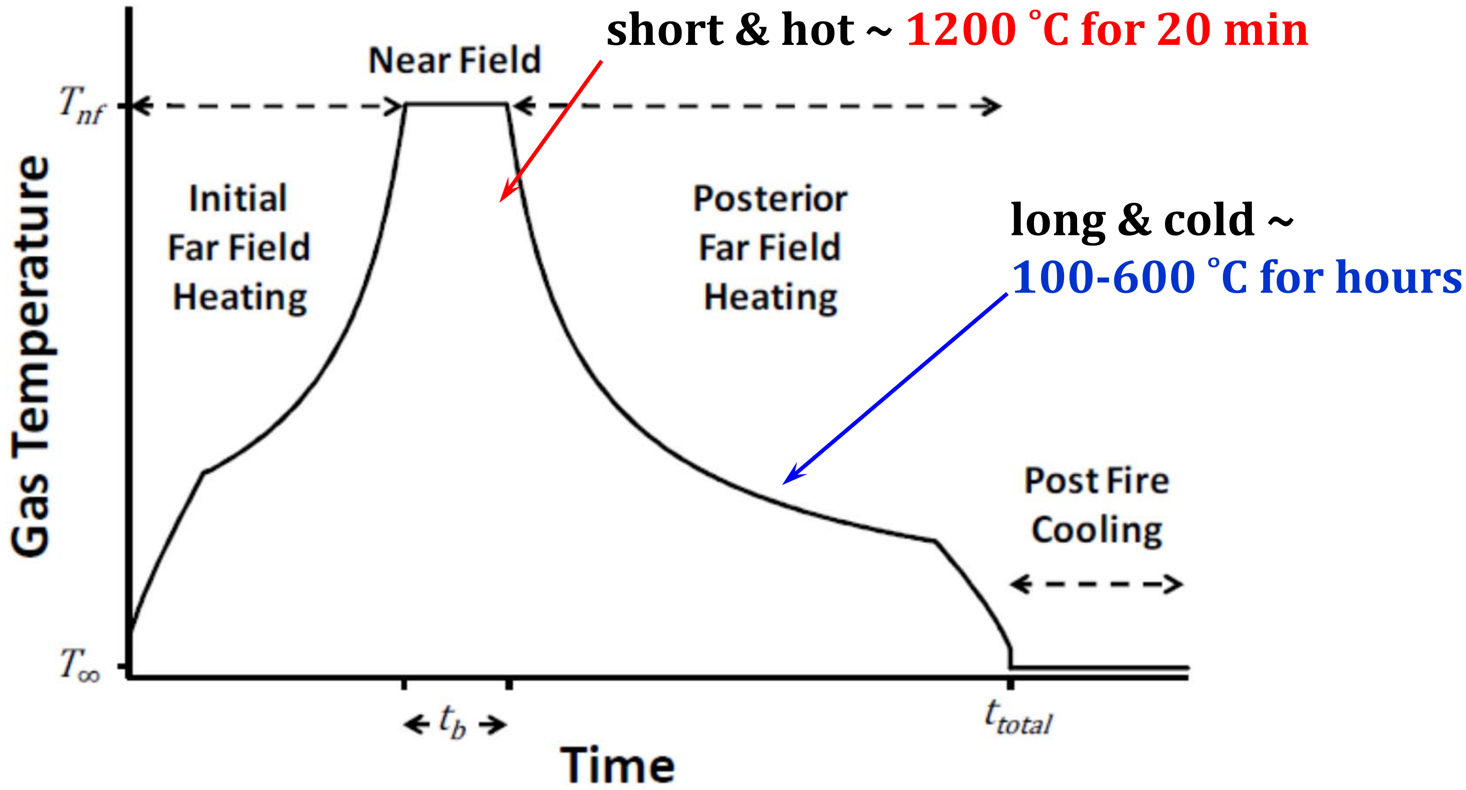
Break of 5 min

Traveling Fires



Travelling Fires

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



Stern-Gottfried and Rein, Fire Safety Journal, 2012

Far Field = Ceiling Jet – but now it travels!

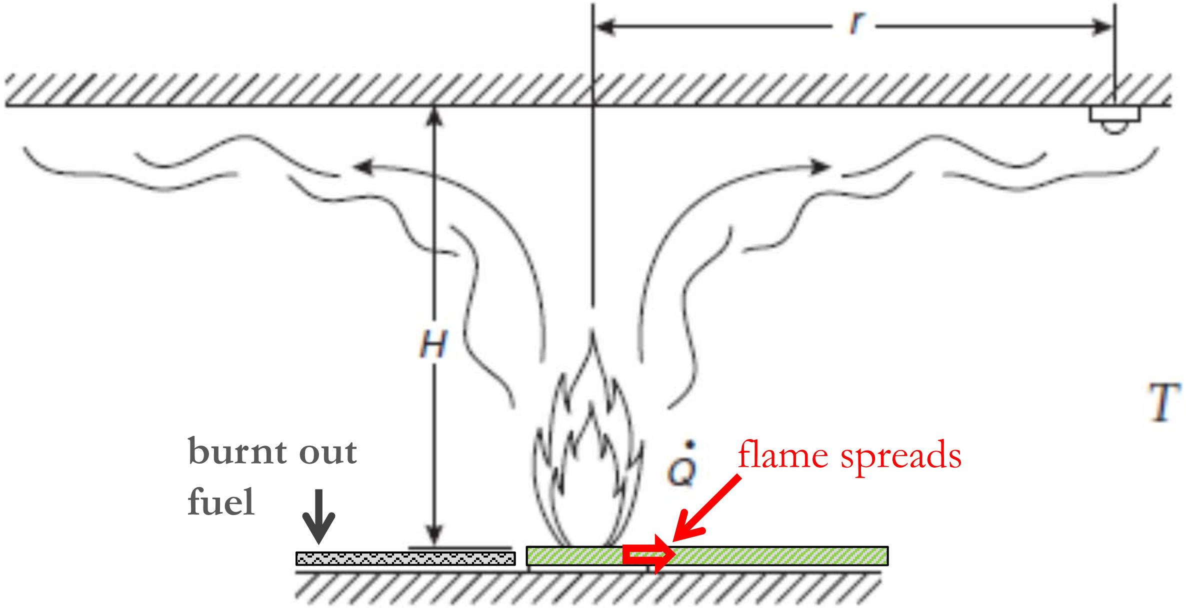


Figure 2-2.1. *Ceiling jet flow beneath an unconfined ceiling.*

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

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

Conservation of Mass
– burning time for near field

- Time during which the near field burns at any given fuel location:

