TSINGHUA-PRINCETON-COMBUSTION INSTITUTE

2022 SUMMER SCHOOL ON COMBUSTION

COMBUSTION FUNDAMENTALS OF FIRE SAFETY

José Torero

University College London

July 11-14, 2022

TSINGHUA-PRINCETON-COMBUSTION INSTITUTE

2022 SUMMER SCHOOL ON COMBUSTION

Schedule

Beijing Time	July 11 (Mon.)	July 12 (Tue.)	July 13 (Wed.)	July 14 (Thu.)	July 15 (Fri.)
08:00 ~ 11:00			**Mechanism Reduction and Stiff Chemistry Solvers** Tianfeng Lu VMN: 52667557219		**Mechanism Reduction and Stiff Chemistry Solvers** Tianfeng Lu VMN: 52667557219
*10:00 ~ 12:00		**Virtual Poster Session** 10:00~12:00 VMN: 388239275		**Virtual Lab Tour** 10:00~12:00 VMN: 231842246	
14:00 ~ 17:00 Session I	**Fundamental of Flames** Suk Ho Chung VMN: 42399313194			**Combustion in Microgravity and Microscale** Kaoru Maruta VMN: 71656262918	
14:00 ~ 17:00 Session II	**Soot** Markus Kraft VMN: 39404905340			**Current Status of Ammonia Combustion** William Roberts VMN: 80506726244	
19:00 ~ 22:00 Session I	**Combustion Chemistry and Kinetic Mechanism Development** Tiziano Faravelli VMN: 35989357660				
19:00 ~ 22:00 Session II	**Combustion Fundamentals of Fire Safety** José Torero VMN: 57002781862				

Note:

[1]Session I and Session II are simultaneous courses.

[2]VMN: Voov Meeting Number

Guidelines for Virtual Participation

1. General Guidelines

- Tencent Meeting software (腾讯会议) is recommended for participants whose IP addresses locate within Mainland China; Voov Meeting (International version of Tencent Meeting) is recommended for other IP addresses. The installation package can be found in the following links:

  a) 腾讯会议
  https://meeting.tencent.com/download/

  b) Voov Meeting
  https://voovmeeting.com/download-center.html?from=1001

- All the activities listed in the schedule are "registrant ONLY" due to content copyright.
- To facilitate virtual communications, each participant shall connect using stable internet and the computer or portable device shall be equipped with video camera, speaker (or earphone) and microphone.

2. Lectures

- The lectures are also "registrant ONLY". Only the students who registered for the course can be granted access to the virtual lecture room.
- To enter the course, each registered participant shall open the software and join the conference using the corresponding Voov Meeting Number (VMN) provided in the schedule; only participants who show unique identification codes and real names as "**xxxxxx-Last Name, First Name**" will be granted access to the lecture room; the identification code will be provided through email.
- During the course, each student shall follow the recommendation from the lecturer regarding the timing and protocol to ask questions or to further communicate with the lecturer.
- For technical or communication issues, the students can contact the TA in the virtual lecture or through emails.
- During the course, the students in general will not be allowed to use following functions in the software: 1) share screen; 2) annotation; 3) record.

3. Lab Tour

- The event will be hosted by graduate students from Center for Combustion Energy, Tsinghua University and live streamed using provided Voov Meeting Number.
- During the activity, the participants will not be allowed to use following functions in the software: 1) share screen; 2) annotation; 3) record.
- Questions from the virtual participants can be raised using the chat room.

4. Poster Session

- The event will be hosted by the poster authors (one Voov Meeting room per poster) and live streamed using provided Voov Meeting Number.
- During the activity, the participants will not be allowed to use following functions in the software: 1) share screen; 2) annotation; 3) record.
- Questions from the virtual participants can be raised using the chat room or request access to audio and video communication.

Teaching Assistants

- **Fundamentals of Flame (Prof. Suk Ho Chung)**

  TA1: Hengyi Zhou (周恒毅); zhouhy19@mails.tsinghua.edu.cn

  TA2: Xinyu Hu (胡馨予); hxy21@mails.tsinghua.edu.cn

- **Combustion Chemistry and Kinetic Mechanism Development (Prof. Tiziano Faravelli)**

  TA1: Shuqing Chen (陈舒晴); chen-sq19@mails.tsinghua.edu.cn

  TA2: Jingzan Shi (史京瓒); sjz21@mails.tsinghua.edu.cn

- **Current Status of Ammonia Combustion (Prof. William Roberts)**

  TA1: Yuzhe Wen (温禹哲); wyz20@mails.tsinghua.edu.cn

  TA2: Haodong Chen (陈皓东); chd20@mails.tsinghua.edu.cn

- **Soot (Prof. Markus Kraft)**

  TA1: Yuzhe Wen (温禹哲); wyz20@mails.tsinghua.edu.cn

  TA2: Haodong Chen (陈皓东); chd20@mails.tsinghua.edu.cn

- **Combustion Fundamentals of Fire Safety (Prof. José Torero)**

  TA1: Xuechun Gong (巩雪纯); gxc19@mails.tsinghua.edu.cn

  TA2: Weitian Wang (王巍添); wwt20@mails.tsinghua.edu.cn

- **Combustion in Microgravity and Microscale (Prof. Kaoru Maruta)**

  TA1: Hengyi Zhou (周恒毅); zhouhy19@mails.tsinghua.edu.cn

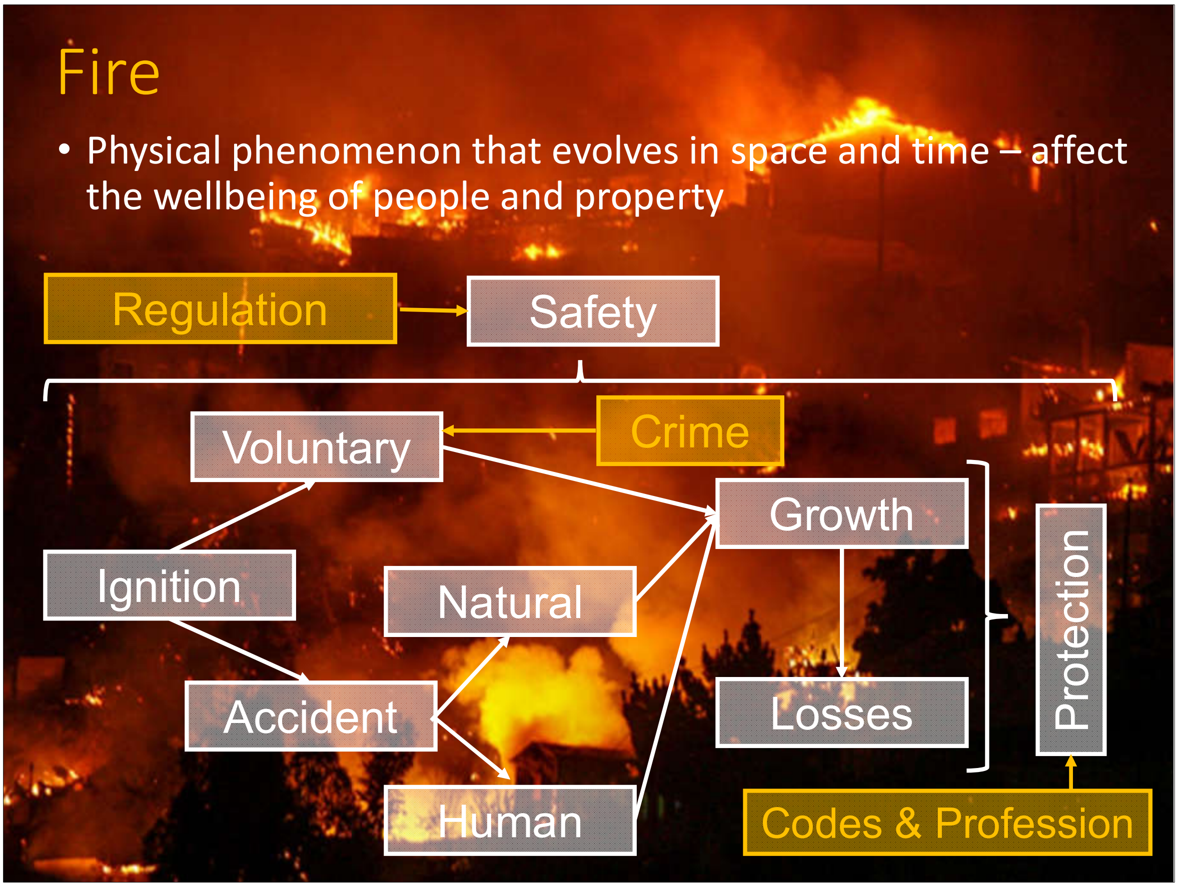
  TA2： Xinyu Hu (胡馨予); hxy21@mails.tsinghua.edu.cn

- **Mechanism Reduction and Stiff Chemistry Solvers (Prof. Tianfeng Lu)**

  TA1: Shuqing Chen (陈舒晴); chen-sq19@mails.tsinghua.edu.cn

  TA2: Jingzan Shi (史京瓒); sjz21@mails.tsinghua.edu.cn

Combustion Fundamentals of Fire Safety
The Grenfell Tower Fire:
Failing to Understand Complexity in
Tall Building Design
José L. Torero
University College London
United Kingdom
Lecture-1

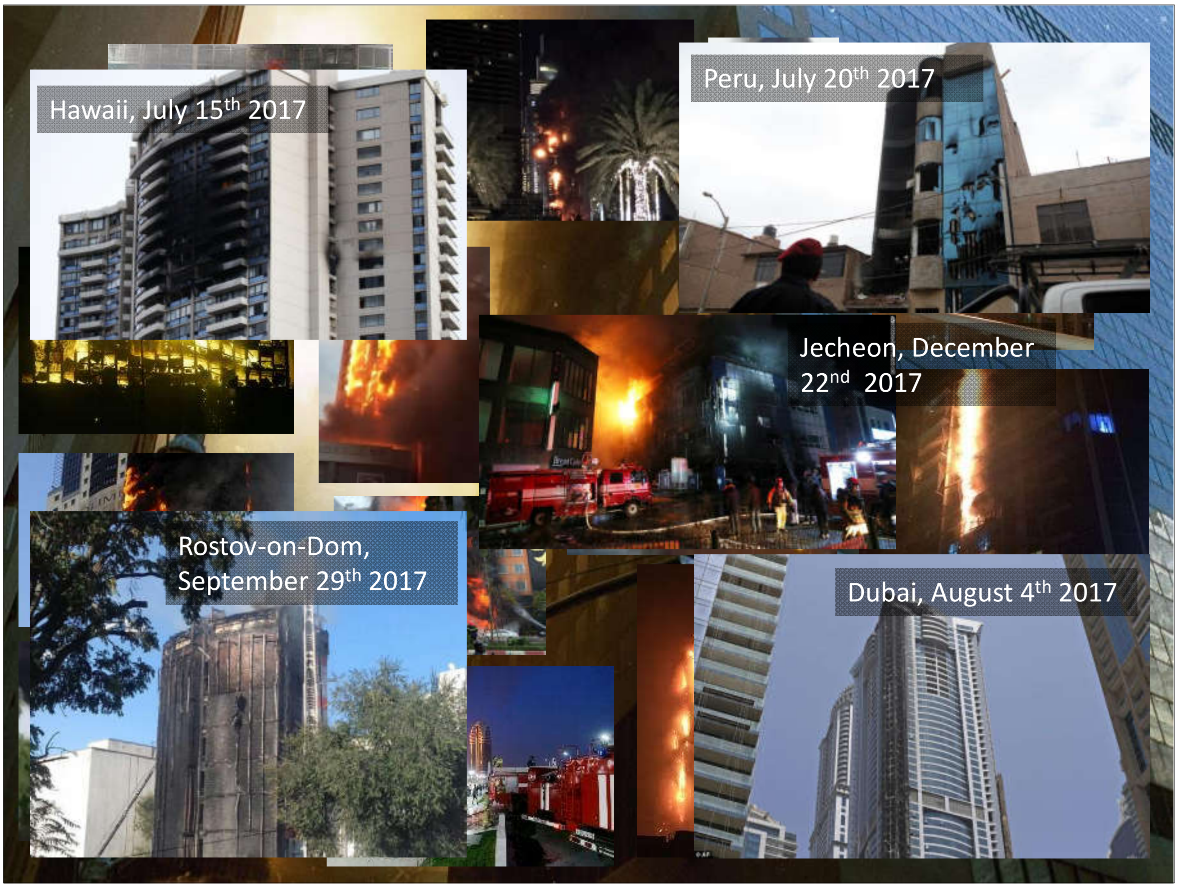


Fire
• Physical phenomenon that evolves in space and time – affect the wellbeing of people and property
Regulation
Safety
Crime
Voluntary
Growth
Ignition
Natural
Protection
Losses
Accident
Human
Codes & Profession

How could this happen?

- 100 + buildings tested – 100% failure
- 10 + buildings being evacuated in the UK
- 5 + buildings being evacuated in Germany
- Several buildings being investigated in the US (including several hotels)
- Several buildings being investigated in Australia (including hospitals) … as you know
- … this is only the beginning …

Andraus Building Sao Paulo, Brazil, February 24th, 1974



Neo200 (February 3rd, 2019)

- “Cigarette blamed for Vic apartment fire”
- “Cladding audit found Melbourne apartment tower posed 'moderate' fire safety risk (Victorian Cladding Taskforce)”
- "While most of the building is not clad at all, where any cladding is used it is compliant with VBA [Victorian Building Authority] standards," Neo200 tweeted in June 2017.
- "This building is extremely safe, it's around 90 per cent made out of concrete panel construction, there's only about a 10 per cent mix of ACM panels," Sahil Bhasin (building inspector) told ABC Radio Melbourne”
- "We didn't hear the alarm until about 15 minutes ago. We thought it was a few blocks down"
- "It was smoky through the stairwell and then when we heard it was on the floor that we were supposed to be on we thought, someone's looking after us”
- "The fire occurred, the sprinklers came on and, assisted with the MFB, the fire was doused.”
- Mr Bhasin, who is the general manager of Roscon, said it appeared the building's fire plan had worked "perfectly”
- "I'll be pushing for a nationwide ban on combustible cladding really to further protect Victorians from being exposed to unacceptable fire risk (VCT)"

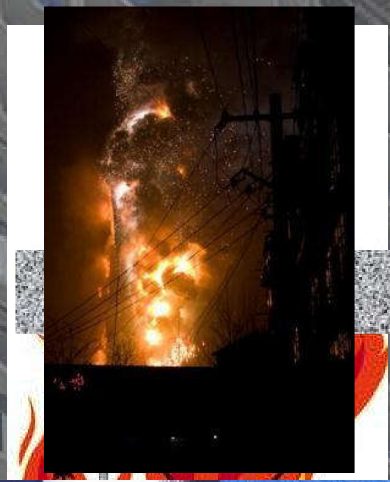
Are Façade Fires an Unavoidable Feature of Modern Architecture?

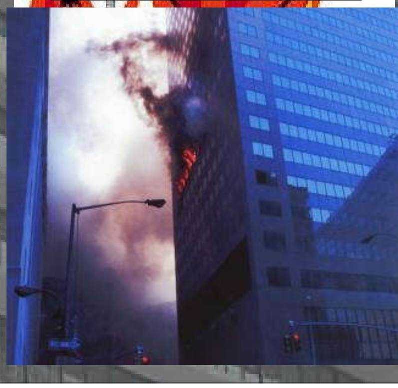
The Key Changes

- o The building envelope
- o New construction methodologies
- o Flammable insulation materials – encapsulation
- o etc …

… it is not "<u>one</u>" problem!

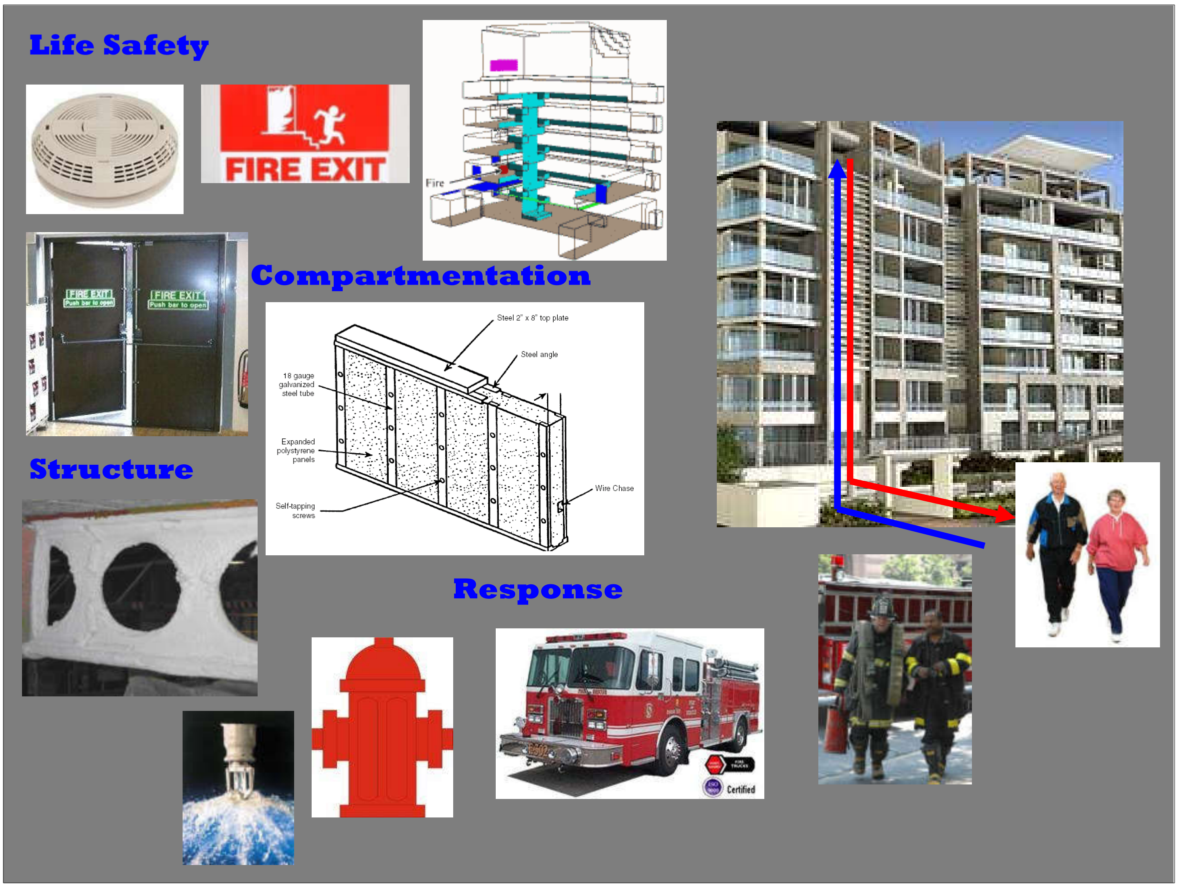
The Building Envelope





Fire Safety Strategies

- Prescriptive Design
- Performance Based Design



Life Safety
FIRE EXIT
Fire
FIRE EXIT Push bar to open
FIRE EXIT Push bar to open
Compartmentation
Steel 2" x 8" top plate
Steel angle
18 gauge galvanized steel tube
Expanded polystyrene panels
Self-tapping screws
Wire Chase
Structure
Response
Certified

Life Safety
FIRE EXIT
Fire
Common Sense
Compartmentation
Locate According to manufacturers Specifications
Specify According to Manufacturers Standard Test Data
Steel 2" x 8" top plate
Steel angle
Expanded polystyrene panels
Self-tapping screws
Wire Chase
Structure
Response
Define according to simple rules (Common Sense)
Common Sense
Common Sense
Certified