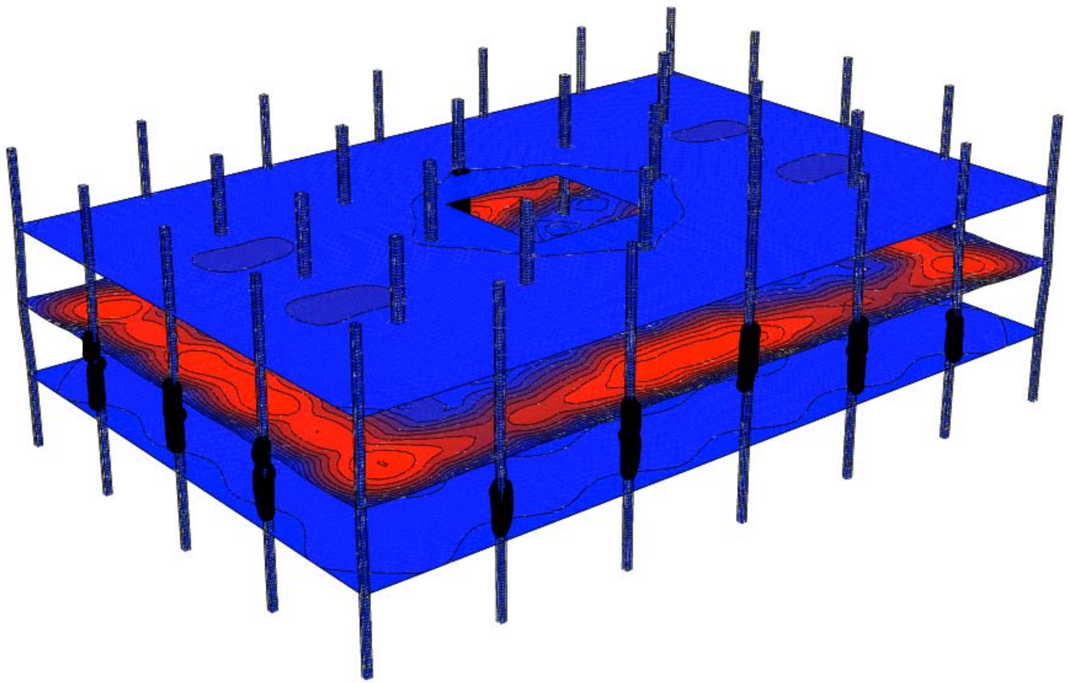
$$t_b = \frac{m''\Delta h_c}{\dot{Q}''}$$

⌘ For typical office buildings, burning time is ~20 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)

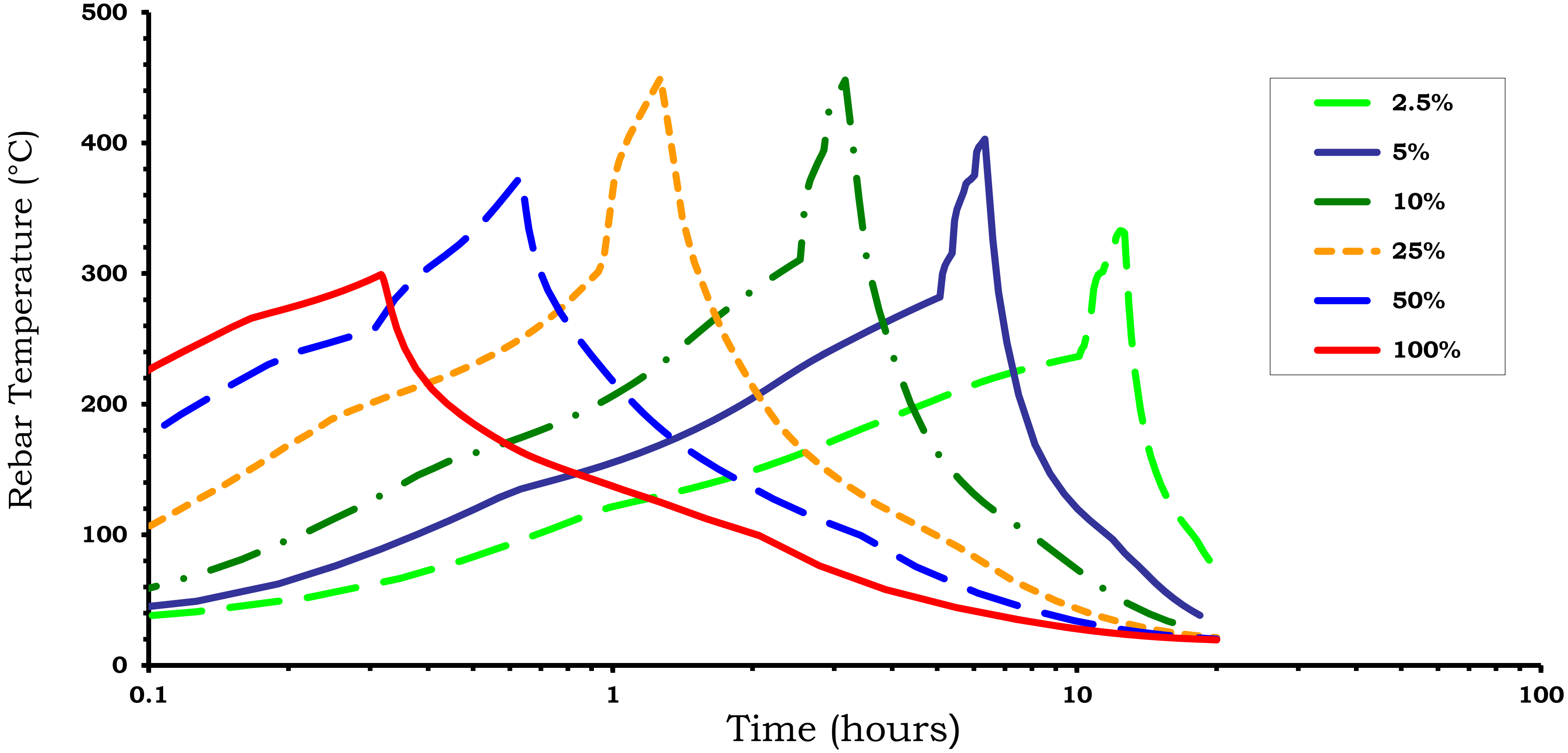
Stern-Gottfried and Rein, Fire Safety Journal, 2012