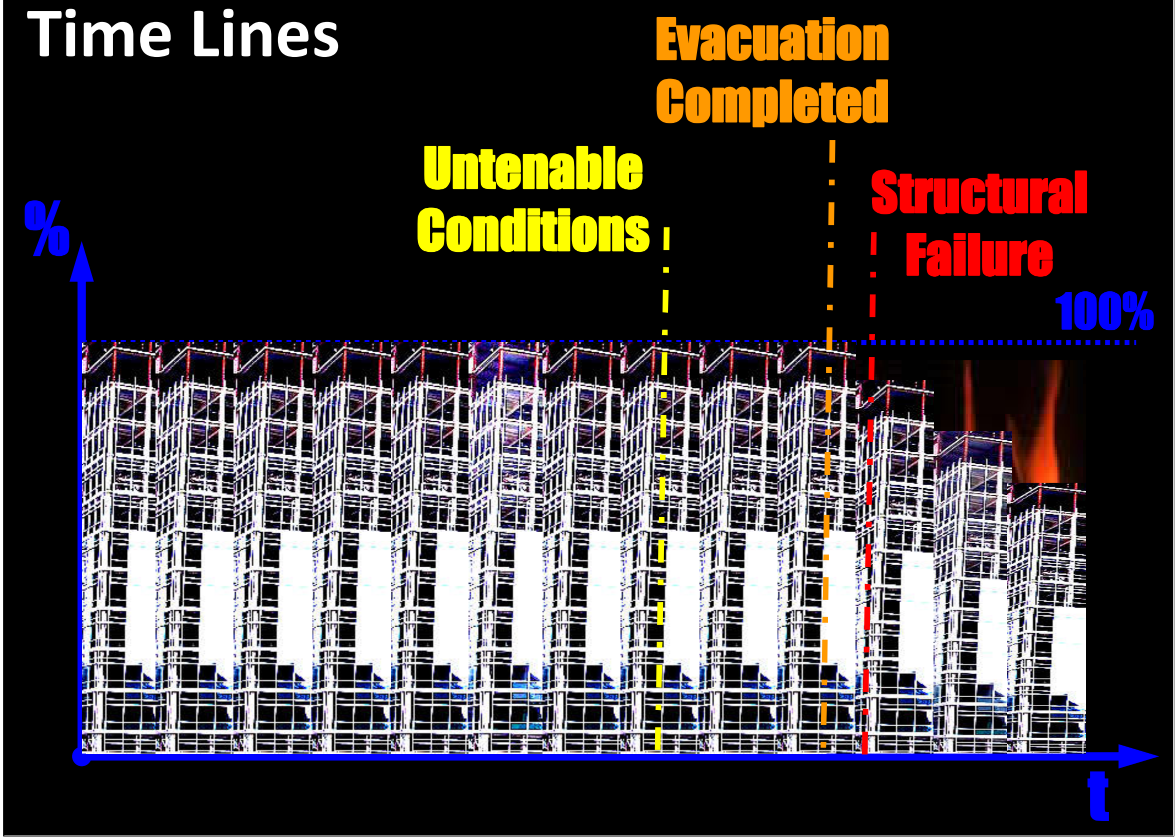

787


CENTRAL STN
QueenslandRail
QueenslandRail

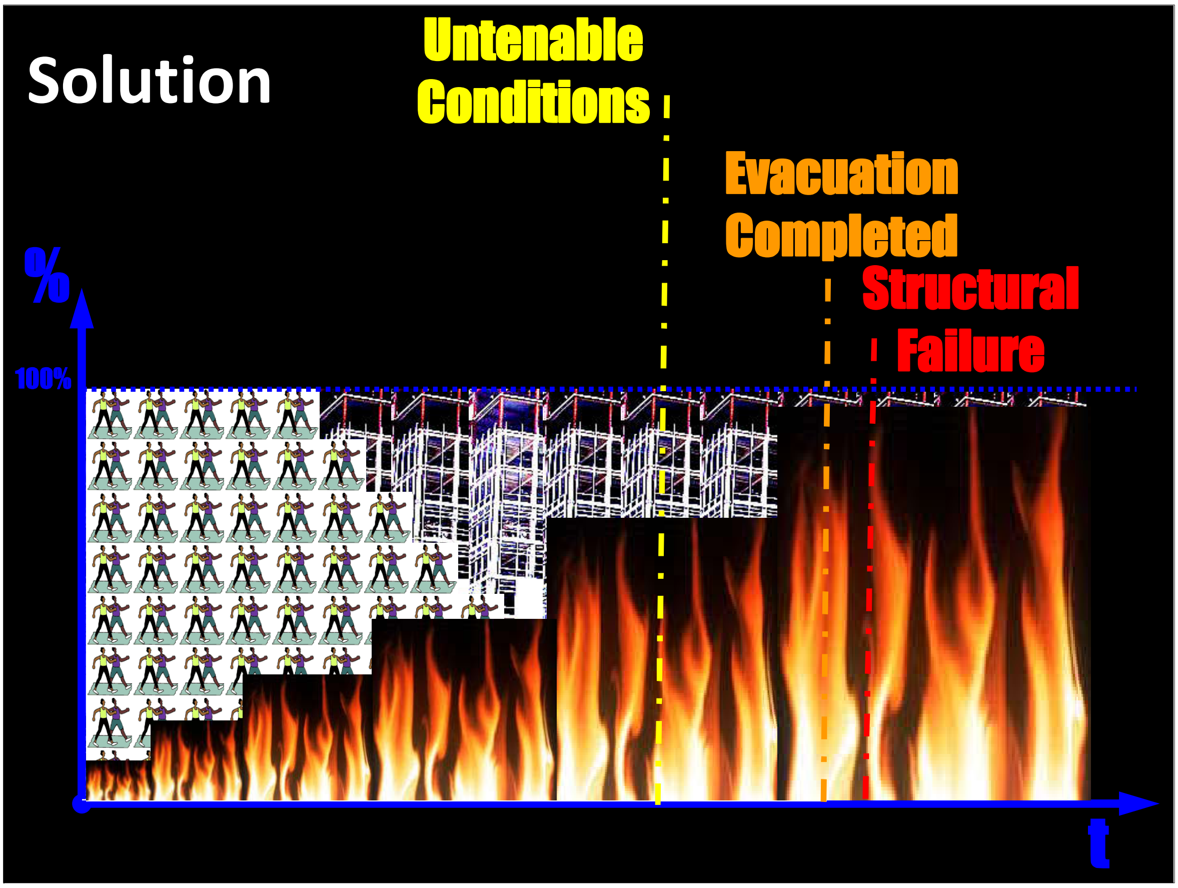
Fire Safety Strategies

- Evacuation
  - Detection
  - Alarm
  - Displacement away from the fire
  - Crowd management
- Compartmentalization
  - Slows fire growth
  - Minimizes smoke spread
- Response
  - Automatic (fire suppression)
  - External
  - Internal
- Structural Integrity

Time Lines



Solution

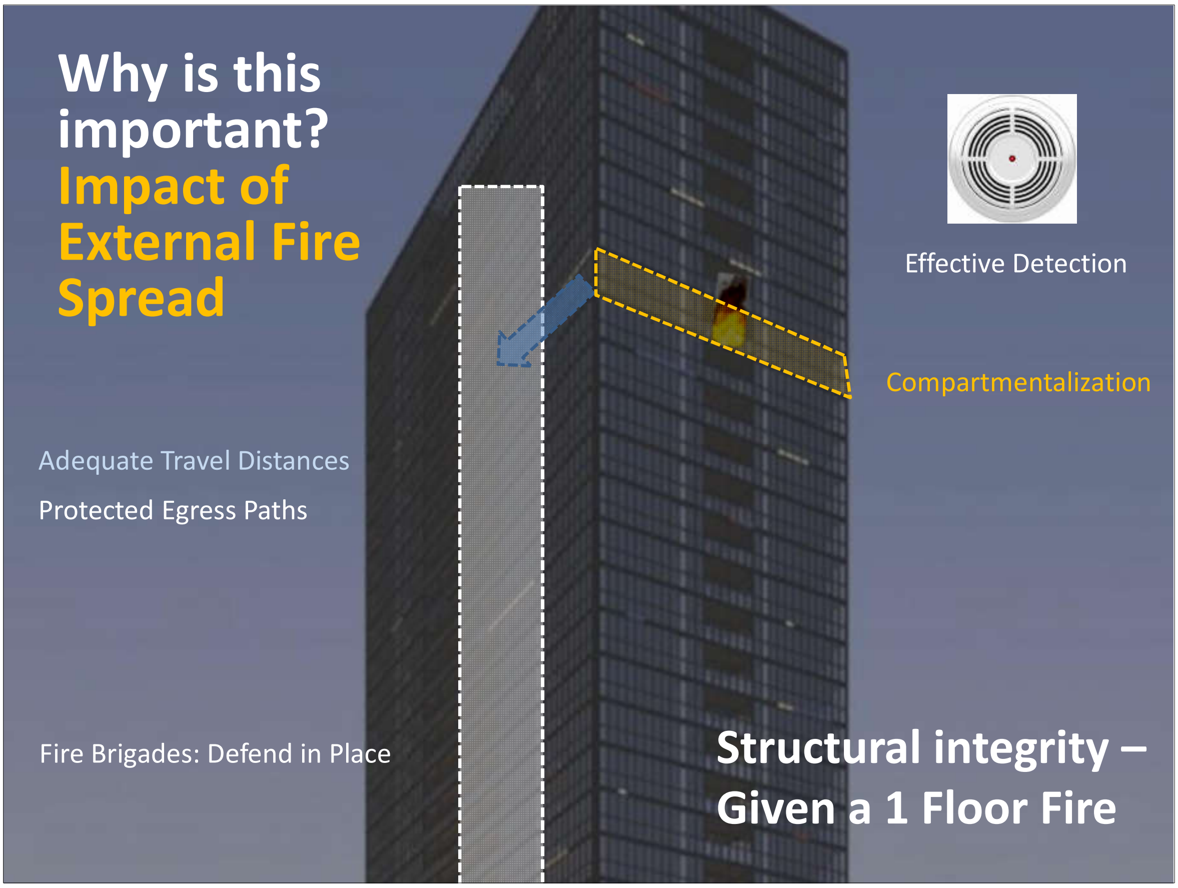


The Objectives

$$t_e <<<< t_f$$

$$t_e <<<< t_s$$

$$t_s \longrightarrow \infty$$

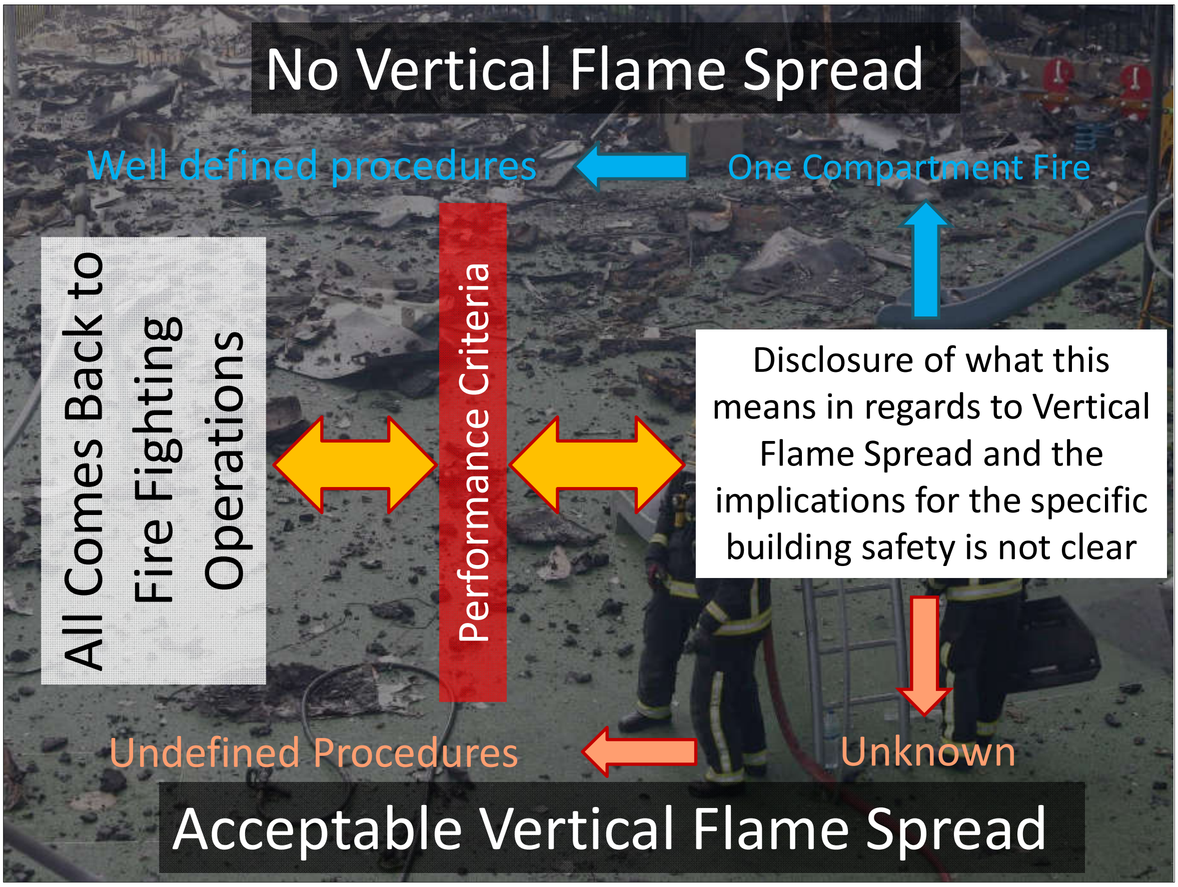

Why is this important?
Impact of External Fire Spread
Effective Detection
Compartmentalization
Adequate Travel Distances
Protected Egress Paths
Fire Brigades: Defend in Place
Structural integrity – Given a 1 Floor Fire


How do things change?
• Detection
• Egress
• Protection of egress paths – compartmentation
• Active fire suppression: Sprinklers
• Structural integrity
• Fire Brigade operations
• etc …

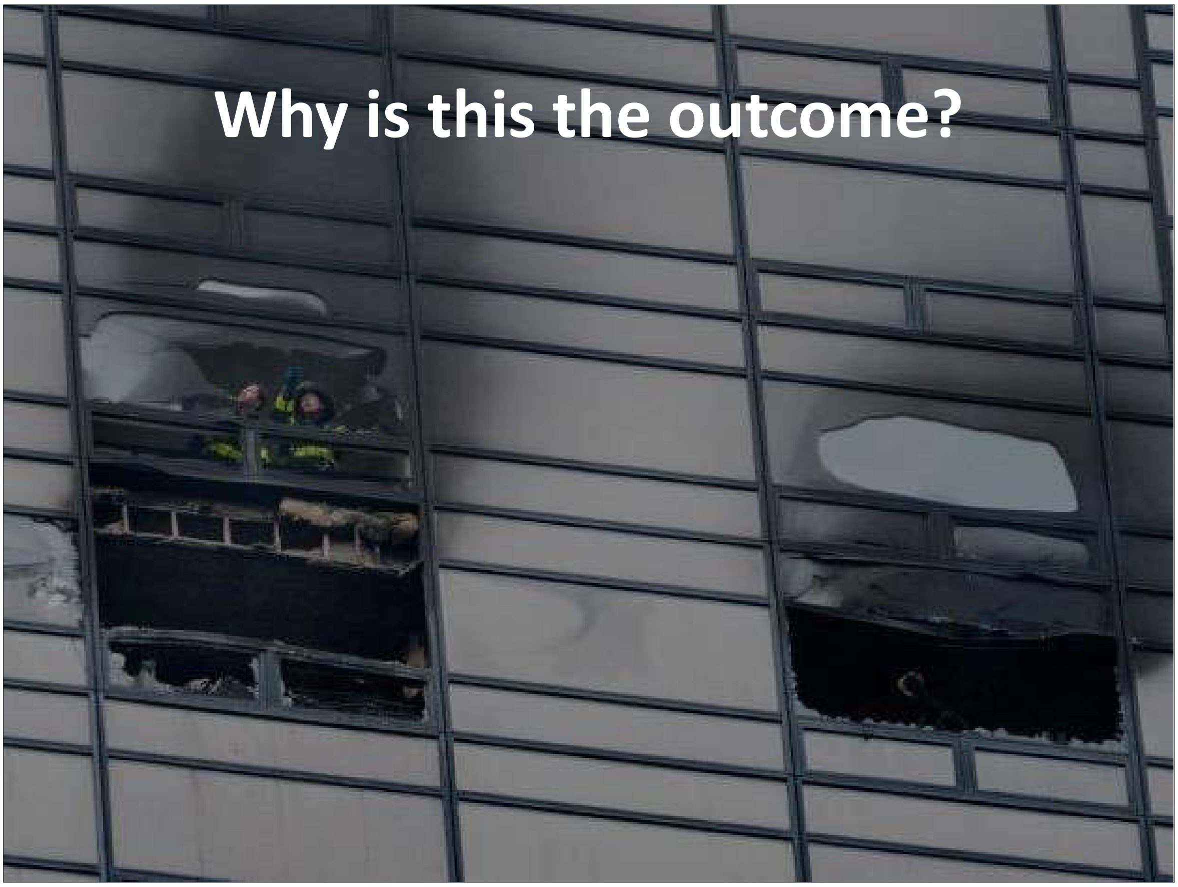
Shepherds Bush Court, August 19th 2016

Is it possible for firefighters to identify when this will happen?

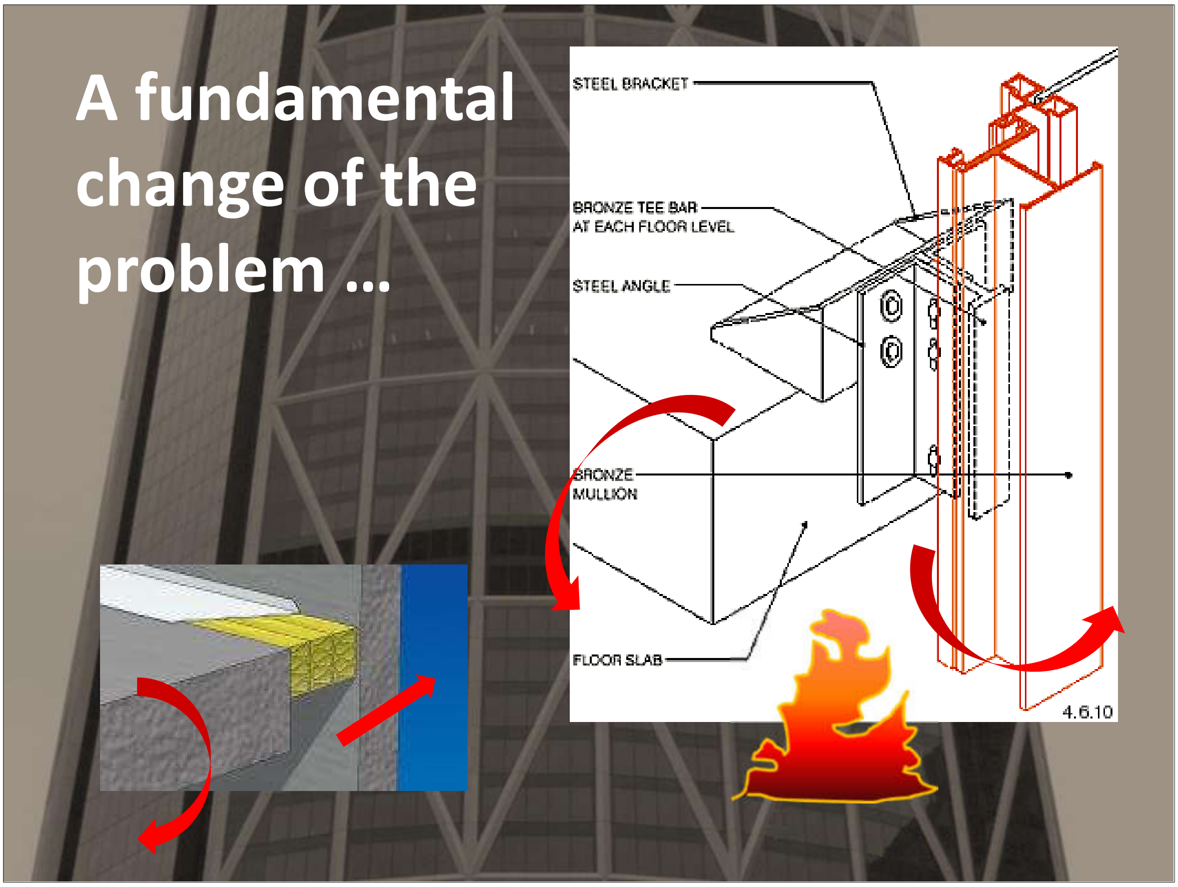
Grenfell Tower Fire, June 14th 2017

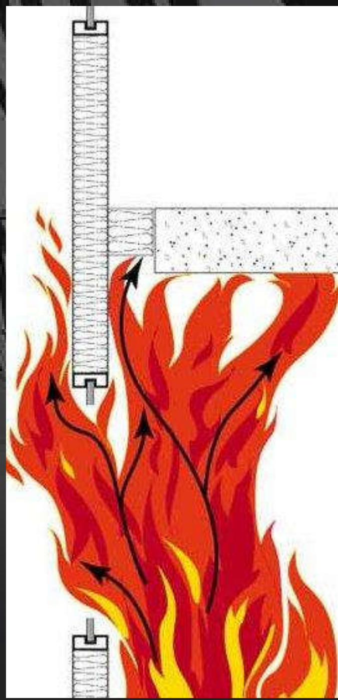



How is this different?


Why is this the outcome?


What has truly changed?

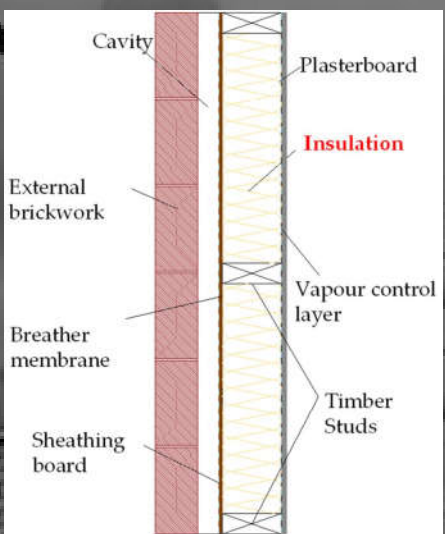

A fundamental change of the problem …
STEEL BRACKET
BRONZE TEE BAR
AT EACH FLOOR LEVEL
STEEL ANGLE
BRONZE
MULLION
FLOOR SLAB
4.6.10



Filling the opening?

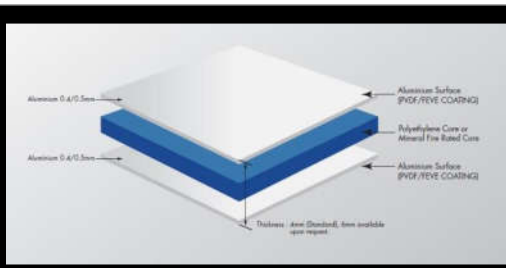
- Relative displacement
- Construction Detailing

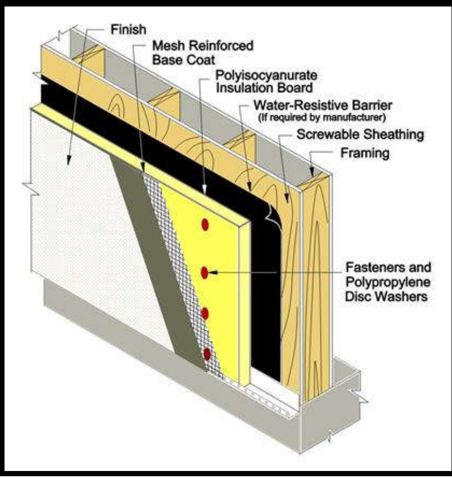
Complex Building Systems



- Complex: Building systems are "multi-purpose" (energy, stability, durability, comfort, life cycle, fire barriers, etc.)
- Dependent on labour skill and cost: Tolerances, installation times, modification during construction, etc.
- If the objective is to guarantee encapsulation then this is the problem that needs to be solved!

Encapsulation



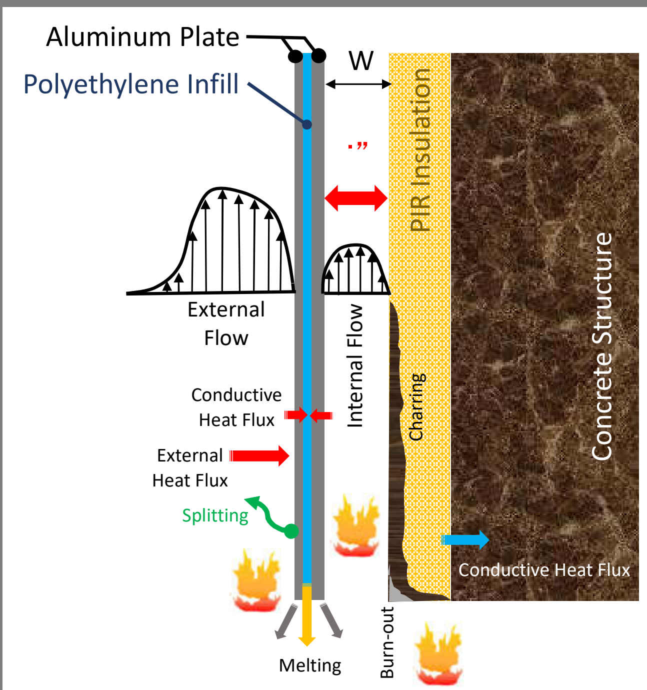


Encapsulation

Protective Layers

How do we establish performance for encapsulation/ protective layers?

Complexity

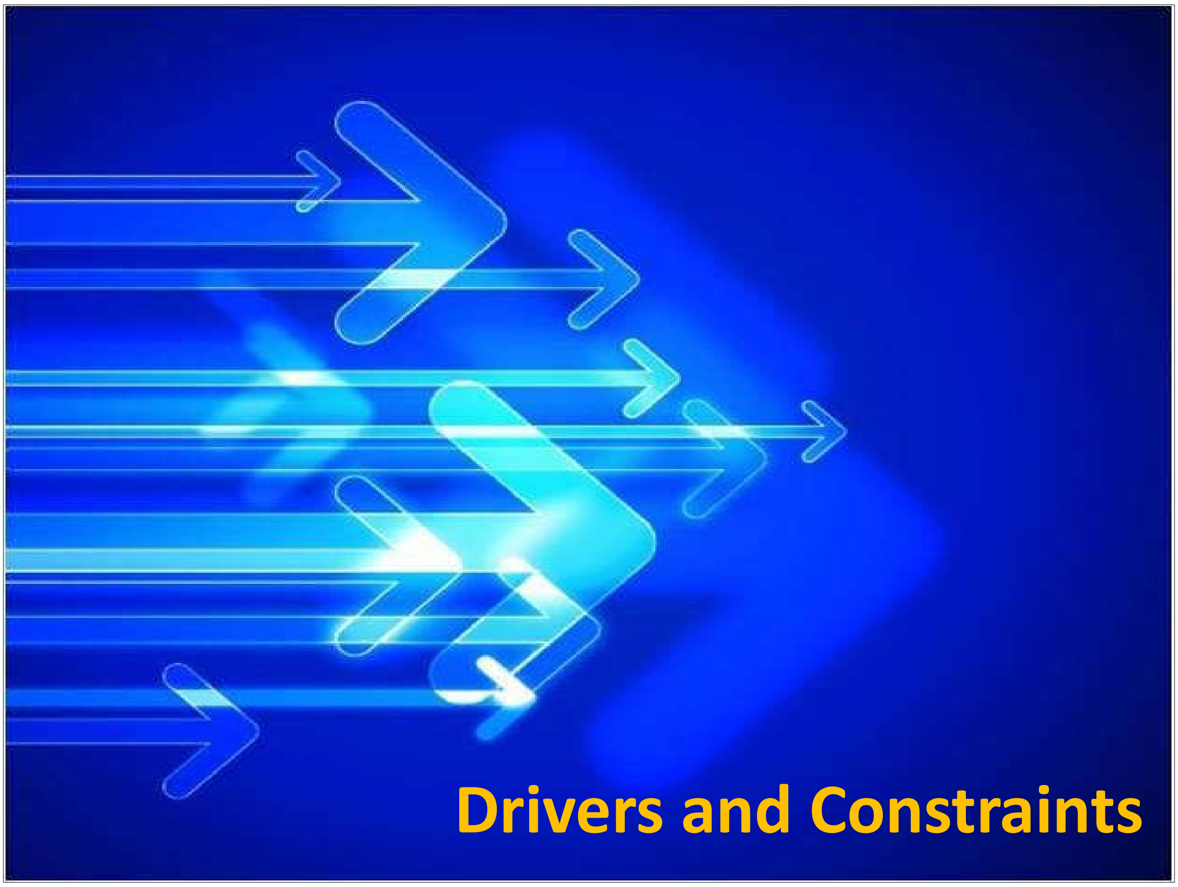


- External fires change everything and severely expose building occupants
- The fire safety strategy is designed for "no" external flame spread
- How can performance be assessed?


Flammability to Encapsulation = Complexity
Challenged our understanding of how to achieve quality, safe, robust, resilient infrastructure
Design principles
Design practises
Performance assessment
Regulatory frameworks
Professional boundaries
Integrated design
Definition of competence
… etc.

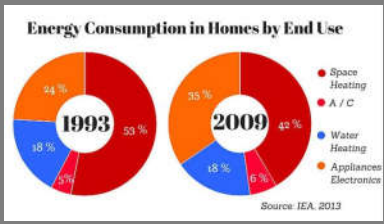

"The Wake Effect"
… or the unintended consequences of our actions

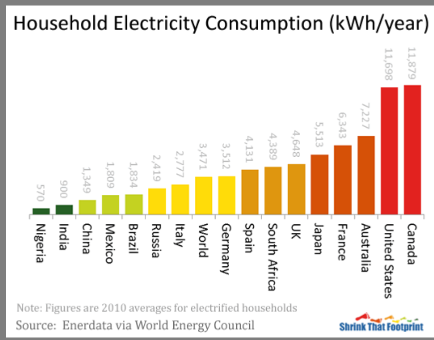

Why are we back to the 1970's?
Joelma fire, Sao Paulo, Brazil, Friday, February 1st, 1974

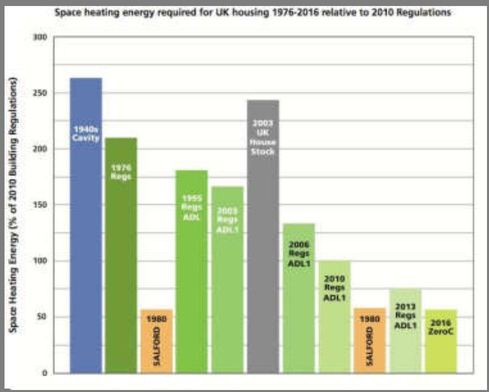

Drivers and Constraints

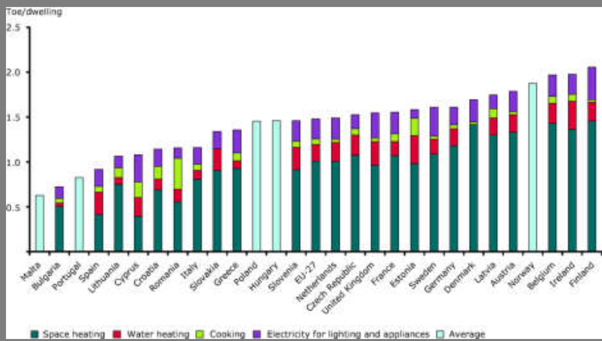
Energy: Quantifiable Performance

- Energy conservation targets



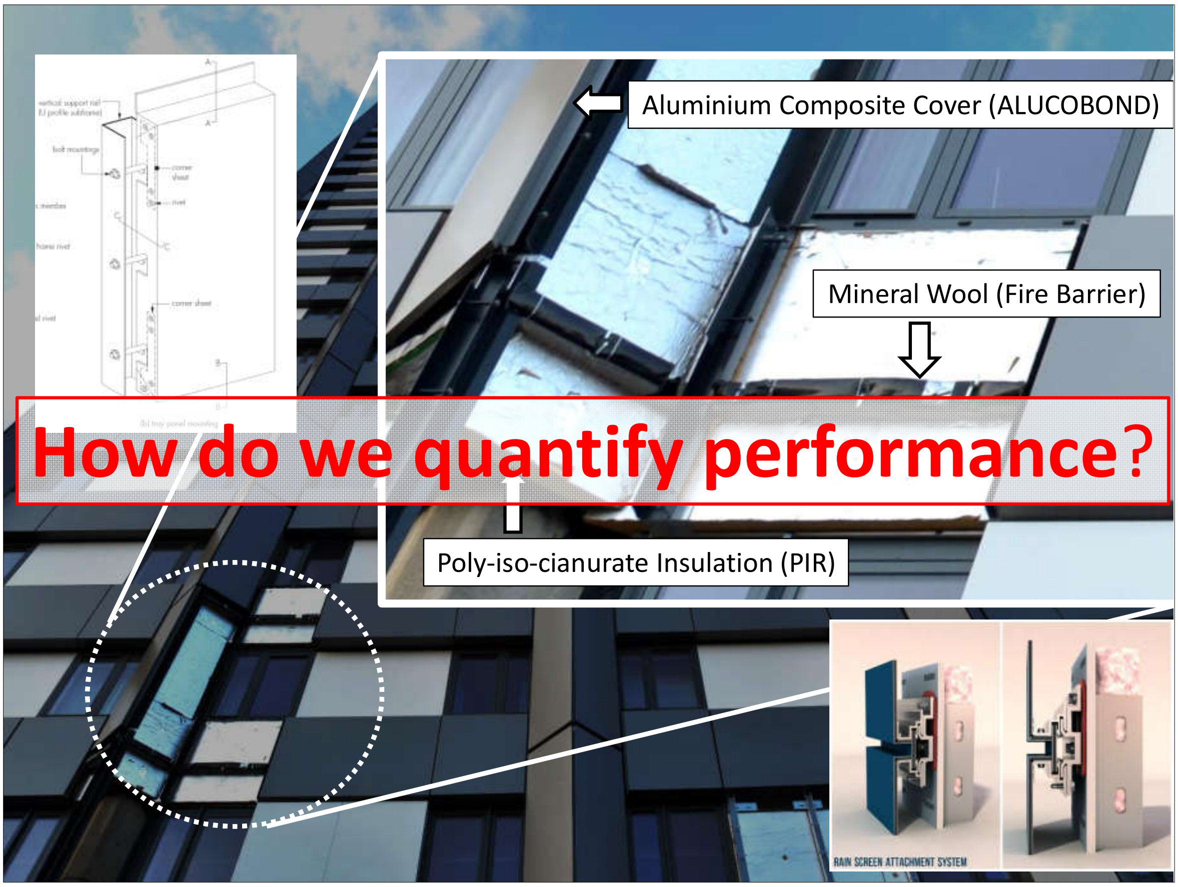


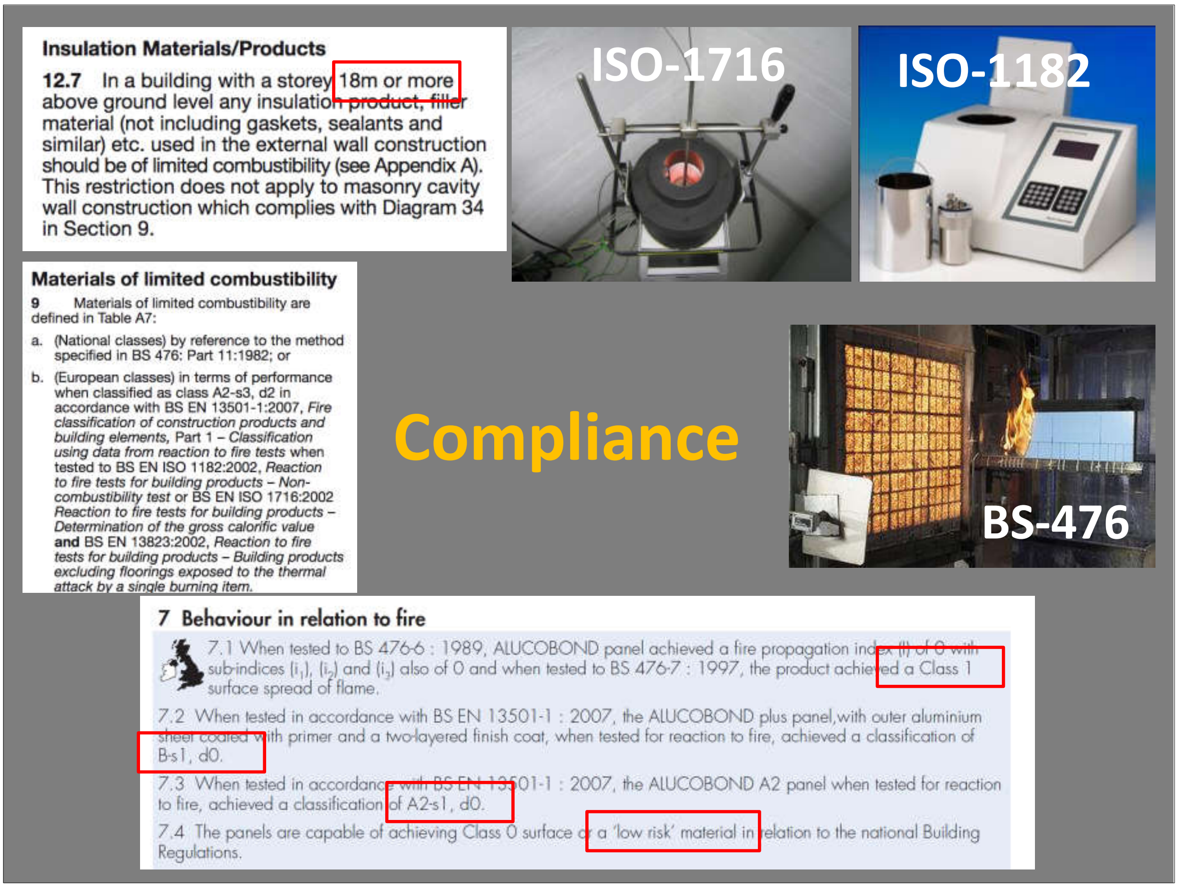




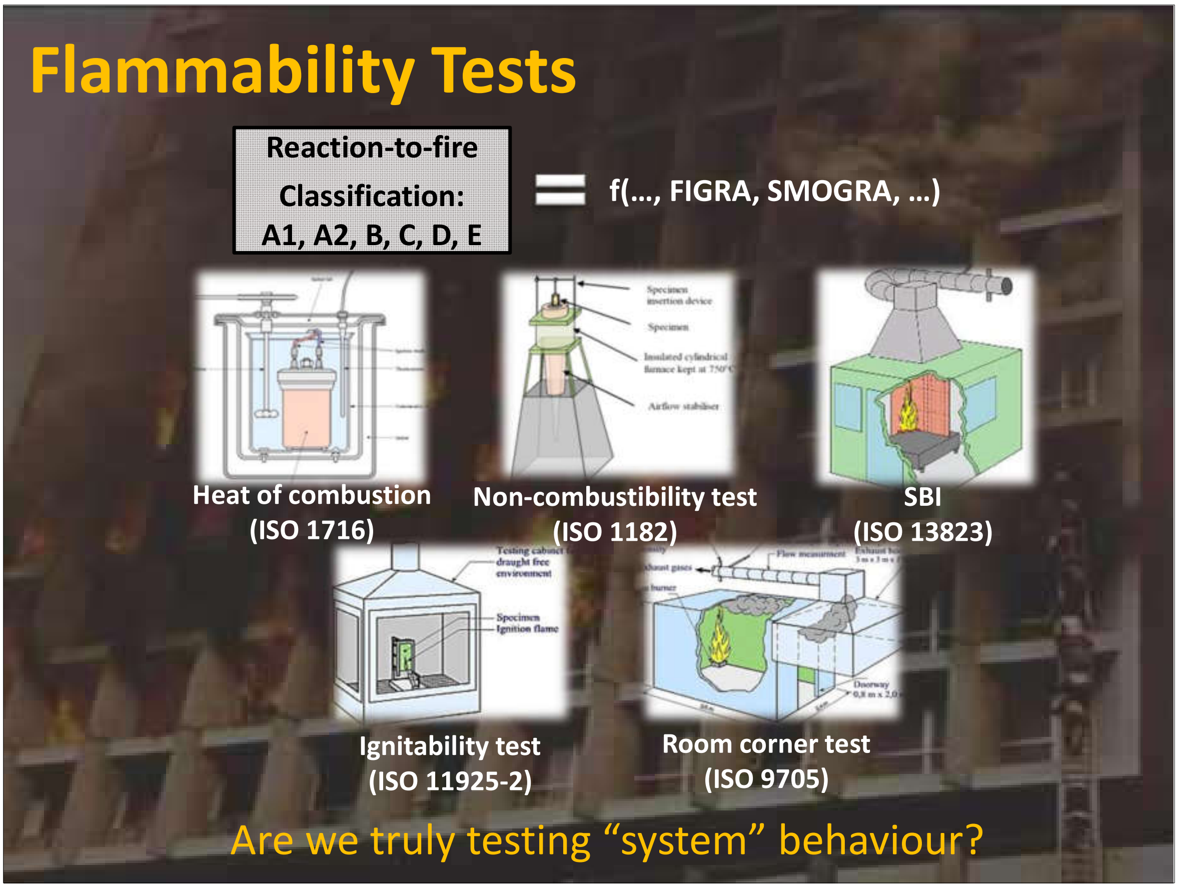
Social Housing: 1960’s – 1970’s


harley
Harley Facades Limited
2009
GRENFELL TOWER, NOTTING HILL
Architect: Studio E
Client: Royal Borough of Kensington & Chelsea
Main contractor: Rydon Group
Scope of works: over-cladding with ACM cassette rainscreen, window replacement, curtain walling, louvres, feature metalwork
Harley contract value: £2.6m
Harley Facades Limited
Harley House
Brooklands Park
Farningham Road
Crowborough
East Sussex
TN6 2JD
T: 01892 669784
F: 01892 669785
harleyfacades.co.uk
2016
Grenfell Tower