Case Study:
Generic Multi-Storey Concrete Structure



Law et al, *Engineering Structures* 2011

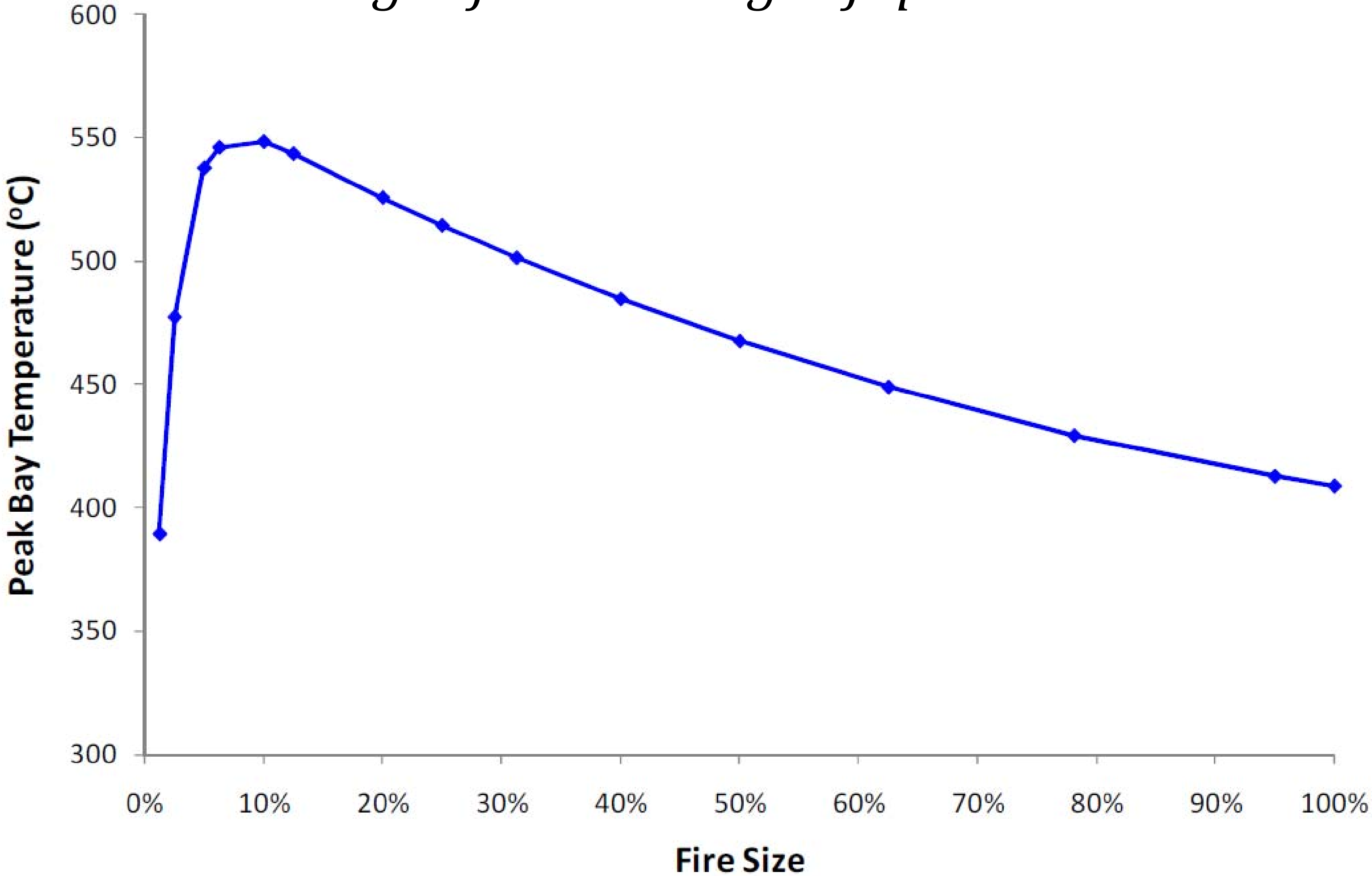
Structural Results – Rebar Temperature



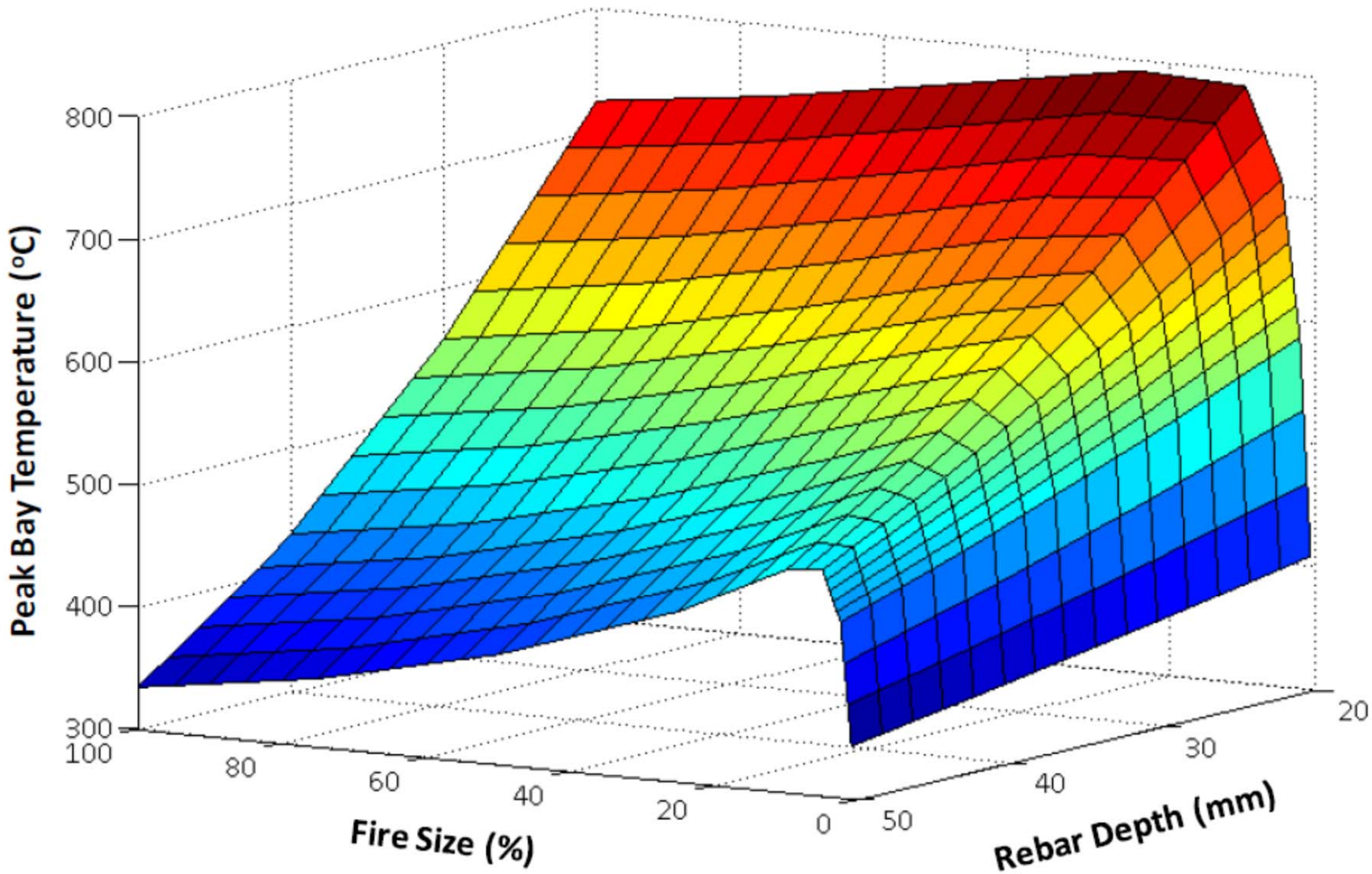
Law et al, *Engineering Structures* 2011