Aluminium Composite Cover (ALUCOBOND)
Mineral Wool (Fire Barrier)
How do we quantify performance?
Poly-iso-cianurate Insulation (PIR)
RAIN SCREEN ATTACHMENT SYSTEM

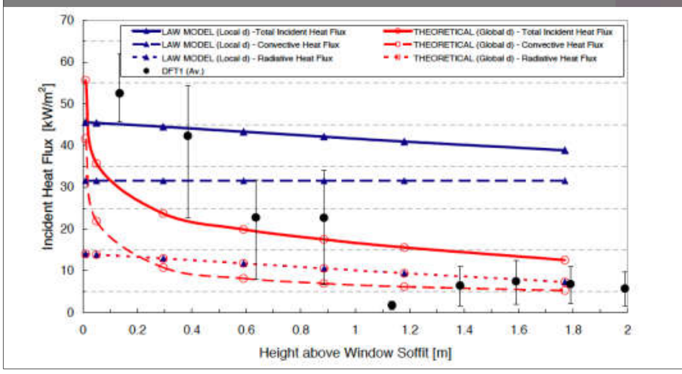

Insulation Materials/Products
12.7 In a building with a storey 18m or more above ground level any insulation product, filler material (not including gaskets, sealants and similar) etc. used in the external wall construction should be of limited combustibility (see Appendix A). This restriction does not apply to masonry cavity wall construction which complies with Diagram 34 in Section 9.
ISO-1716
ISO-1182
Materials of limited combustibility
9 Materials of limited combustibility are defined in Table A7:
a. (National classes) by reference to the method specified in BS 476: Part 11:1982; or
b. (European classes) in terms of performance when classified as class A2-s3, d2 in accordance with BS EN 13501-1:2007, Fire classification of construction products and building elements, Part 1 – Classification using data from reaction to fire tests when tested to BS EN ISO 1182:2002, Reaction to fire tests for building products – Non-combustibility test or BS EN ISO 1716:2002 Reaction to fire tests for building products – Determination of the gross calorific value and BS EN 13823:2002, Reaction to fire tests for building products – Building products excluding floorings exposed to the thermal attack by a single burning item.
Compliance
BS-476
7 Behaviour in relation to fire
7.1 When tested to BS 476-6 : 1989, ALUCOBOND panel achieved a fire propagation index (I) of 0 with sub-indices (i1), (i2) and (i3) also of 0 and when tested to BS 476-7 : 1997, the product achieved a Class 1 surface spread of flame.
7.2 When tested in accordance with BS EN 13501-1 : 2007, the ALUCOBOND plus panel, with outer aluminium sheet coated with primer and a two-layered finish coat, when tested for reaction to fire, achieved a classification of B-s1, d0.
7.3 When tested in accordance with BS EN 13501-1 : 2007, the ALUCOBOND A2 panel when tested for reaction to fire, achieved a classification of A2-s1, d0.
7.4 The panels are capable of achieving Class 0 surface or a 'low risk' material in relation to the national Building Regulations.


Is this a solely a material flammability issue?

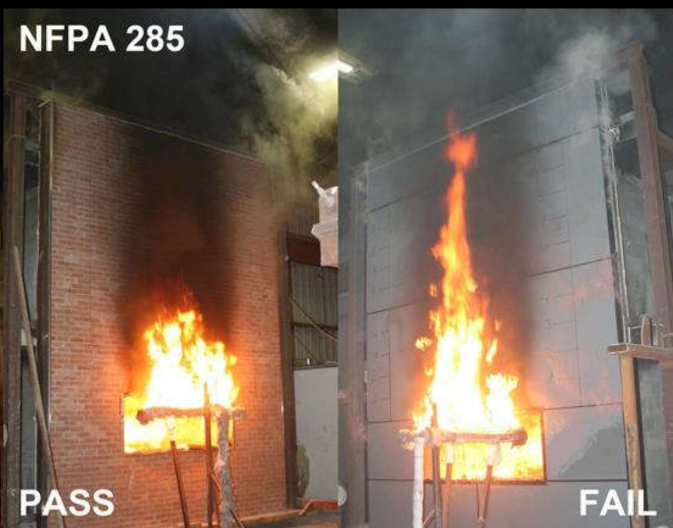

Flammability Tests
Reaction-to-fire
Classification:
A1, A2, B, C, D, E
= f(…, FIGRA, SMOGRA, …)
Heat of combustion
(ISO 1716)
Non-combustibility test
(ISO 1182)
SBI
(ISO 13823)
Ignitability test
(ISO 11925-2)
Room corner test
(ISO 9705)
Are we truly testing “system” behaviour?


Does this test provide system performance?
Does this test assess true mechanical behaviour?
Fire-resistance
Pass-Fail
R,E,I

Spill Plumes



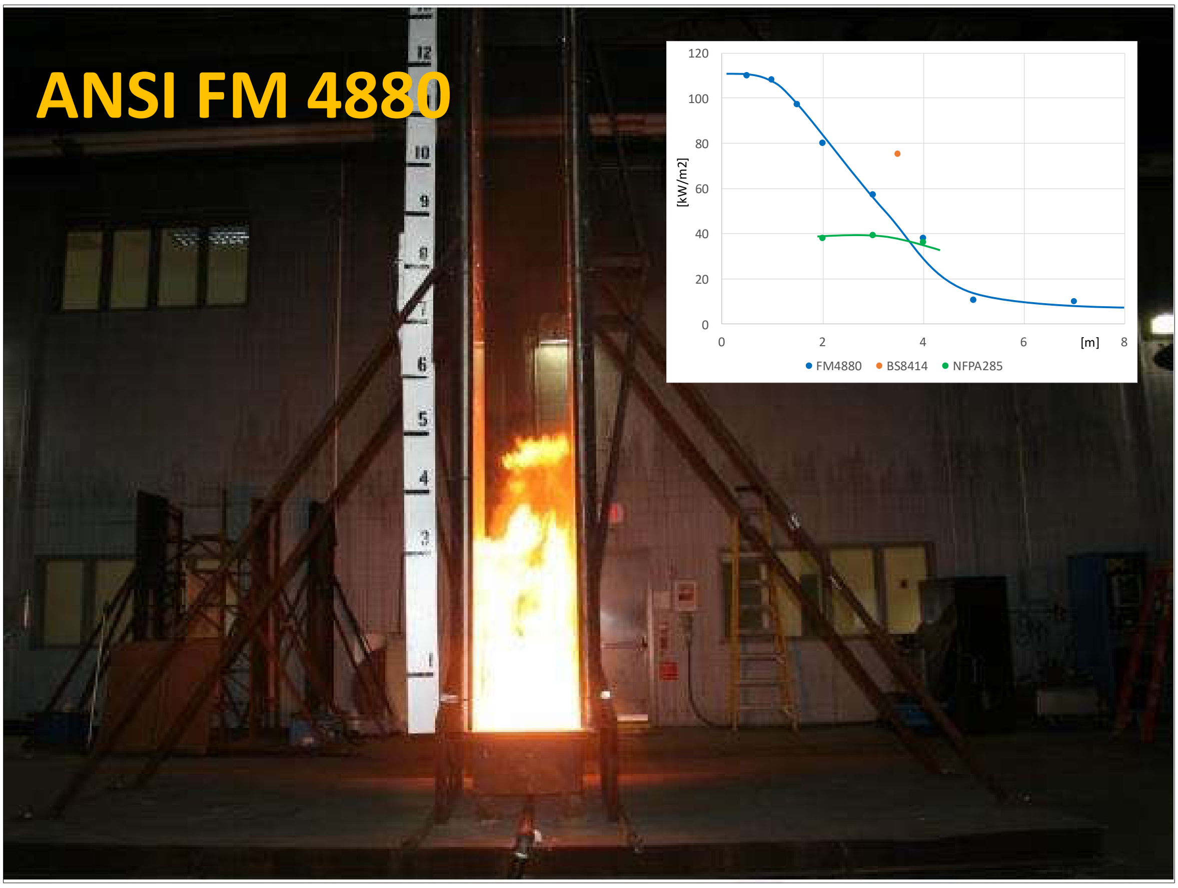
Are these the right tests?



48.4.1.5 Wall Assembly Flammability.

48.4.1.5.1 The wall assembly shall be tested in accordance with, and the results shall comply with, the acceptance criteria of NFPA 285, *Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Non-Load-Bearing Wall Assemblies Containing Combustible Components.*

48.4.1.5.2 The requirement of 48.4.1.5.1 shall not apply to one-story buildings complying with 48.3.3.4(4).



Performance

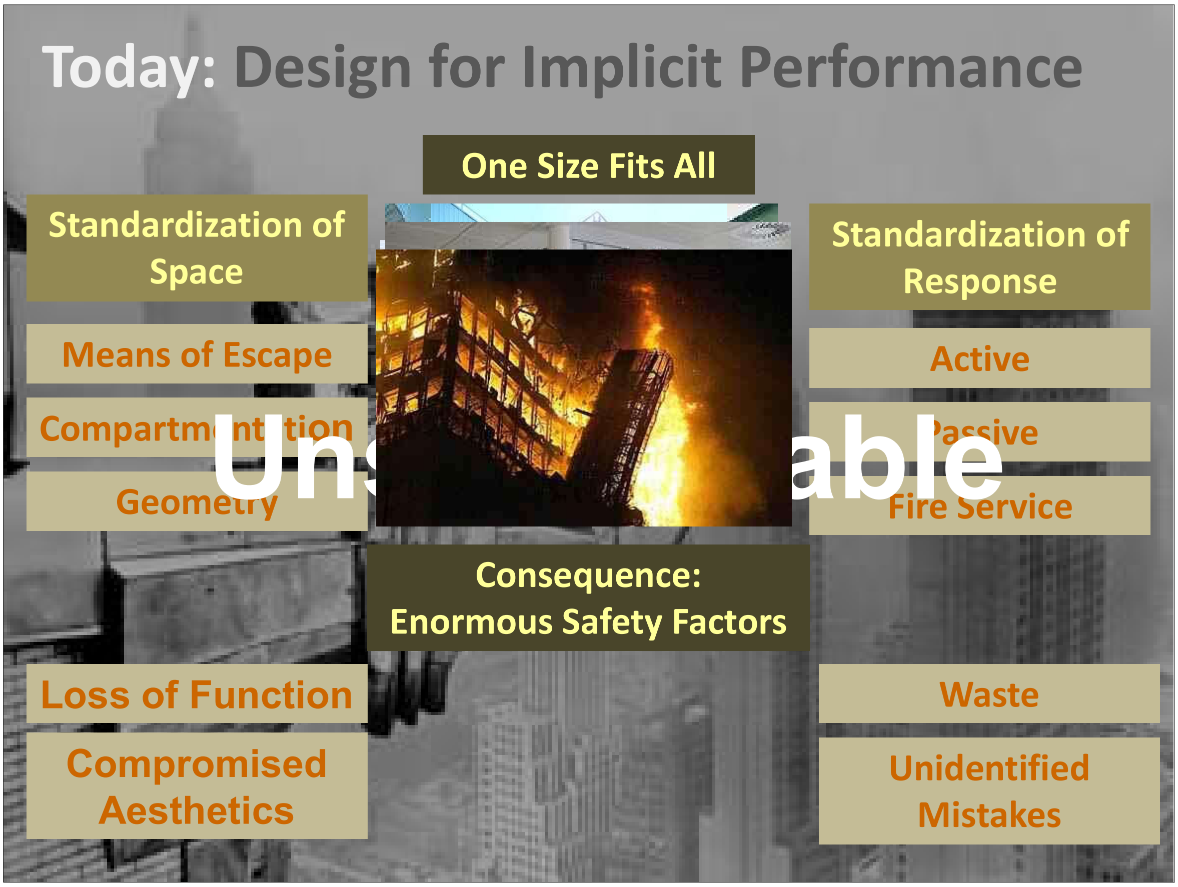
… we know perfectly well how to do it …

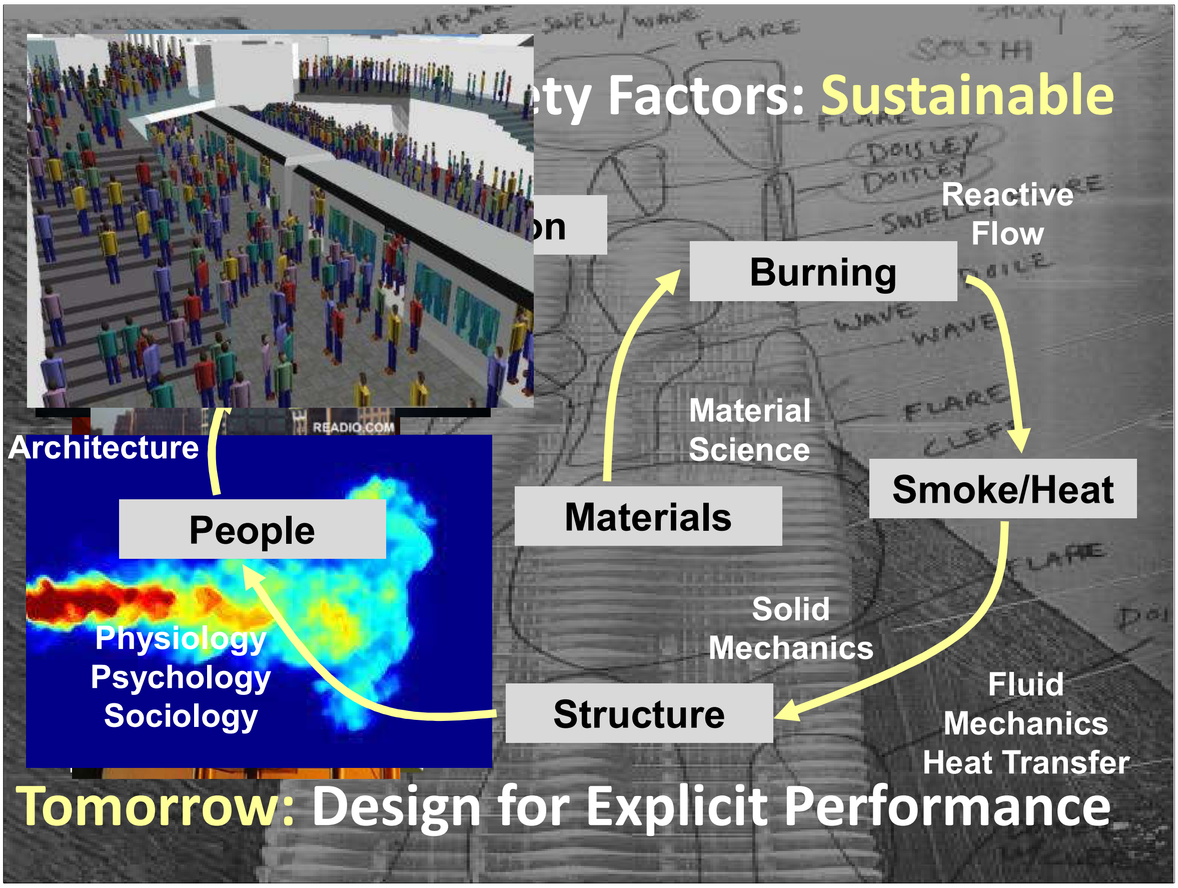
… but it requires "bespoke" performance protocol for each particular system … there is no standardize test because we are testing "system behaviour": Building + Envelope

… Past: One test for all materials

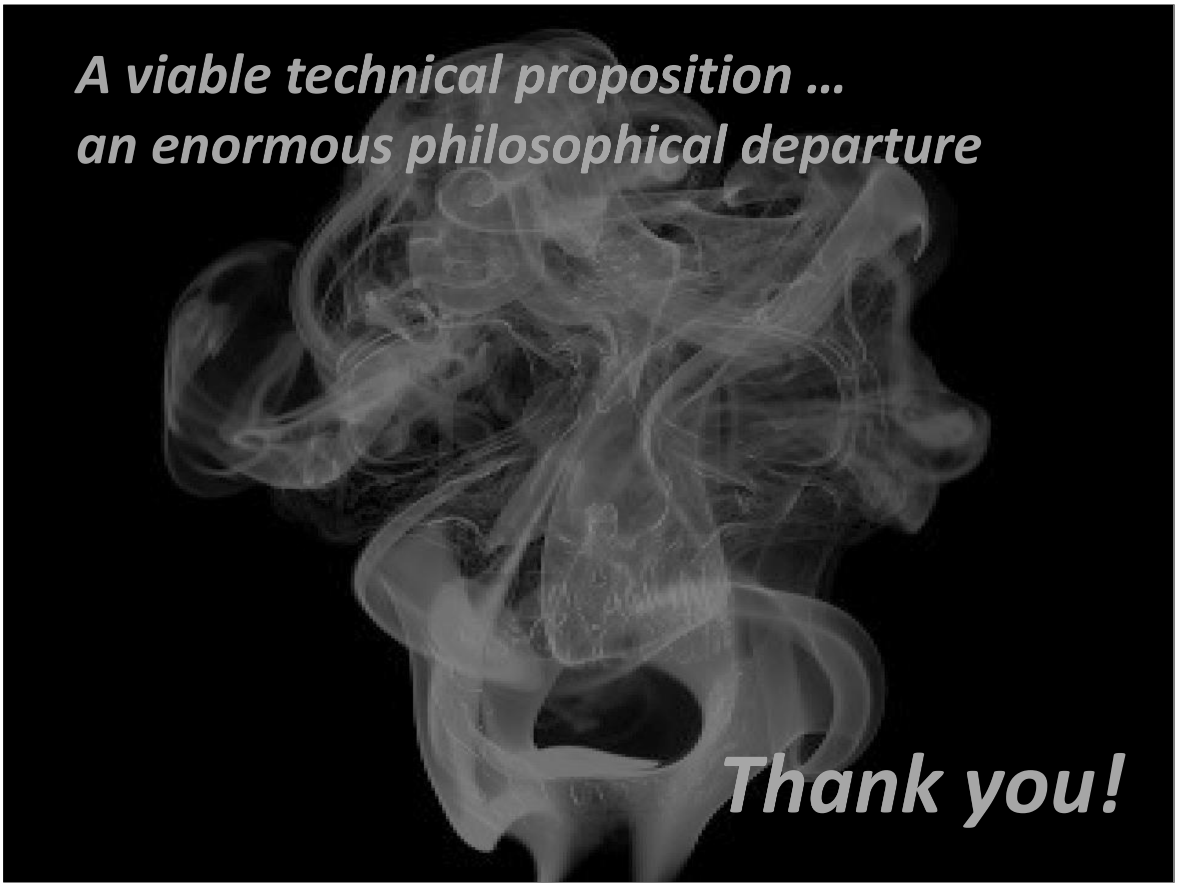
… Today: A bespoke performance protocol for each system


How do we bring attention to the "wake"?
Safety is not a constraint
It is not the bad test
It is not the bad material
It is the lack of understanding of the consequences of our actions


Today: Design for Implicit Performance
One Size Fits All
Standardization of Space
Means of Escape
Geometry
Standardization of Response
Active
Fire Service
Consequence: Enormous Safety Factors
Loss of Function
Compromised Aesthetics
Waste
Unidentified Mistakes



ety Factors: Sustainable
Reactive
Flow
Burning
Material
Science
Smoke/Heat
Materials
Architecture
People
Solid
Mechanics
Physiology
Psychology
Sociology
Structure
Fluid
Mechanics
Heat Transfer
Tomorrow: Design for Explicit Performance



A viable technical proposition …
an enormous philosophical departure
Thank you!

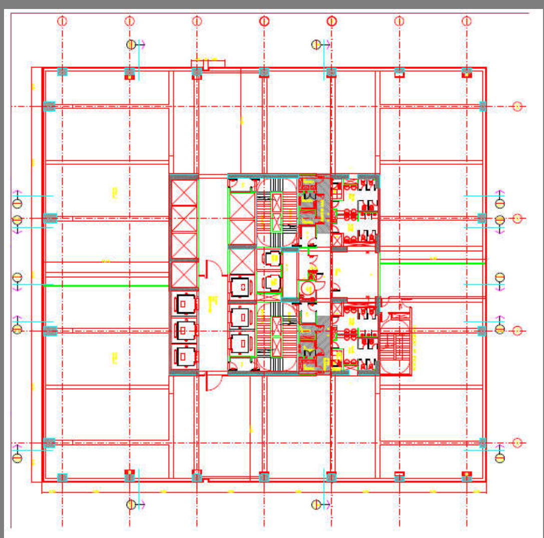
Egress

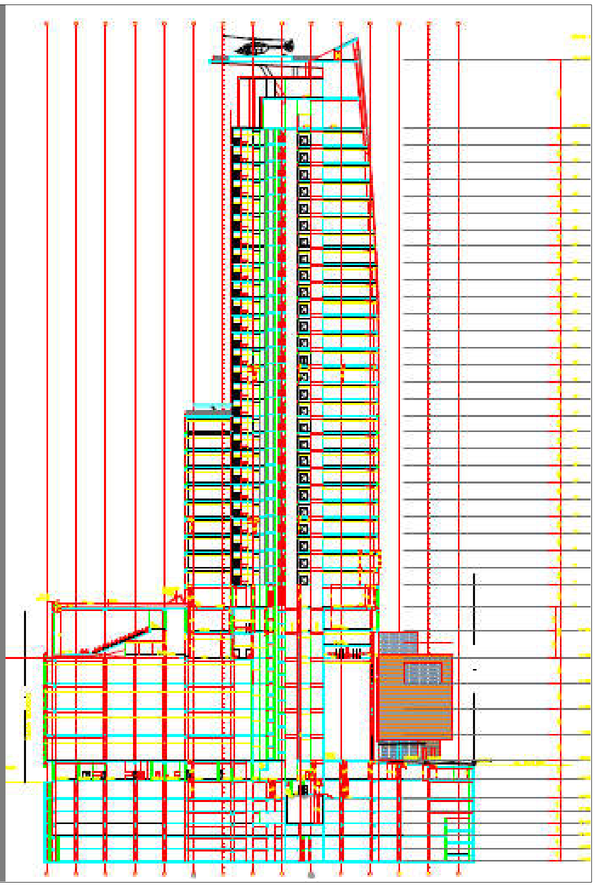
José L. Torero
University College London
United Kingdom

Lecture – 2

Joelma fire, Sao Paulo, Brazil,
Friday, February 1st, 1974

How do I get everyone out?





Objectives

$t_e <<<< t_f$ RSET<<<<ASET

$t_e <<<< t_S$

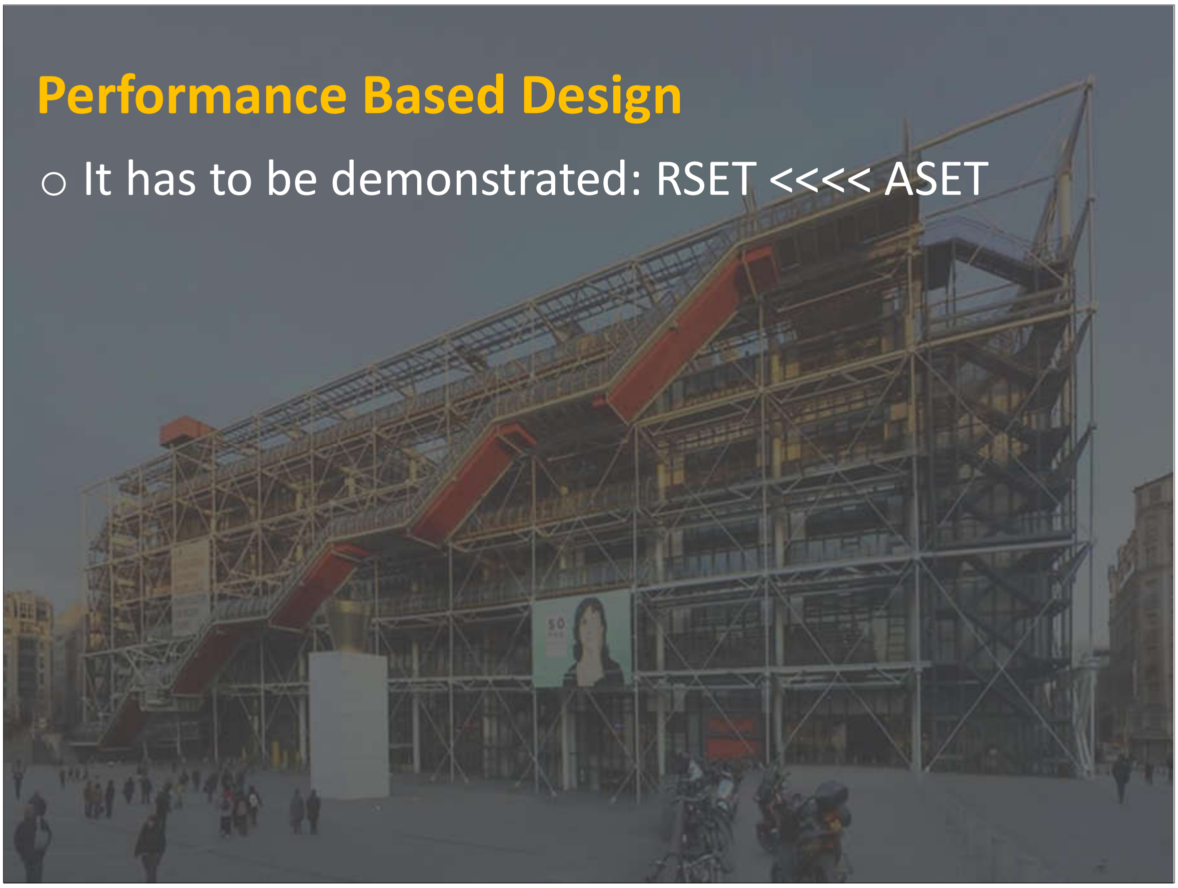
$t_s \longrightarrow \infty$

Fire Safety Strategy

Prescriptive Design

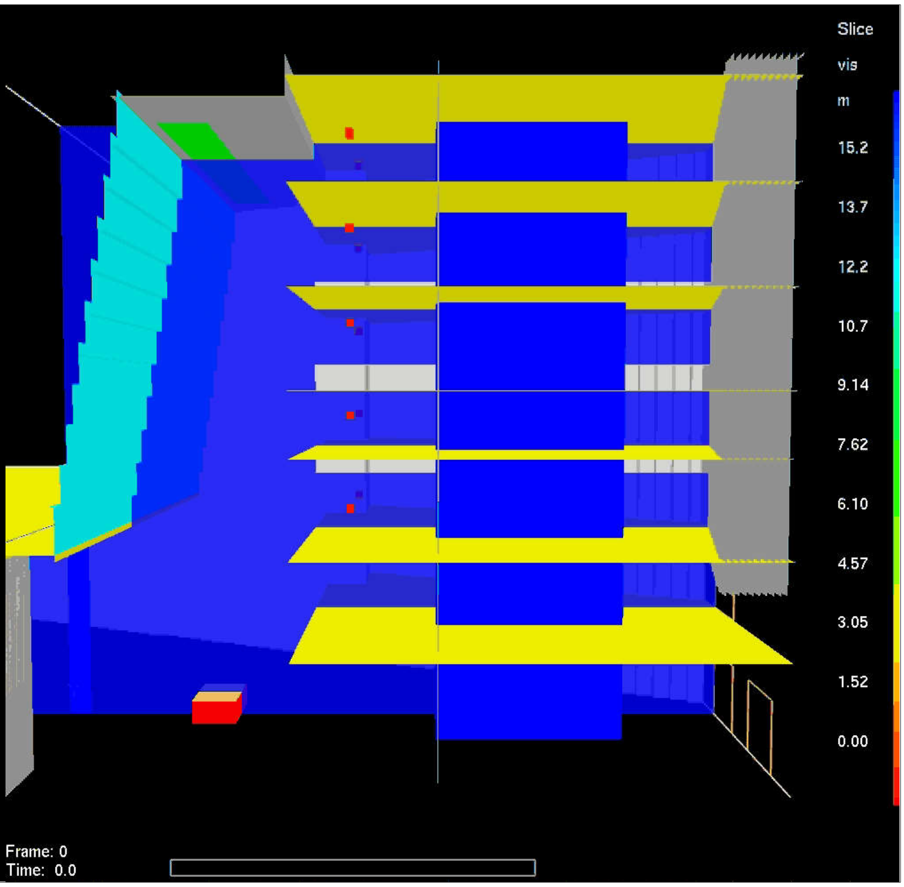
- If codes are followed RSET <<<< ASET

  – by definition


Performance Based Design
○ It has to be demonstrated: RSET <<<< ASET


ASET
○ A.S.E.T.: Available Safe Egress Time (t_f)

- Models can be used for the definition of the evolution of the fire (t_f)

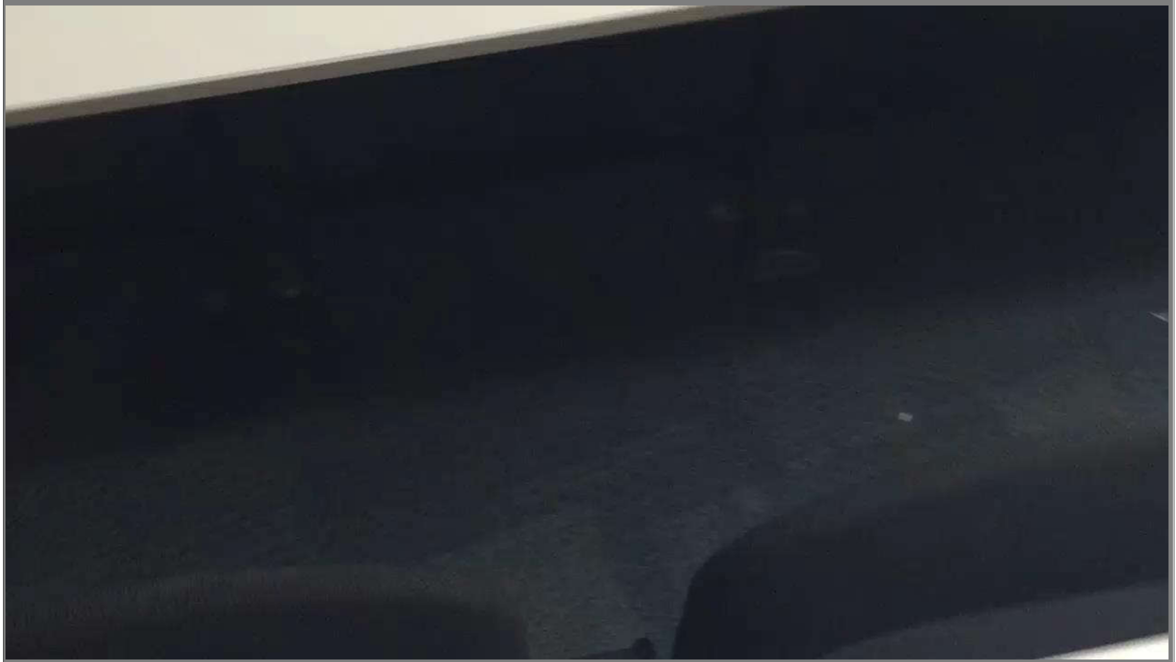


Or … Congregation Spaces (Theatres)

- Successful evacuation
- Empire Palace Theatre
  - 9 May 1911
  - Disastrous fire on stage
  - 3000 audience evacuated in 2.5 minutes
  - 11 deaths backstage
  - http://en.wikipedia.org/wiki/Edinburgh_Festival_Theatre
- Post-war building studies report
  - Fire grading of buildings, HMSO, 1952
  - 2.5 minute clearing time for a space!

The Great Lafayette and God Save the King

A.S.E.T. is 2.5 min



RSET

- We need to establish egress times(t_e)
- R.S.E.T. (t_e) – Required Safe Egress Time

Egress Time (t_e)

$$t_e = t_{de} + t_{pre} + t_{mov}$$

- t_e – Egress time
- t_{de} – Detection time
- t_{pre} – Pre-Movement time
- t_{mov} – Displacement time

Detection time (t_{de})

- Depends on the technology used but it is generally much smaller than all other times ($t_{de} \approx 0$)

$$t_e = t_{pre} + t_{mov}$$

George

Luna Club

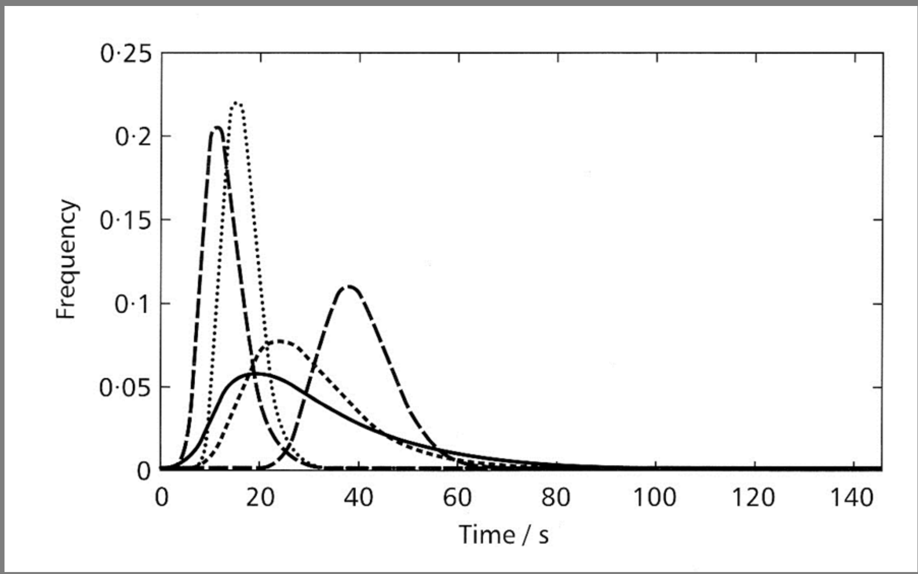
Rhode Island Night Club

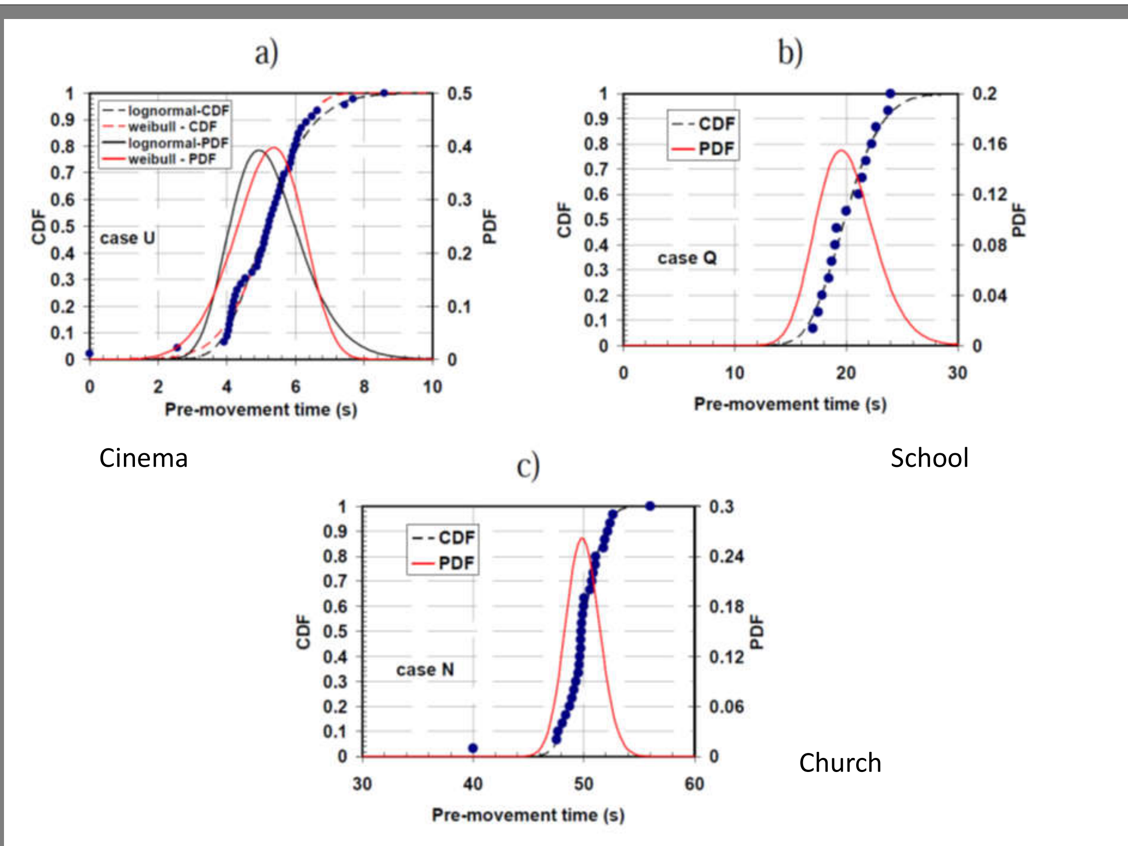
Choice of Materials

- The growth of the fire needs to be limited to enable egress to occur under ideal conditions
- If flames spread too fast then panic is induced
  - Egress is unpredictable
- If flames spread too fast there is not enough time to evacuate before reaching t_f