Family of fires
– not just one fire cast in stone

range of sizes = range of spread rates



Effect of fire size and rebar depth



Stern-Gottfried and Rein, Fire Safety Journal, 2012

Comparison with Traditional Methods

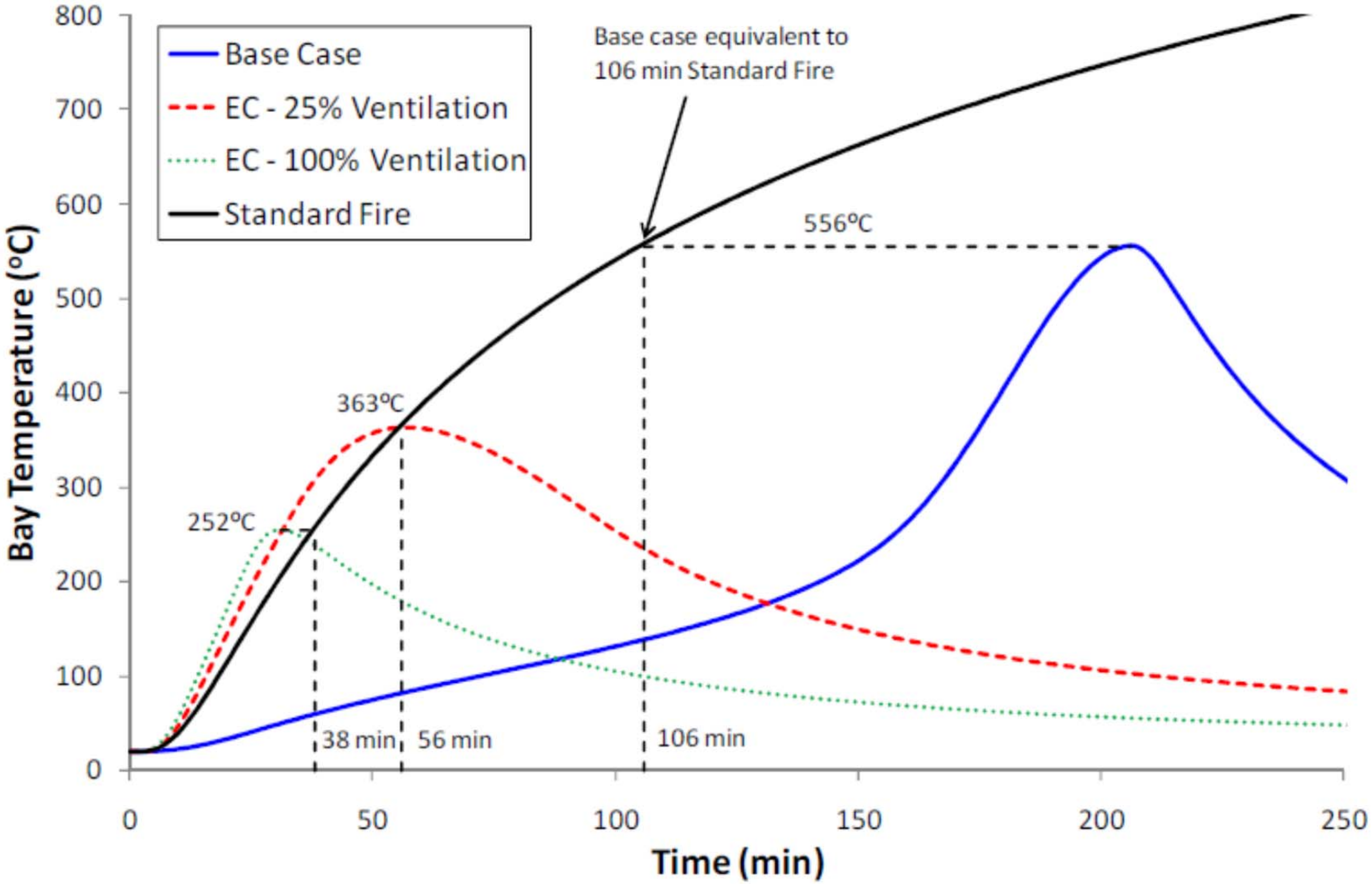
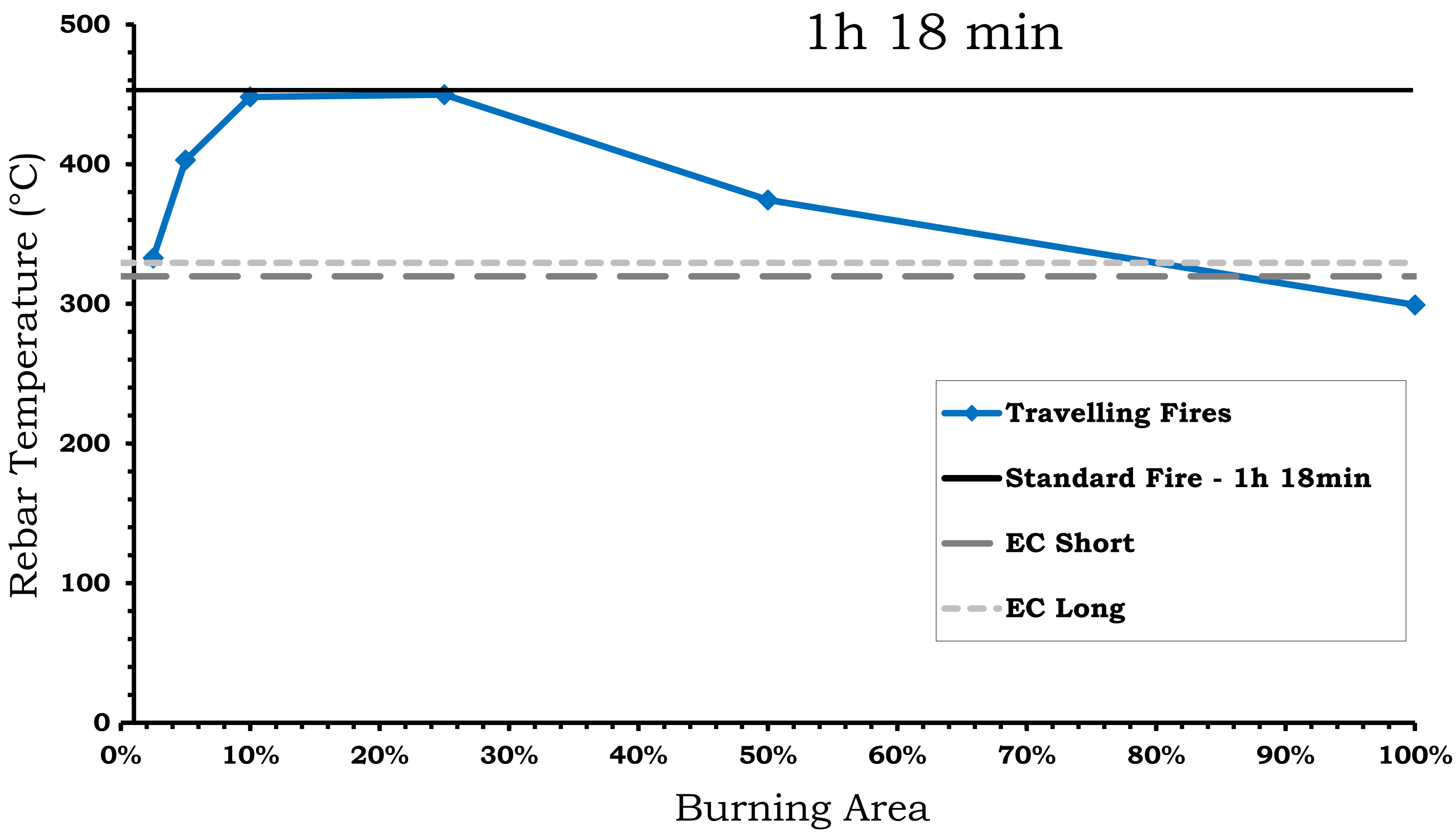


Figure 2.17: Comparison of bay temperatures calculated using the base case, the standard fire, and two Eurocode parametric temperature-time curves.