Pre-Movement Time (t_{pre})

- Purely statistical – can be very long and brings great uncertainty





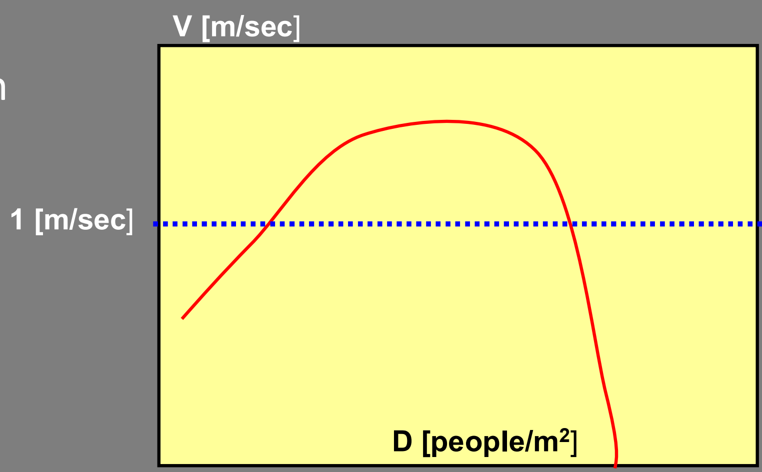
Cinema

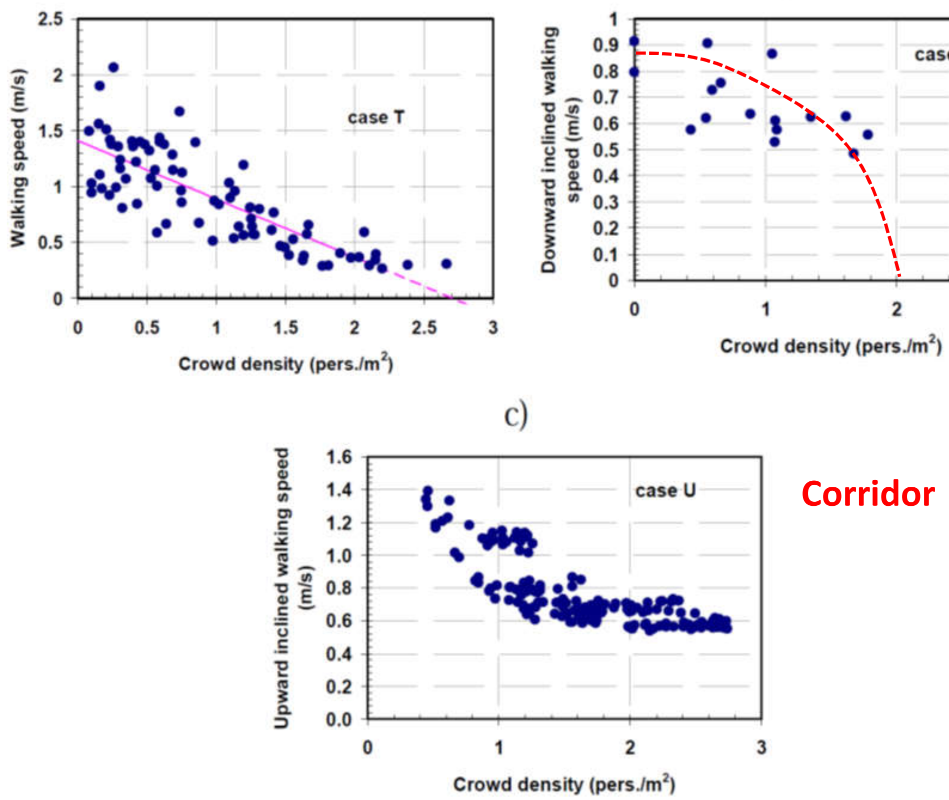
School

Church

Principles of Egress

- Avoid panic behaviour
  - Reduces uncertainty
- Guide people to behave like an ensemble
  - Signalling
  - Illumination





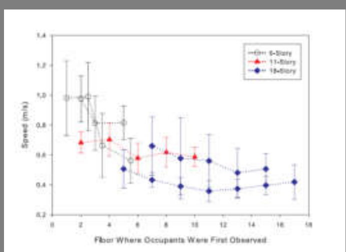
Corridor

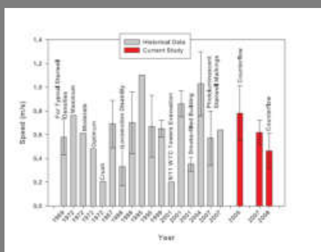
Displacement time (t_{mov})

- Based on experiments

Velocities

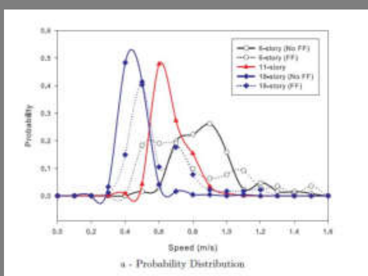
- Allow to calculate displacement times and times to flow through doors ($t_{mov}=d/V_e$)

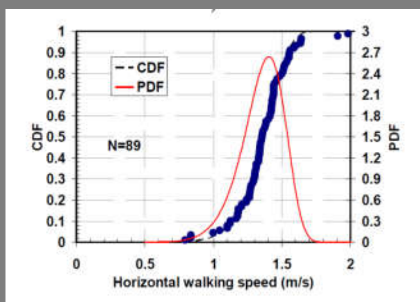




Corridors

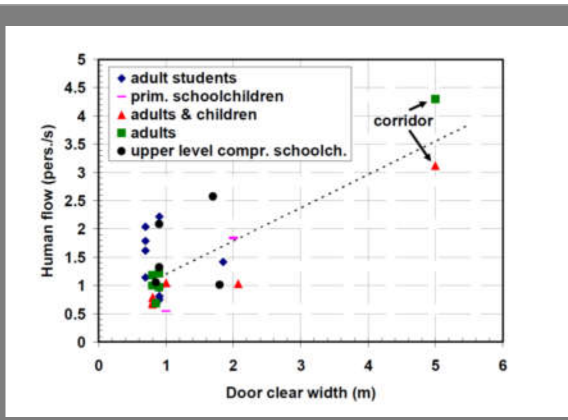
Stairs



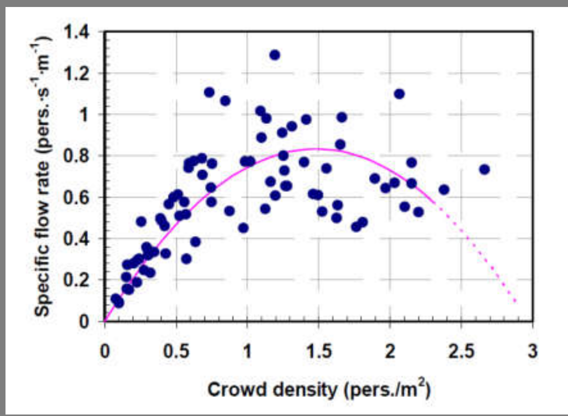


Doors

Fixed Density



Variable Density



Compatibility

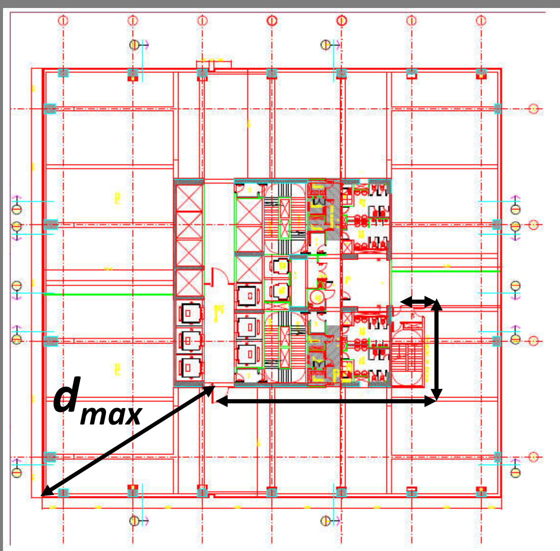
Width of stairs

- Time to fully evacuate a floor (t_{ff})
- Time to displace down a floor (t_{df})

$$t_{df} \approx t_{ff}$$

Egress Exercise

Code Requirements



- Untenable conditions (t_f)
  - If the space is standardized then t_f can be assumed constant
- $t_e < t_f$

Minimum width

≈0

- $t_f > \cancel{\frac{d_{max}}{V_e}} + \frac{N}{W.p} + t_{pm}$
- Maximum egress distances are defined so t_{mov} can be neglected

Hand Calculations

- Hand calculation of displacement times t_{mov}
  - Simple geometry
  - Precision is a function of available data and t_{pre}
- Ideal application: tall buildings, train stations, stadia with limited egress options, no cross-flows, etc.

Software

- Commercial Codes: Simulex, Exodus, etc.
- Freeware: FDS-(evac), etc.

Software

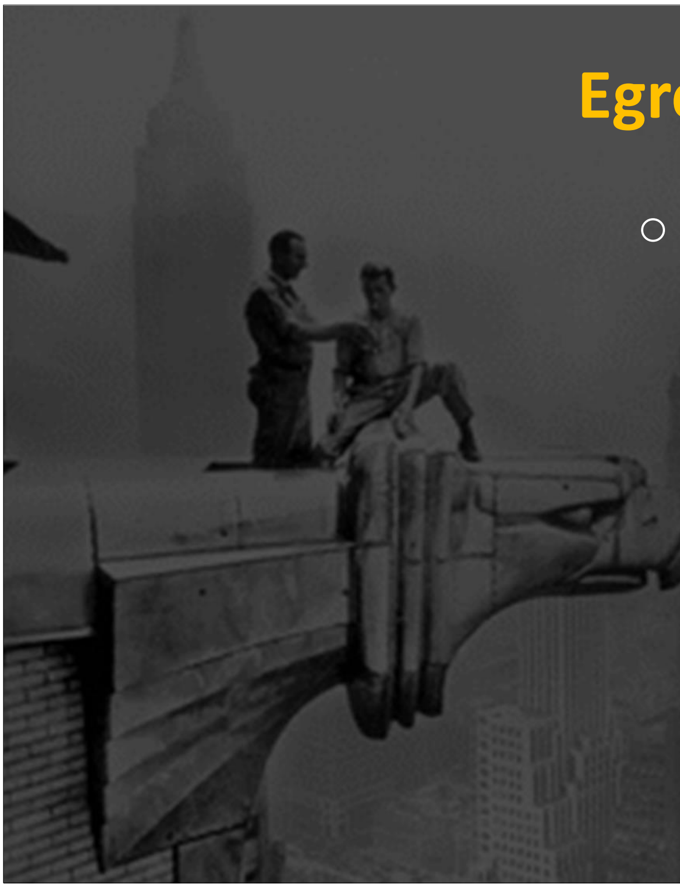
- Computations of t_{mov}
  - Complex geometry
  - Precision also depends of available data and t_{pre}
- Ideal application:
  - Shopping centres, infrastructure with very large surface area and multiple egress paths, cross flow, etc.

Example

	Evacuation trail	ASERI	buildingEXODUS	PedGo	Simulex
Total building	8.78 min	ca. 9 min	ca. 8.5 min	ca. 8 min	ca. 8 min
2nd floor	50–149 s	40–82 s	38–74 s	44–94 s	44–82 s
4th floor	45–75 s	35–86 s	49–73 s	50–82 s	41–86 s
5th floor	61–101 s	36–87 s	35–83 s	42–89 s	42–90 s
6th floor	31–102 s	42–82 s	35–78 s	41–95 s	42–85 s
7th floor	67–132 s	43–96 s	37–77 s	39–96 s	43–95 s
10th floor	51–102 s	33–117 s	41–83 s	39–92 s	43–90 s
15th floor	48–155 s	38–83 s	38–81 s	45–88 s	42–80 s

Hand calculations

- Very similar results



Egress Calculations

- Precision is given by the experimental data not by the complexity of the model
  - Hand calculations for simple geometries
  - Computations (software) for complex geometries

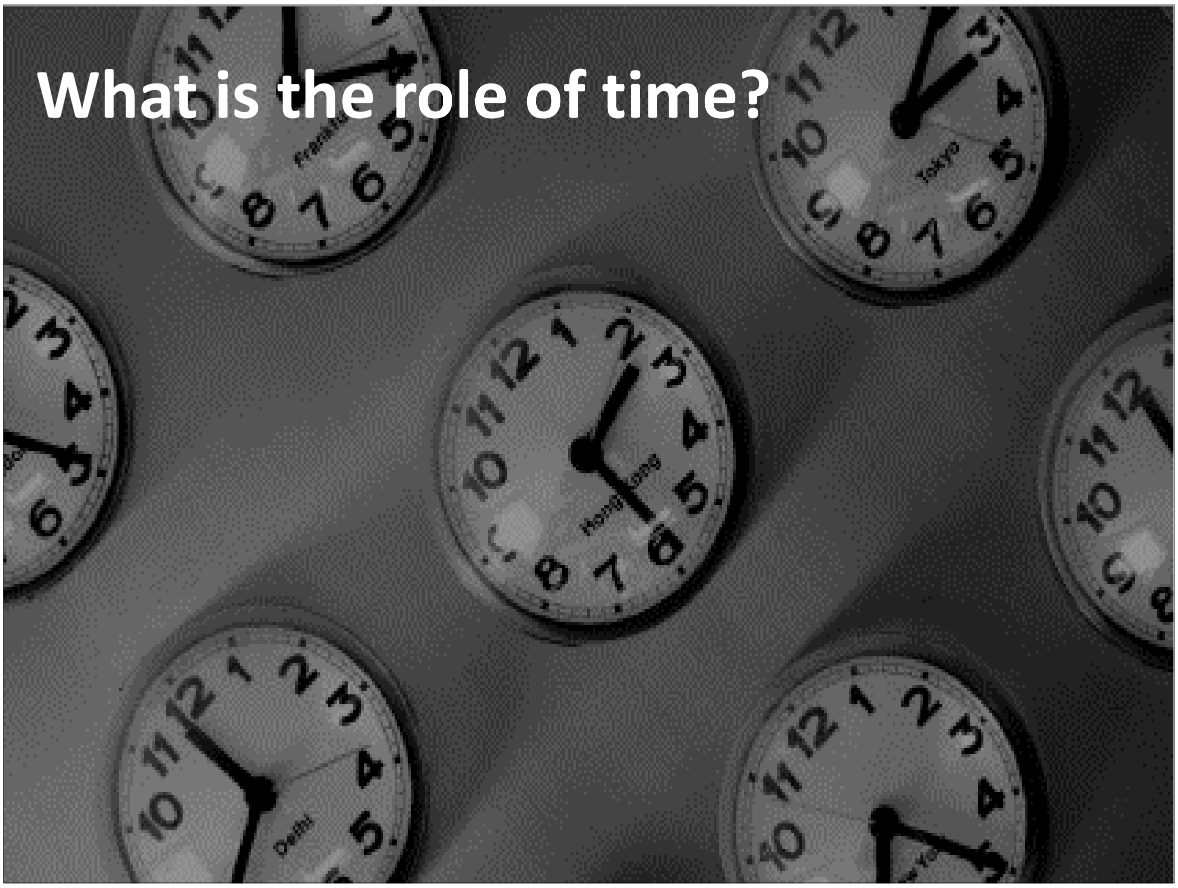
Timeline

- 1st floor: 10 sec
- 3 floors: 30 sec
- 8 floors: 60 sec
- 16 floors: 120 sec
- 25 floors: 180 sec
- Building: 240 sec


How does this
change egress?


Fire Dynamics
José L. Torero
University College London
United Kingdom
Lecture -3

What is the role of time?



Objectives

$t_e <<<< t_f$ RSET<<<<ASET

$t_e <<<< t_S$

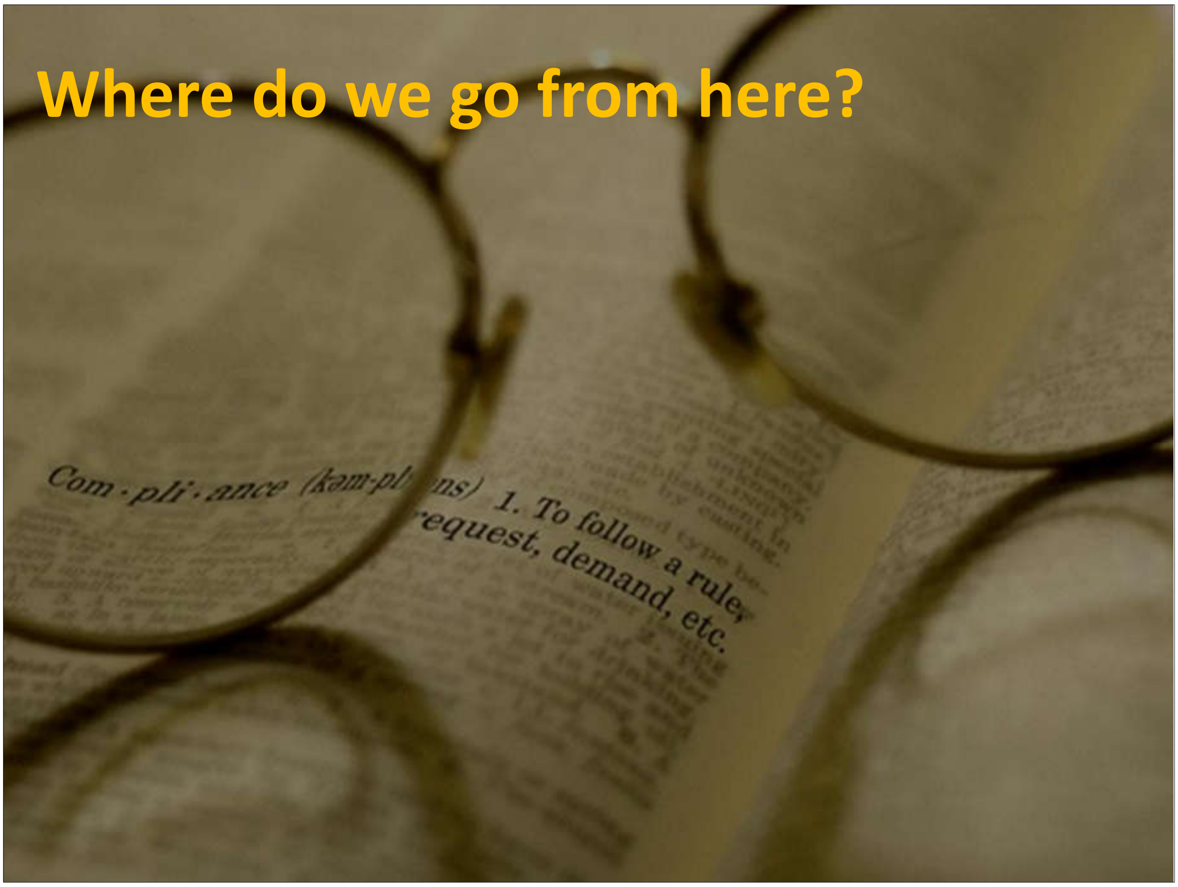
$t_s \rightarrow \infty$

Fire Safety Strategy

RSET

- We need to establish egress times(t_e)
- R. T. (t_e) –
  Req afe
  Egress

Where do we go from here?