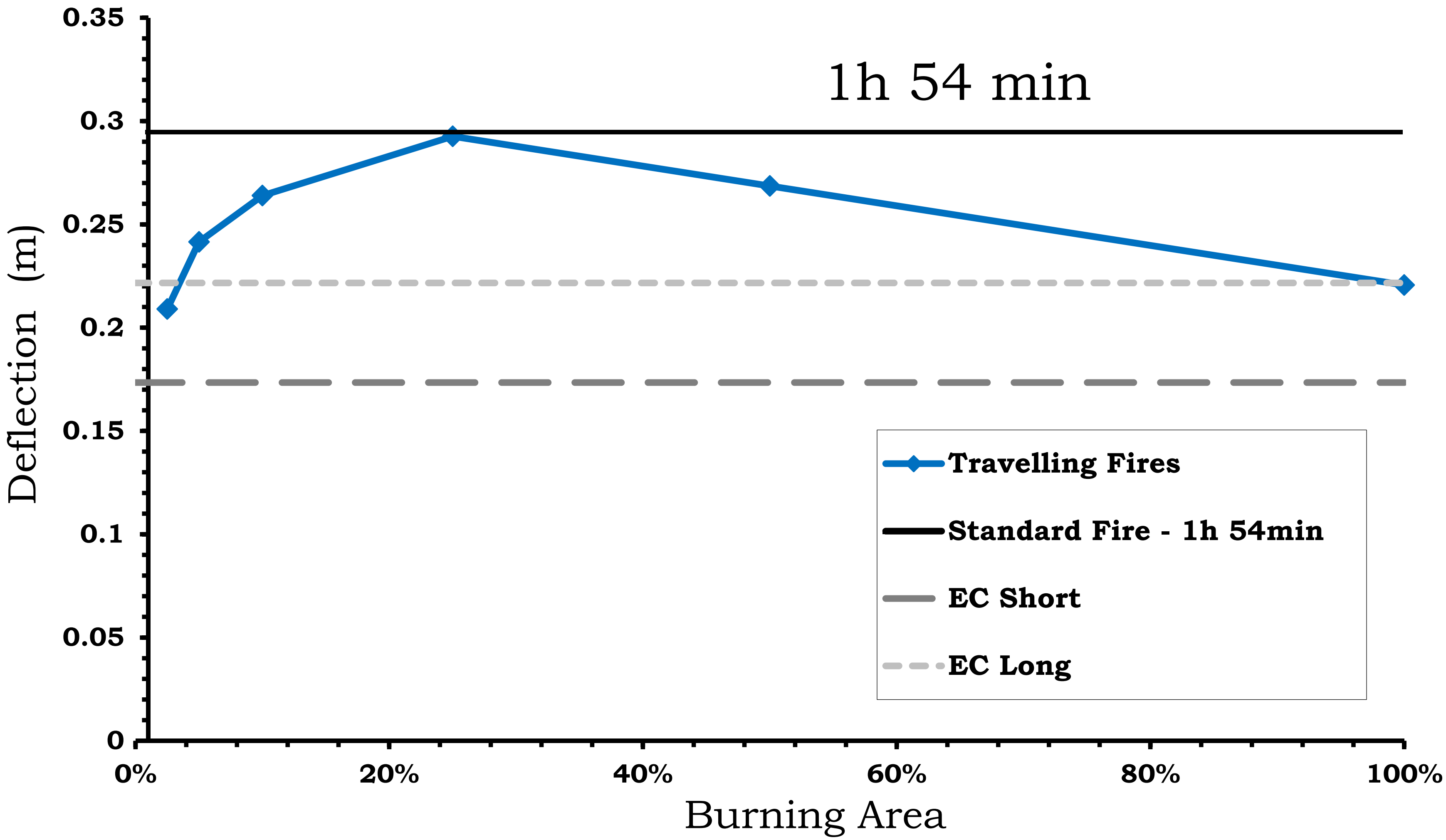
Stern-Gottfried and Rein, Fire Safety Journal, 2012

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:

ARUP

The Leverhulme Trust

The Royal Academy of Engineering

Collaborators:

J Stern-Gottfried

A Law

A Jonsdottir

M Gillie

J Torero

- Stern-Gottfried and Rein, *Fire Safety Journal, 2012*
- Stern-Gottfried, *PhD Thesis, 2011*
- Law et al, *Engineering Structures* 2011
- Jonsdottir et al, *Fire Risk Management* 2009
- Rein et al, *Interflam* 2007, London

ARUP

Fire Technology

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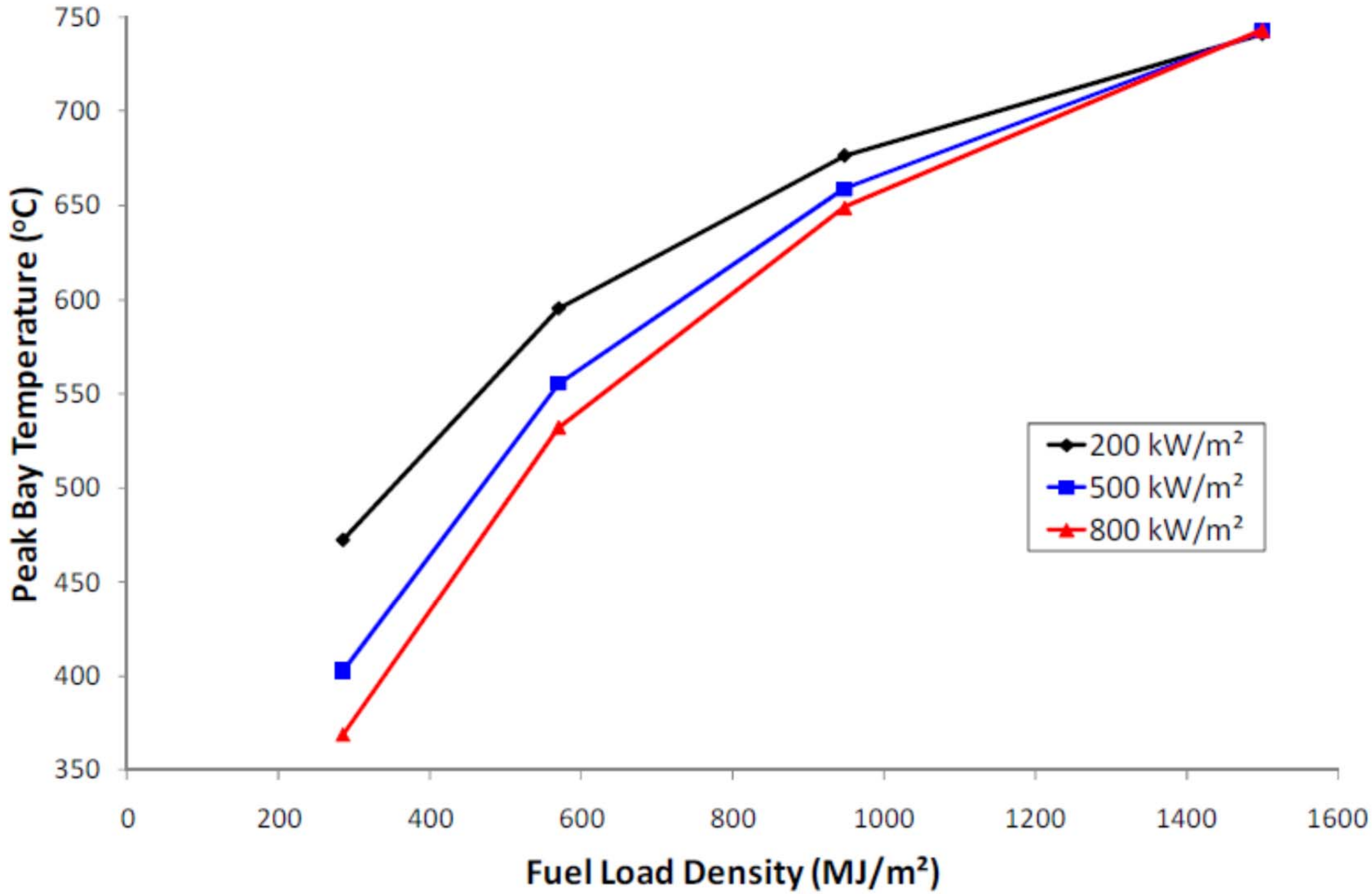
Effect of fuel load



Stern-Gottfried and Rein, Fire Safety Journal, 2012

Effect of near field temperature

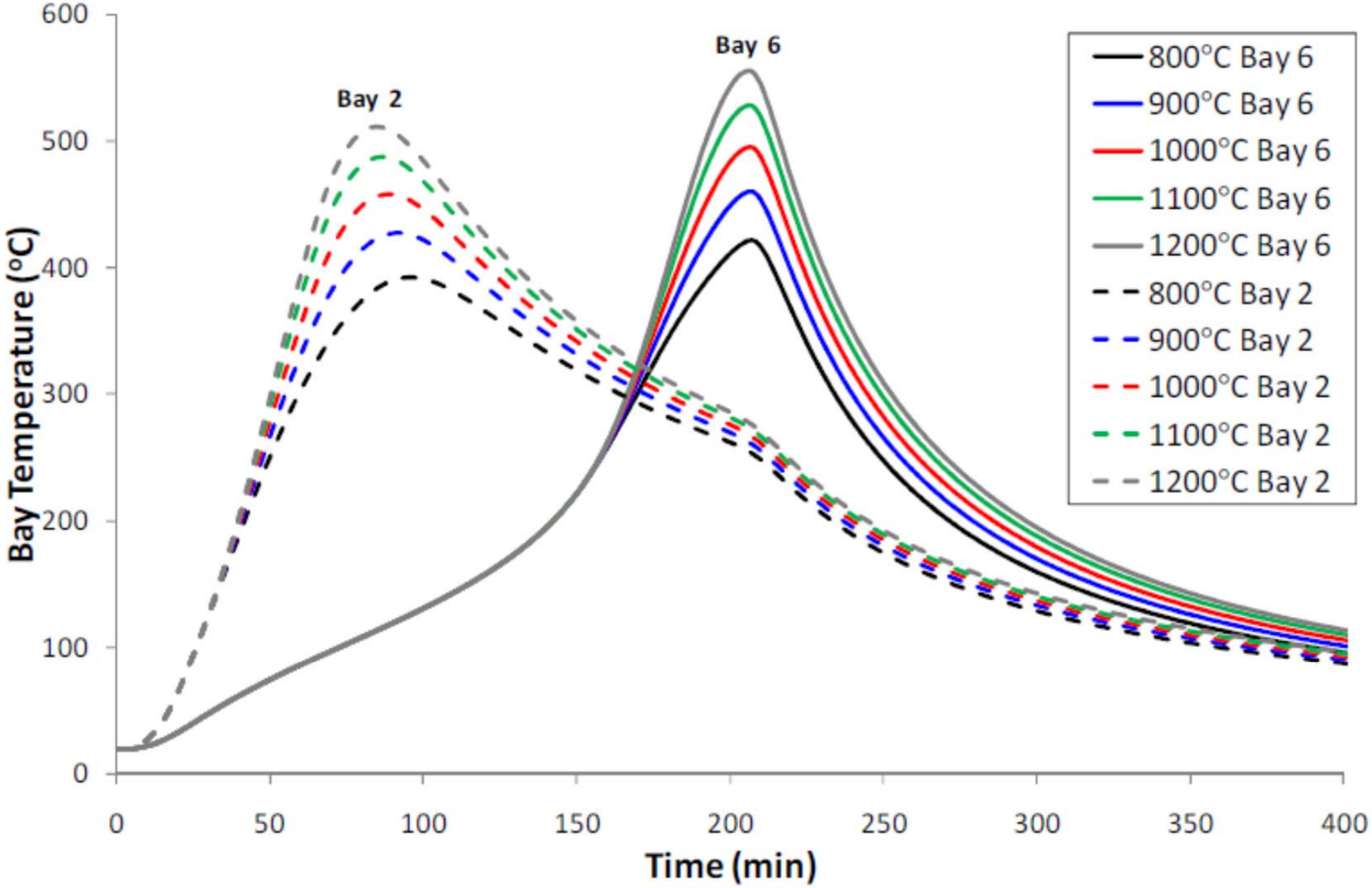
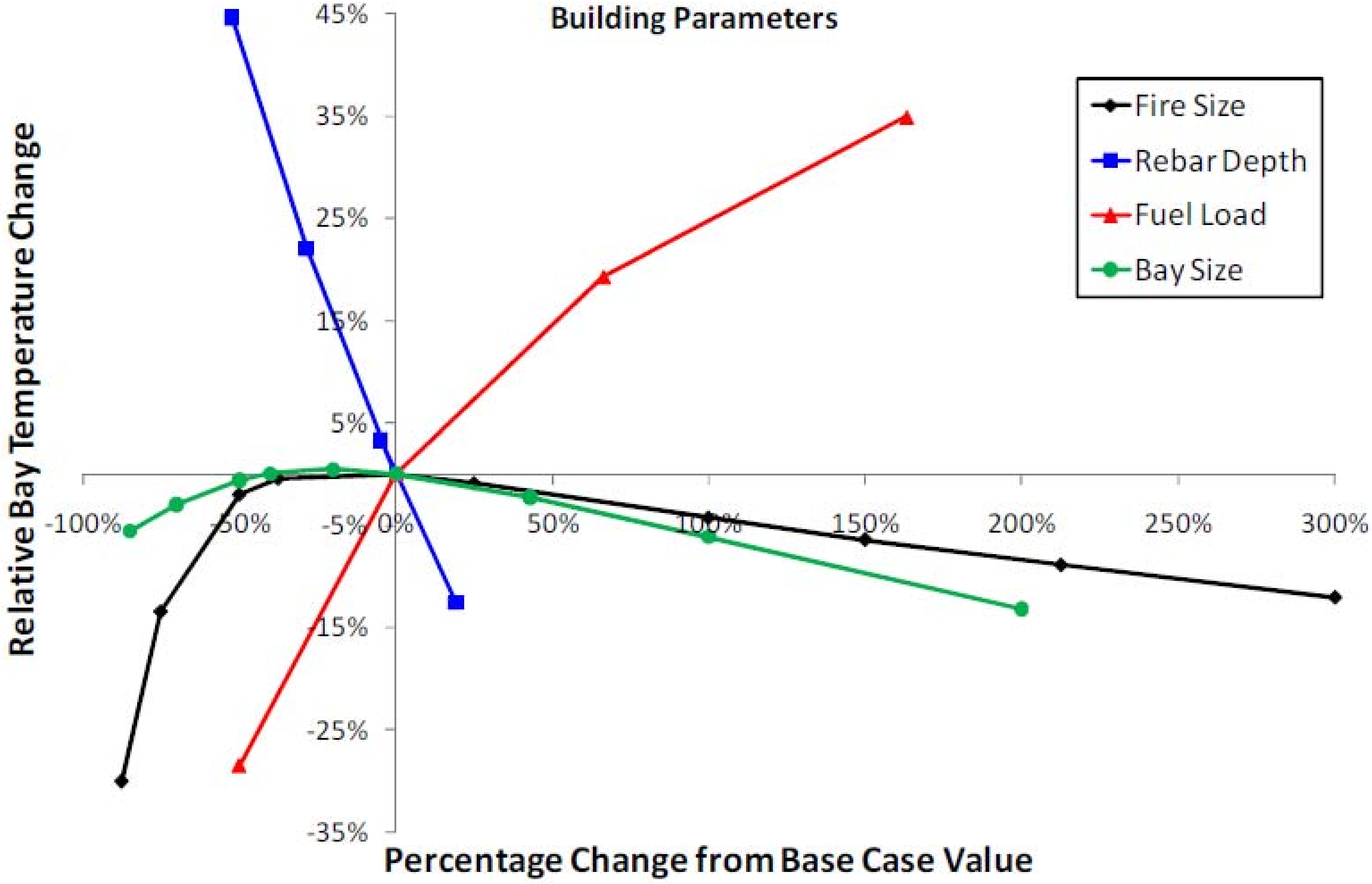
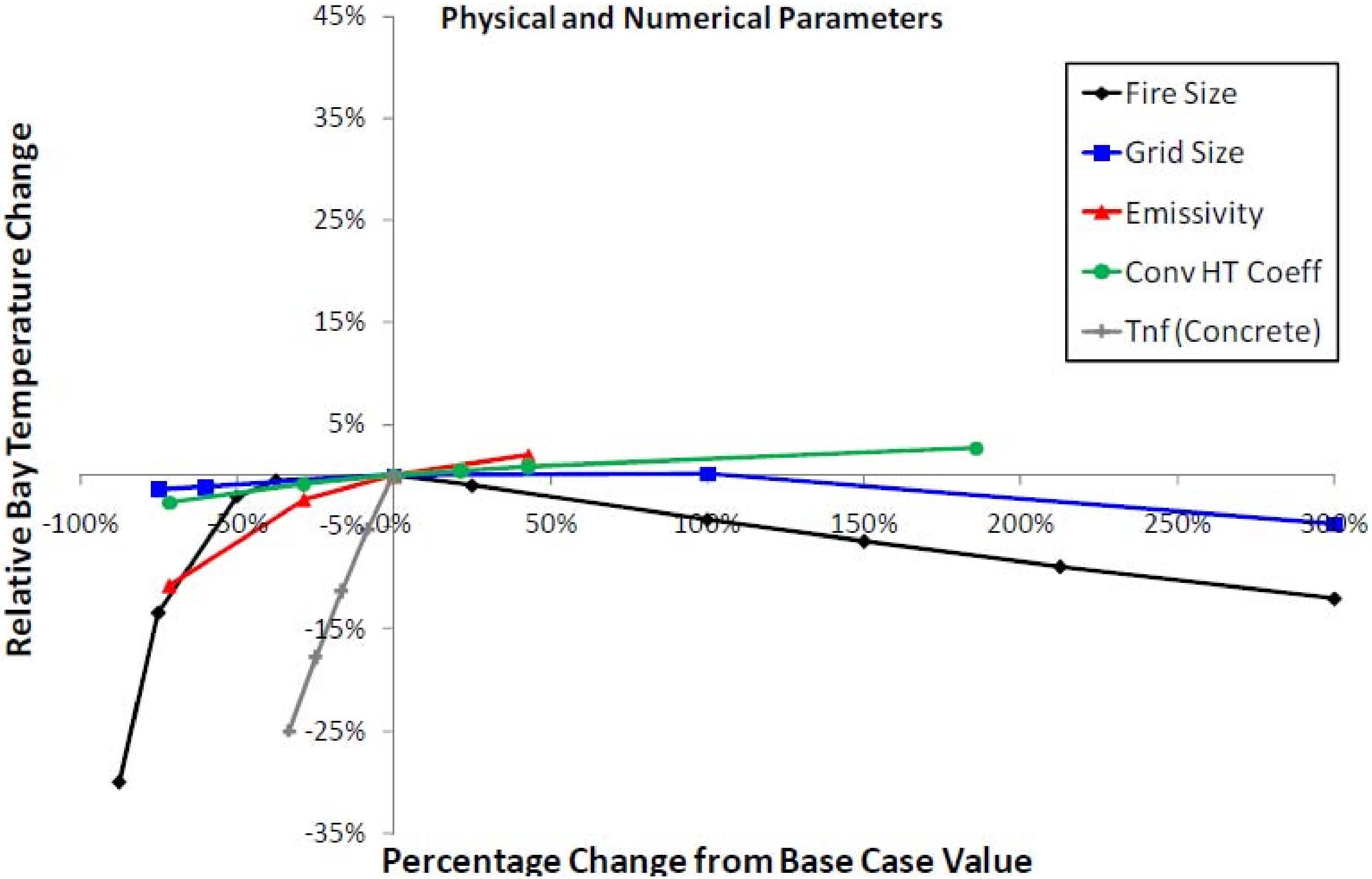