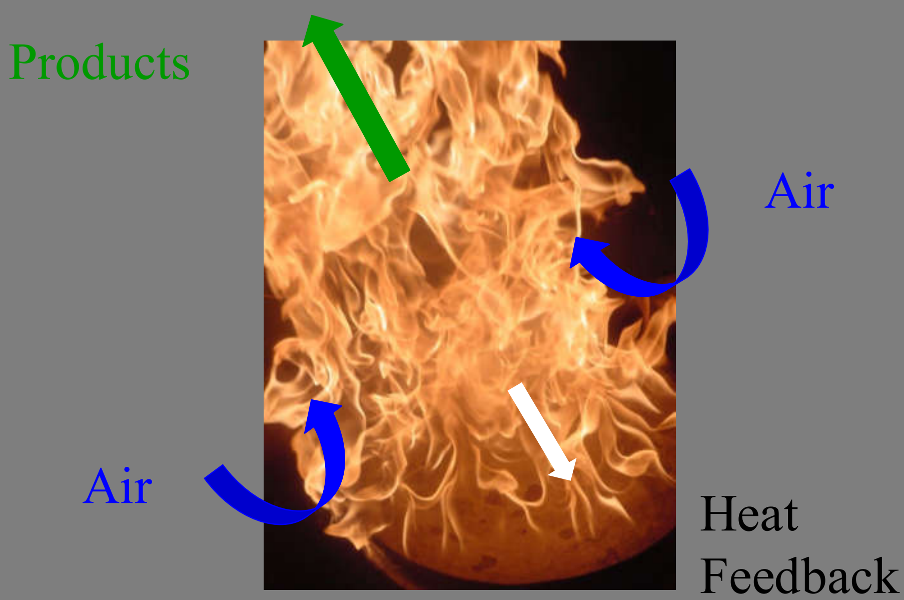
ASET

- A.S.E.T.: Available Safe Egress Time (t_f)

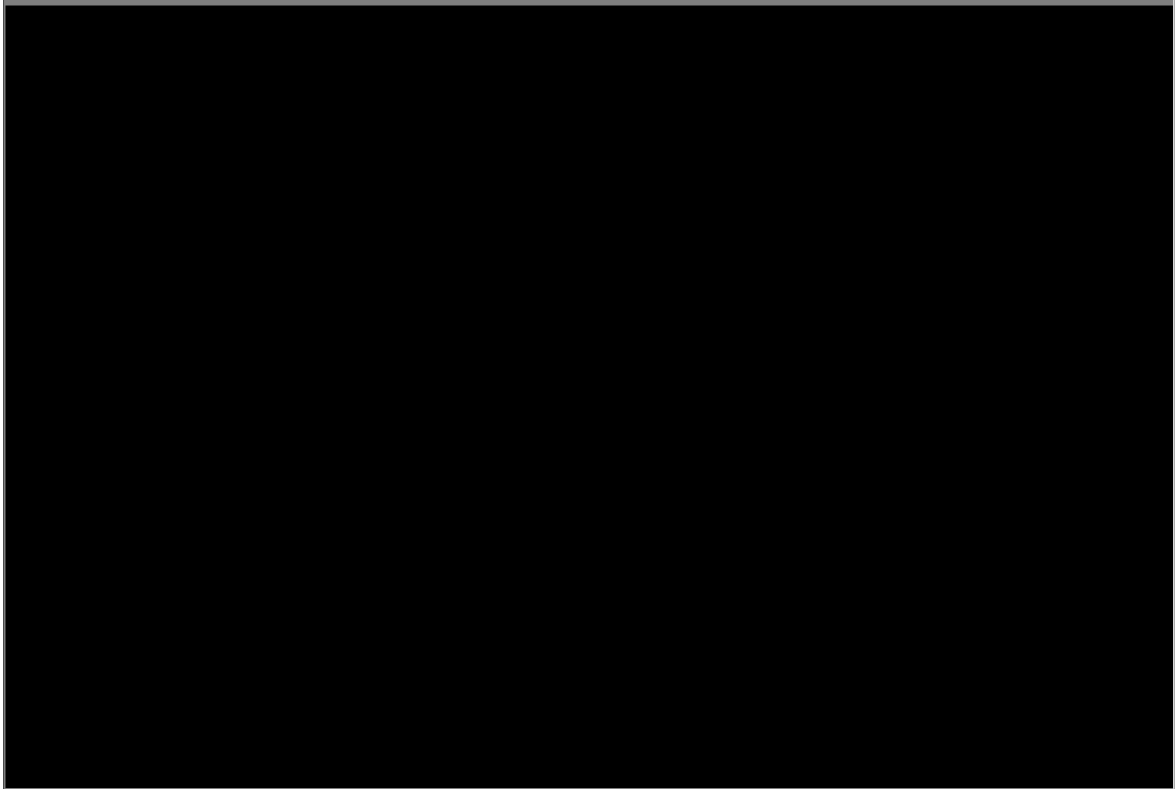
Explosion?

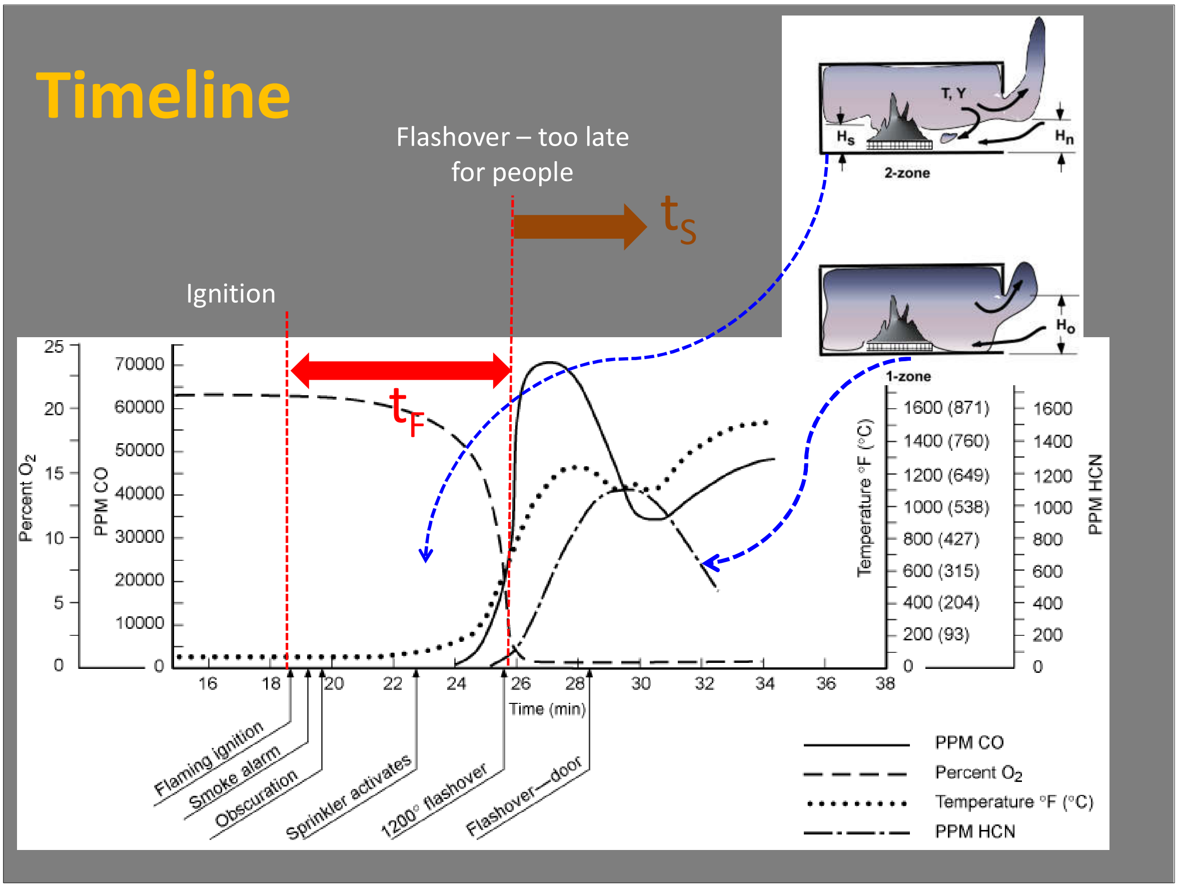
- What is the difference between a fire and an explosion?
  - Non-premixed Flame
  - Pre-mixed Flame
- We will not address explosions
  - The strategy for explosions is prevention because t→0

Diffusion Flame

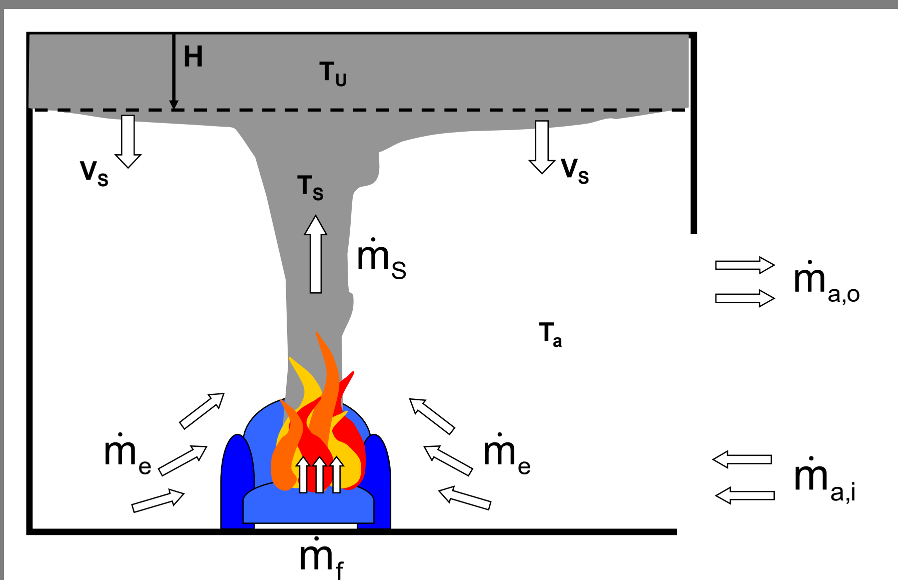


Motion Only Through Spread




Timeline
Flashover – too late for people
tS
Ignition
tF
Percent O2
PPM CO
Time (min)
Flaming ignition
Smoke alarm
Obscuration
Sprinkler activates
1200° flashover
Flashover—door
Temperature °F (°C)
PPM HCN
2-zone
1-zone
PPM CO
Percent O2
Temperature °F (°C)
PPM HCN

The Pre-Flashover Compartment Fire

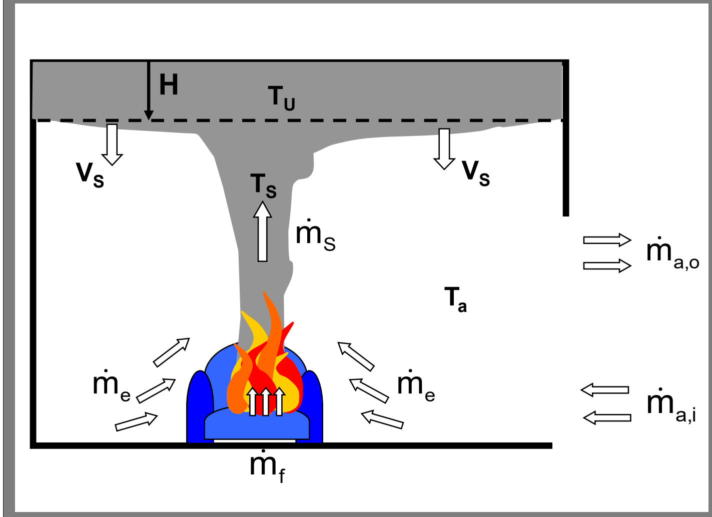


Approach

- Zone Model – Divides the room into two well defined zones
  - Upper Layer – Hot combustion products
  - Lower Layer – Cold air

- Implies strong simplifications but help understand the dynamics of the problem

The Evolution of the Smoke Layer



- **Upper Layer** - The parameters that need to be evaluated are:
  - The temperature of the upper layer: T_u
  - The velocity at which the Upper Layer descends: $V_S = \frac{dH}{dt}$

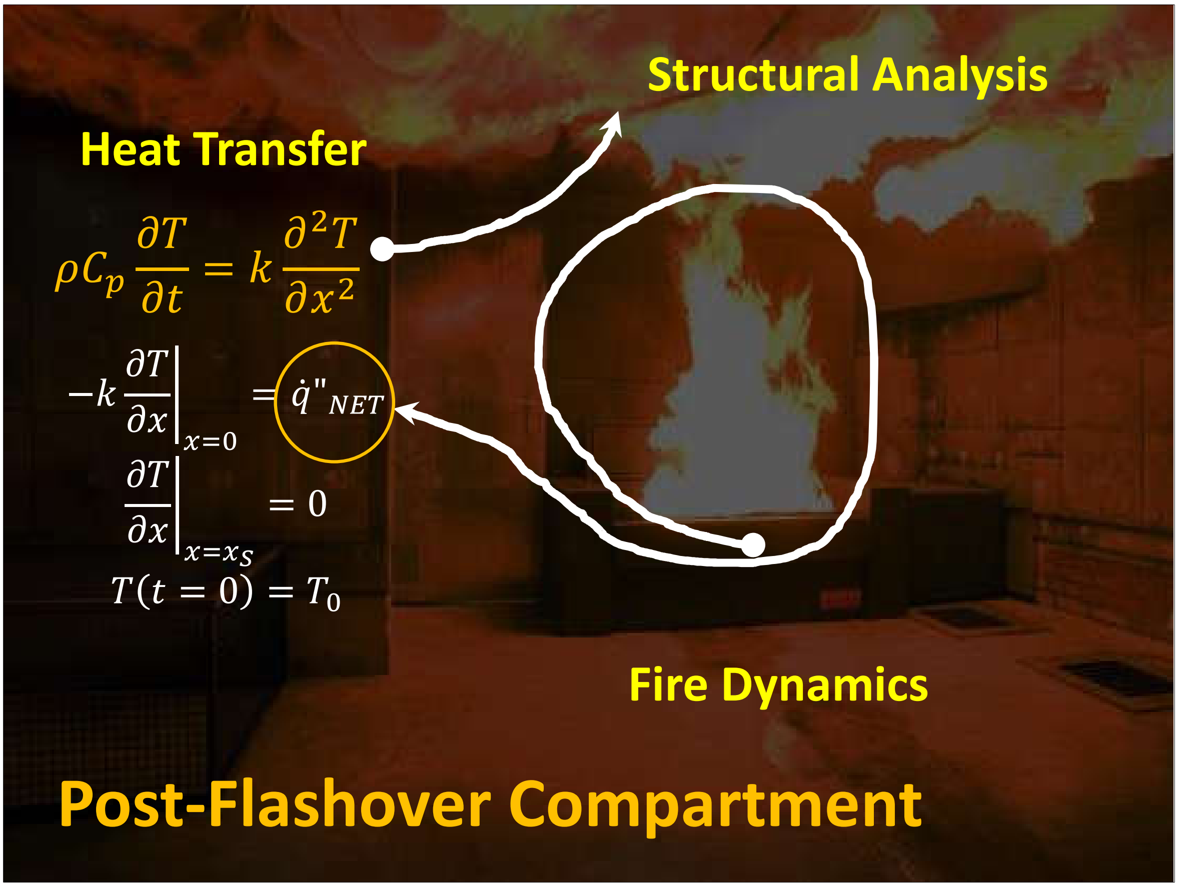
Conservation Equations

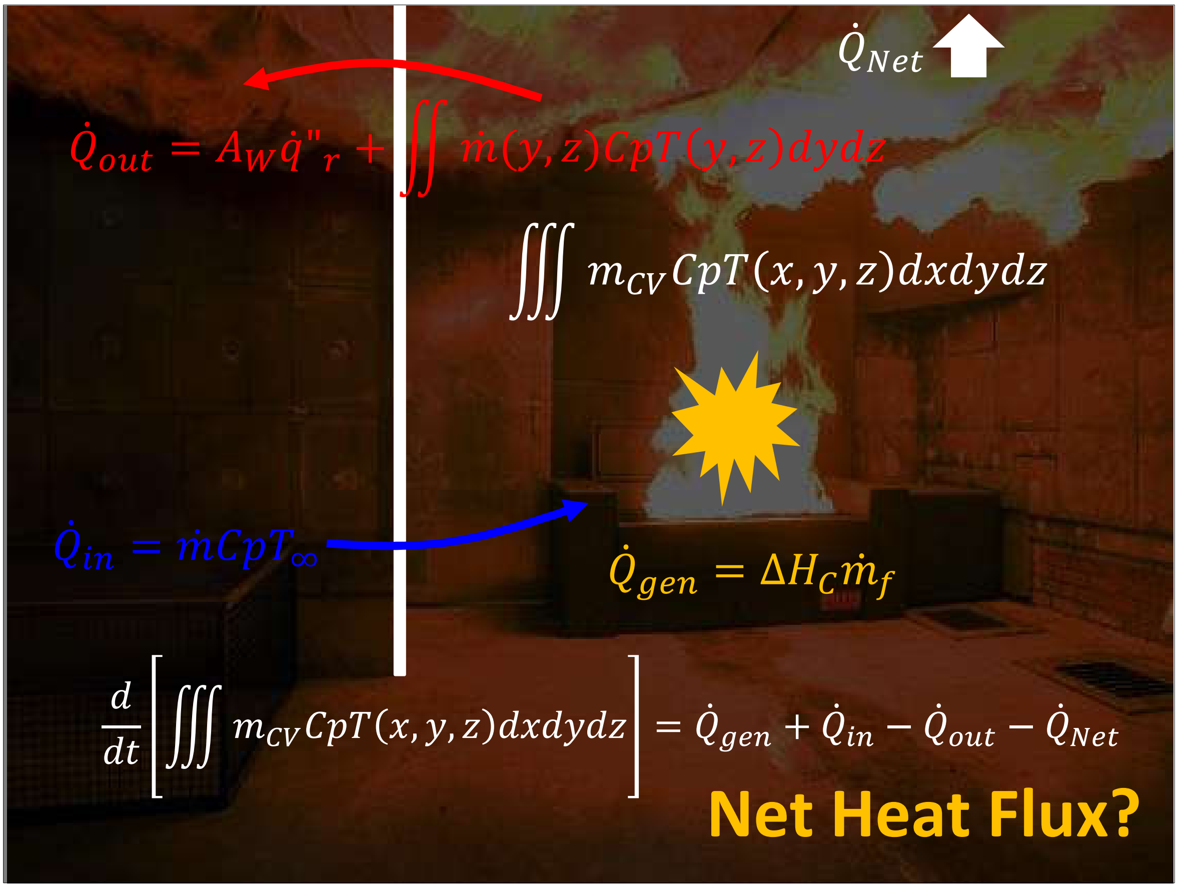
- These parameters can be obtained from, the ideal gas law and conservation of mass and energy in the Upper Layer