Figure 2.13: Bay temperature vs. time for near field temperatures between 800 and 1200°C at Bays 2 and 6.

Stern-Gottfried and Rein, Fire Safety Journal, 2012


Building Parameters
45%
35%
25%
15%
5%
-5%
-15%
-25%
-35%
-100%
-50%
0%
50%
100%
150%
200%
250%
300%
Relative Bay Temperature Change
Percentage Change from Base Case Value
Fire Size
Rebar Depth
Fuel Load
Bay Size



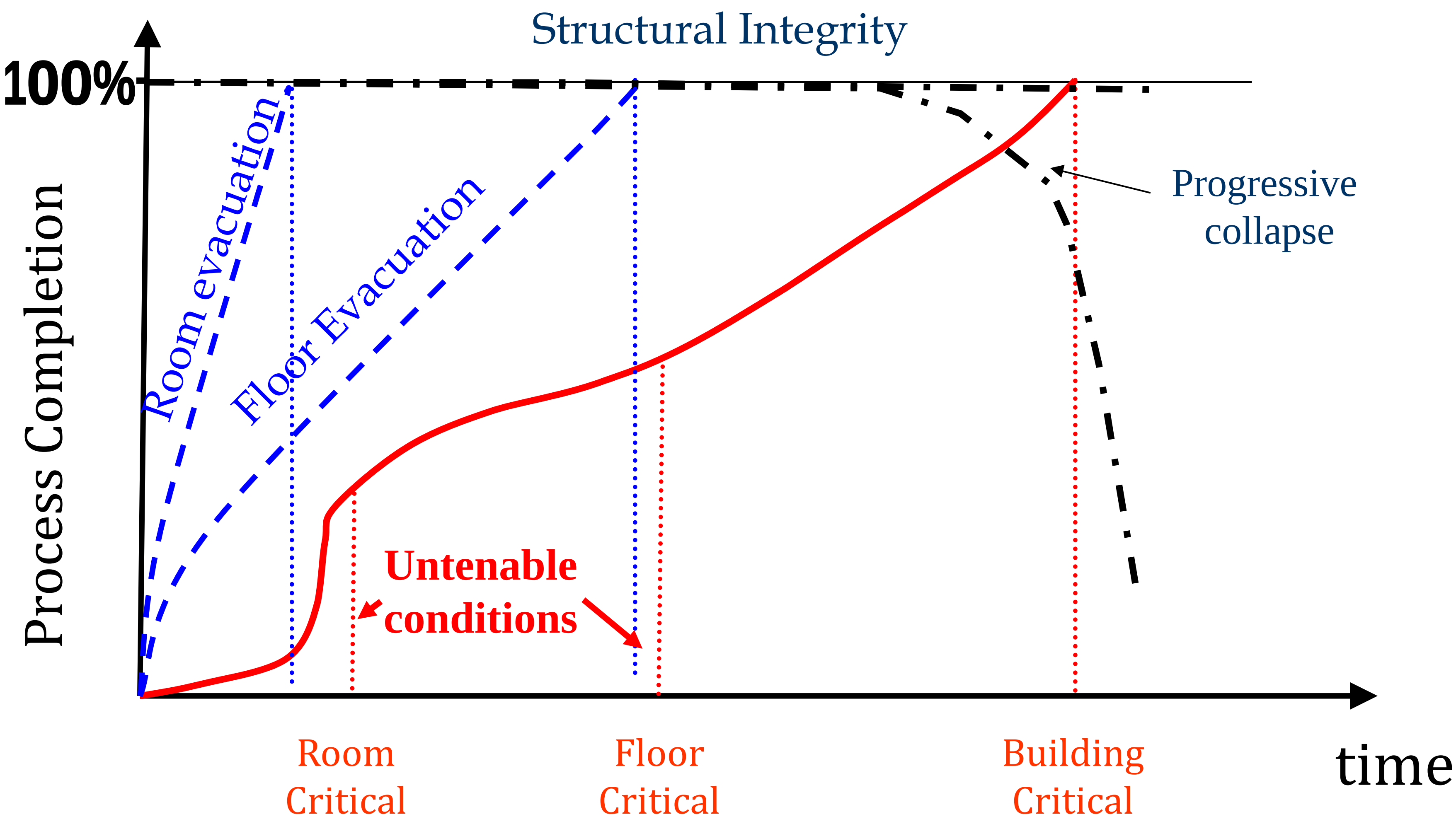
Physical and Numerical Parameters
Relative Bay Temperature Change
Percentage Change from Base Case Value
45%
35%
25%
15%
5%
-5%
-15%
-25%
-35%
-100%
-50%
0%
50%
100%
150%
200%
250%
300%
Fire Size
Grid Size
Emissivity
Conv HT Coeff
Tnf (Concrete)

Travelling Fires

- Real fires are observed to travel
  - ⌘ WTC Towers 2001
  - ⌘ Torre Windsor 2005
  - ⌘ Delft Faculty 2008
  - ⌘ etc…
- Experimental data (and common sense) indicate fires travel in large compartments

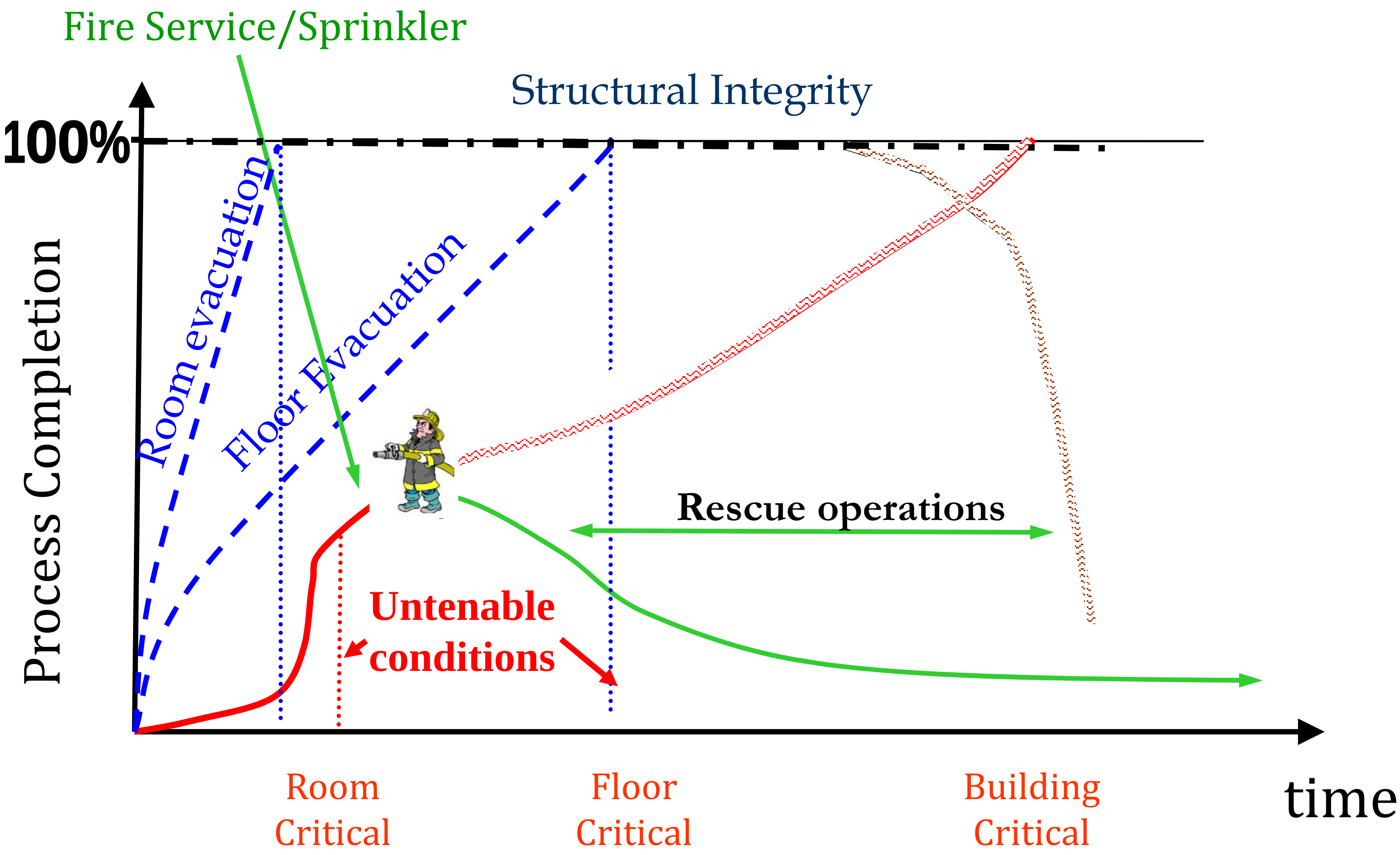
- In larger compartments, the fire does not burn uniformly but burns locally and spreads

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

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



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