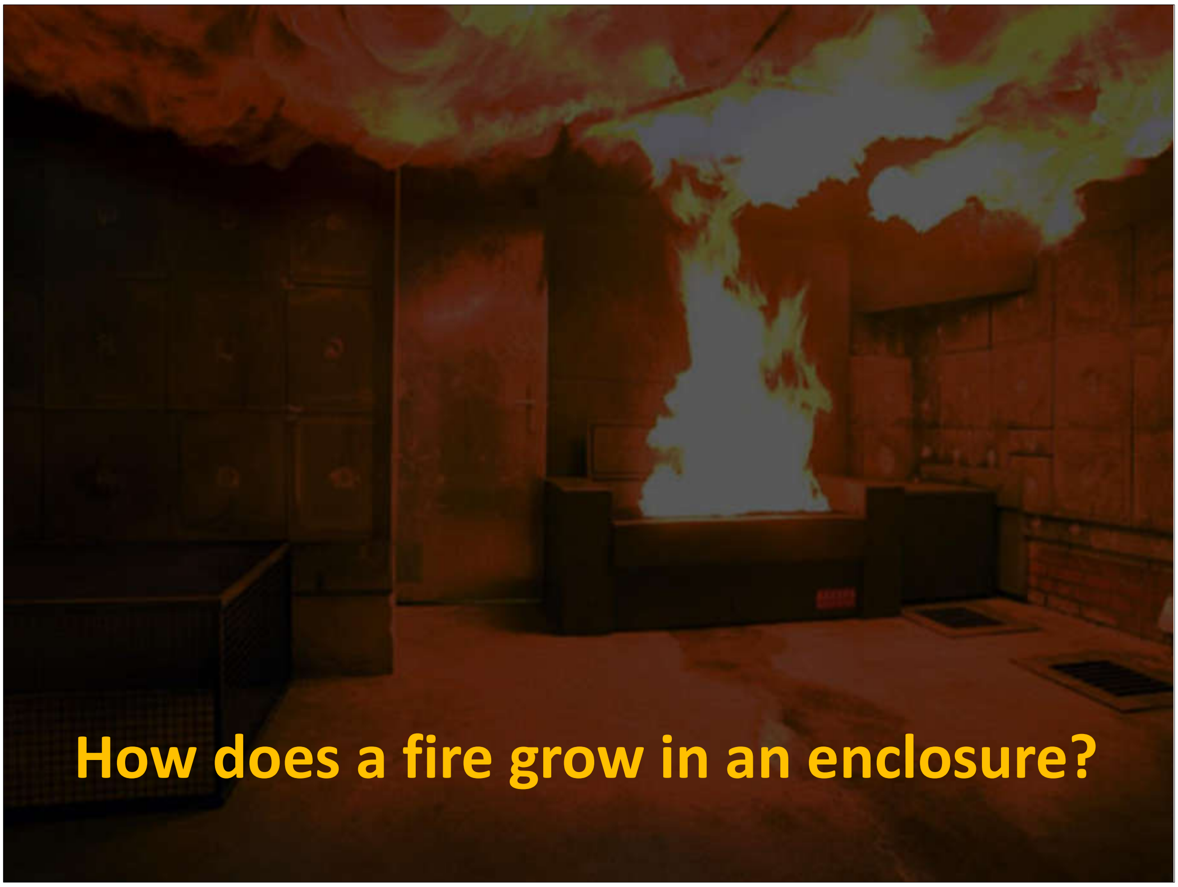
$$P = \rho R T_u$$

$$\frac{\partial}{\partial t}\left(A\rho(T_u)H(t)\right) = \dot{m}_S$$

$$\frac{\partial}{\partial t}\left(A\rho(T_u)H(t)C_p T_u\right) = \dot{m}_S C_p T_S$$




$\dot{Q}_{Net}$
$\dot{Q}_{out} = A_W \dot{q}"_r + \iint \dot{m}(y,z) CpT(y,z)dydz$
$\iiint m_{CV} CpT(x,y,z)dxdydz$
$\dot{Q}_{in} = \dot{m}CpT_\infty$
$\dot{Q}_{gen} = \Delta H_C \dot{m}_f$
$\frac{d}{dt}\left[\iiint m_{CV} CpT(x,y,z)dxdydz\right] = \dot{Q}_{gen} + \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{Net}$
Net Heat Flux?

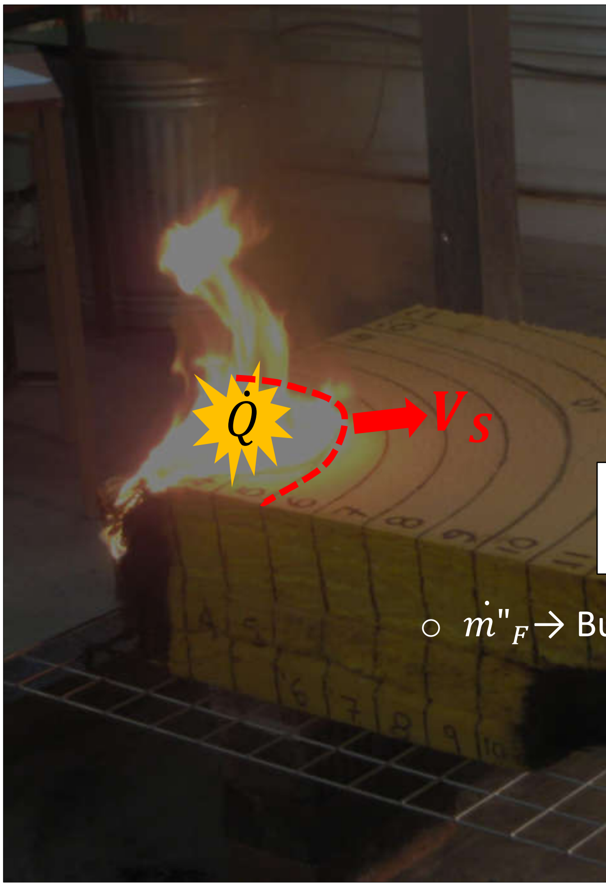

How does a fire grow in an enclosure?

Combustion

- Heat of Combustion (ΔH_C): Energy released per kg of fuel burnt – Complete Combustion

Fuel	ΔH_C [MJ/kg$_{FUEL}$]
Hydrogen	141.80
Propane	50.35
Gasoline	47.30
Paraffin	46.00
Kerosene	46.20
Coal (Lignite)	15.00
Wood	15.00
Peat (dry)	15.00
PVC (Poly-Vinyl-Chloride)	17.50
PE (Poly-Ethylene)	44.60

Burning Rate



$$\dot{Q} = \Delta H_C \dot{m}_F$$

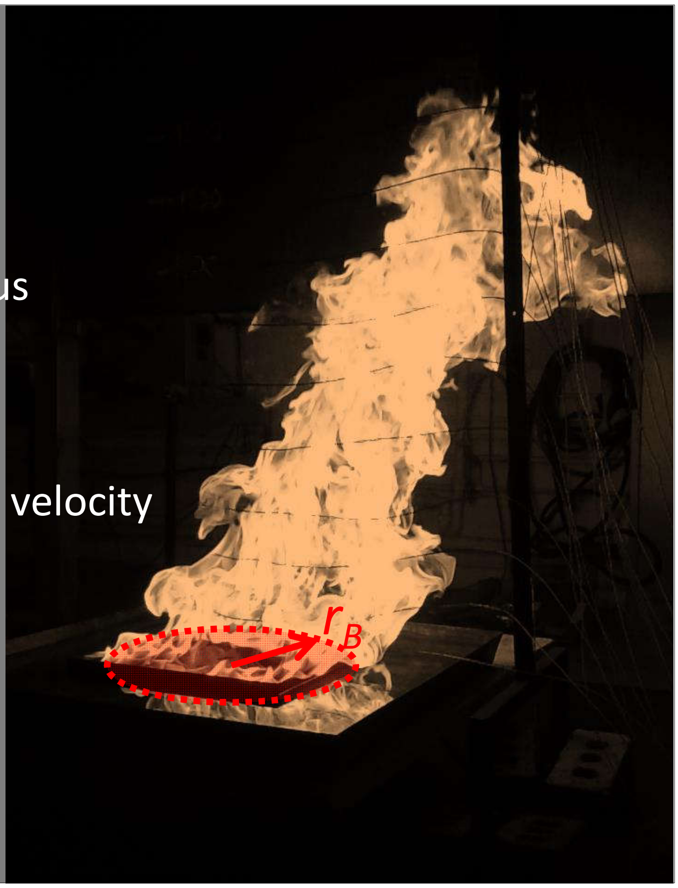
- $\dot{m}_F \rightarrow$ Burning Rate [kg/s]

$$\dot{Q} = \Delta H_C A_B \dot{m}''_F$$

- $\dot{m}''_F \rightarrow$ Burning Rate per unit area [kg/m^{2}s]
- $A_B \rightarrow$ Burning area [m^2]

Design Fire

- $A_B = \pi r_B^2$
  - r_B →burning radius
- $r_B = V_S t$
  - V_S→Flame spread velocity
  - t→time
- $\boxed{A_B = (\pi V_S^2)t^2}$



$$\boxed{\dot{Q} = \Delta H_C A_B \dot{m}''_F}$$

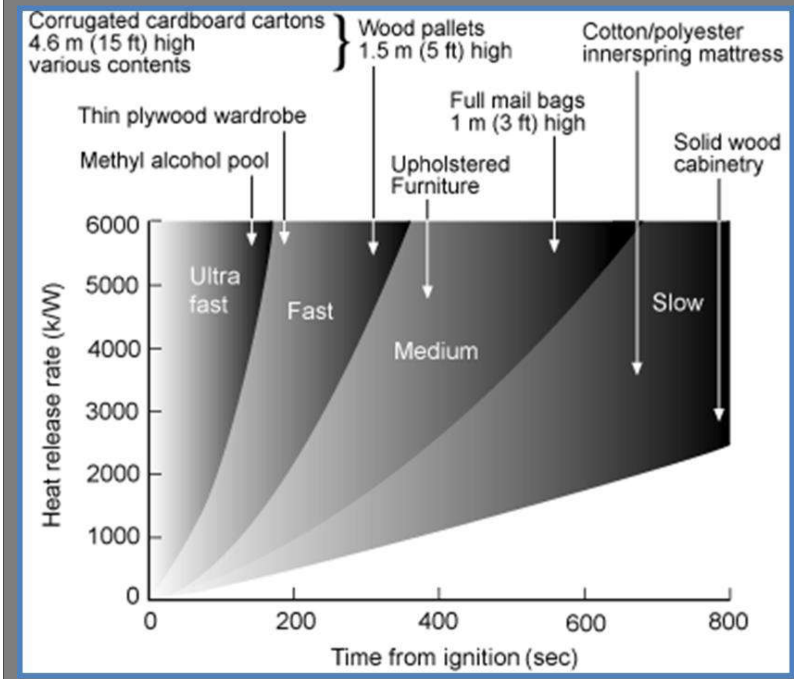
$$\boxed{A_B = (\pi V_S^2)t^2}$$

$$\boxed{\dot{Q} = \left[\pi \Delta H_C V_S^2 \dot{m}''_F\right] t^2}$$

Material Properties

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

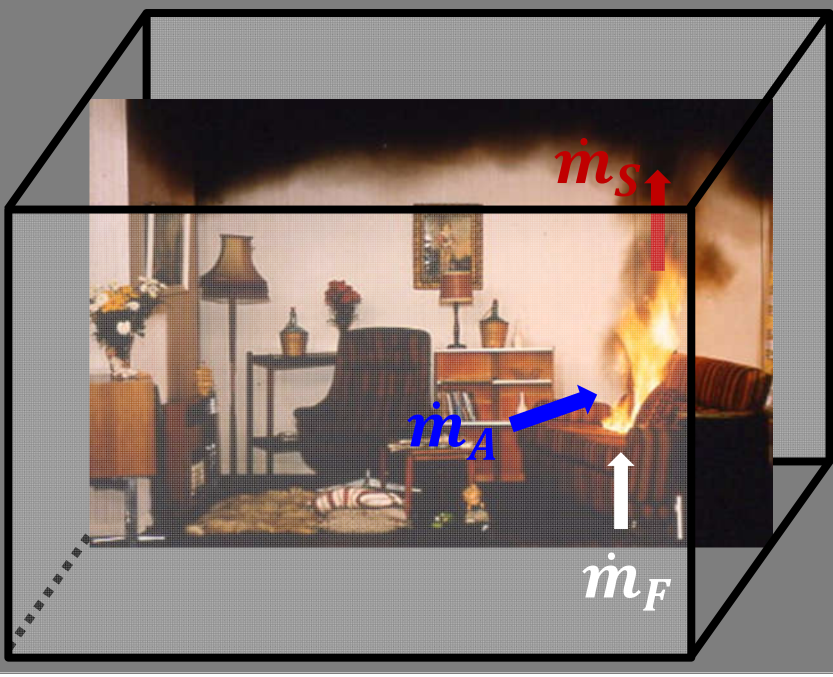
Normalized Design Fires



Class	α
Ultra Fast	0.1876
Fast	0.0469
Medium	0.0117
Slow	0.0029

Conservation of Mass

$$\dot{m}_S = \dot{m}_F + \dot{m}_A$$



$$\frac{\dot{m}_F}{\dot{m}_A} = \frac{10\ cm^3}{100x50x5\ cm^3} = 4\ x\ 10^{-4}$$

$$\boxed{\dot{m}_S = \overset{\approx 0}{\dot{m}_F} + \dot{m}_A}$$

$$\boxed{\dot{m}_S \approx \dot{m}_A}$$

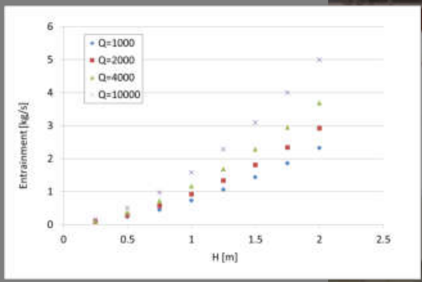
Conservation of Energy

$$\dot{Q} = \dot{m}_A C_p (T_S - T_A)$$

- C_p → Specific Heat (J/kgK)
- T_S → Smoke temperature
- T_A → Ambient temperature

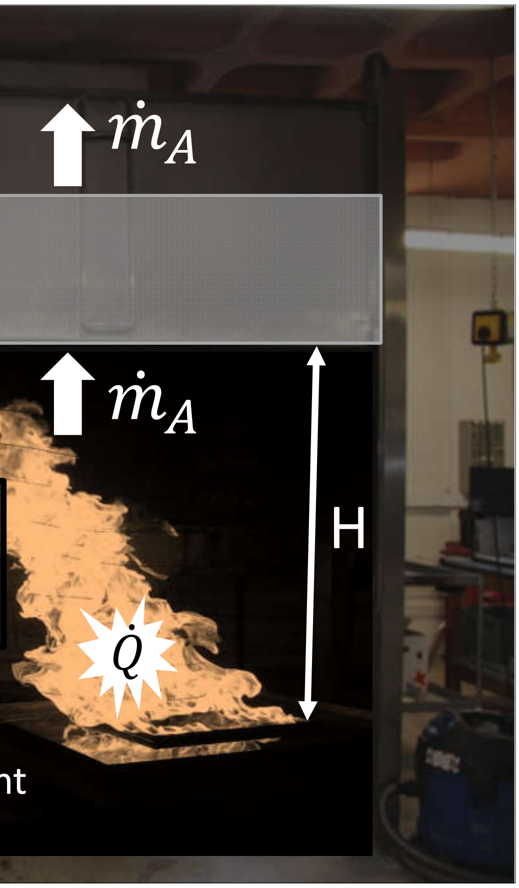
$$\boxed{T_S = T_A + \frac{\dot{Q}}{\dot{m}_A C_p}}$$

Entrainment



$$\dot{m}_A = E\left(\frac{g\rho_A^2}{C_p T_A}\right)^{1/3}\dot{Q}^{1/3}H^{5/3}$$

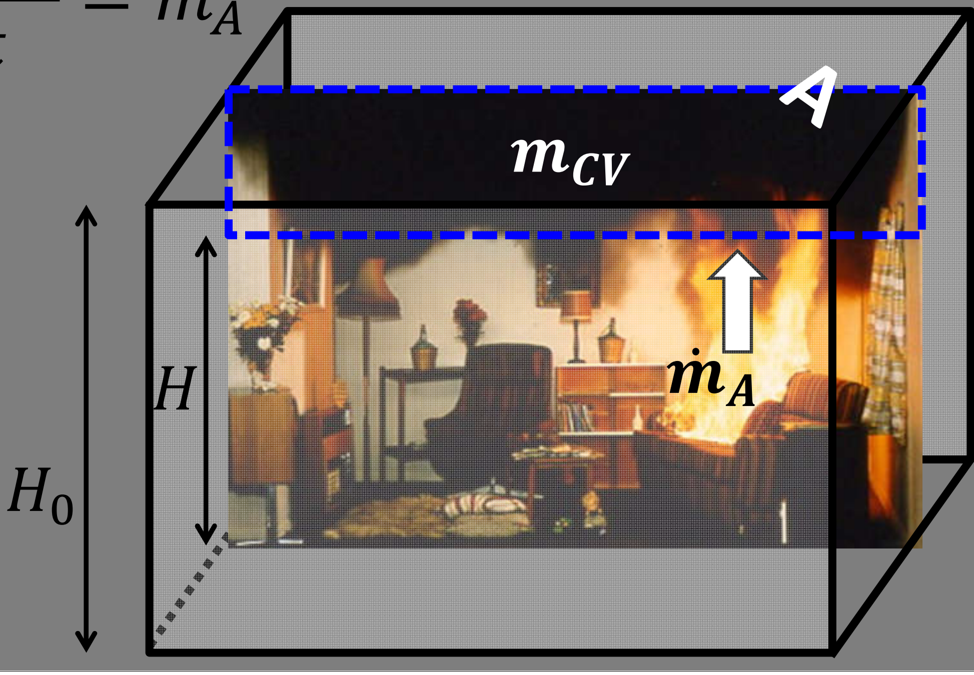
- ρ_A→Ambient density
- g→gravity (9.81 m/s^2)
- $E = 0.2$→Entrainment constant
- H→ Entrainment height



Conservation of Mass: Hot Layer

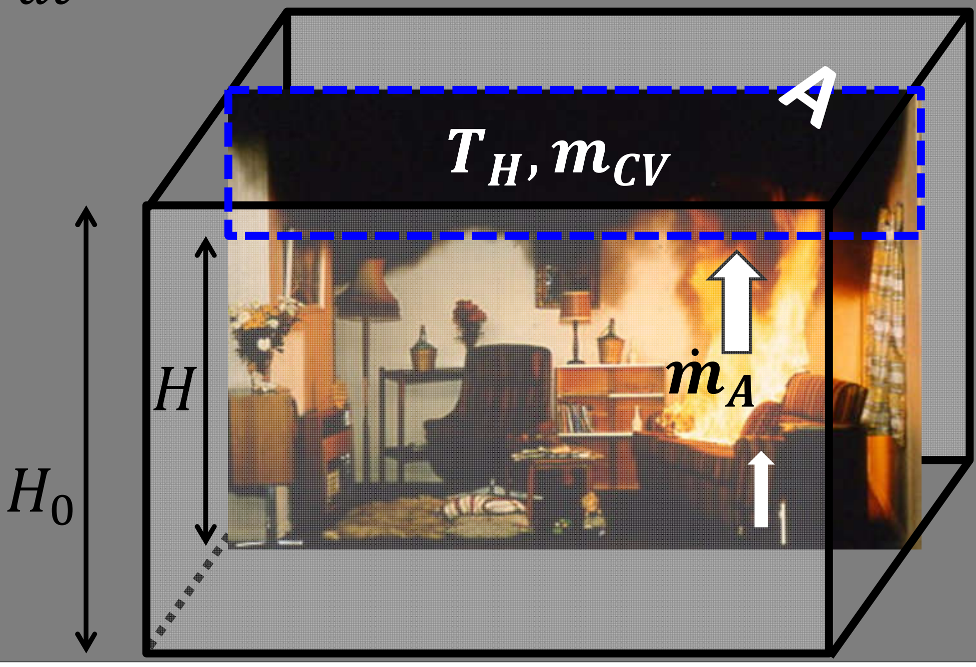
$$\frac{dm_{CV}}{dt} = \dot{m}_A$$

$$m_{CV} = \rho_H A(H_0 - H)$$



Conservation of Energy

$$\frac{d(m_{CV}C_pT_H)}{dt} = \dot{m}_A C_p T_S$$

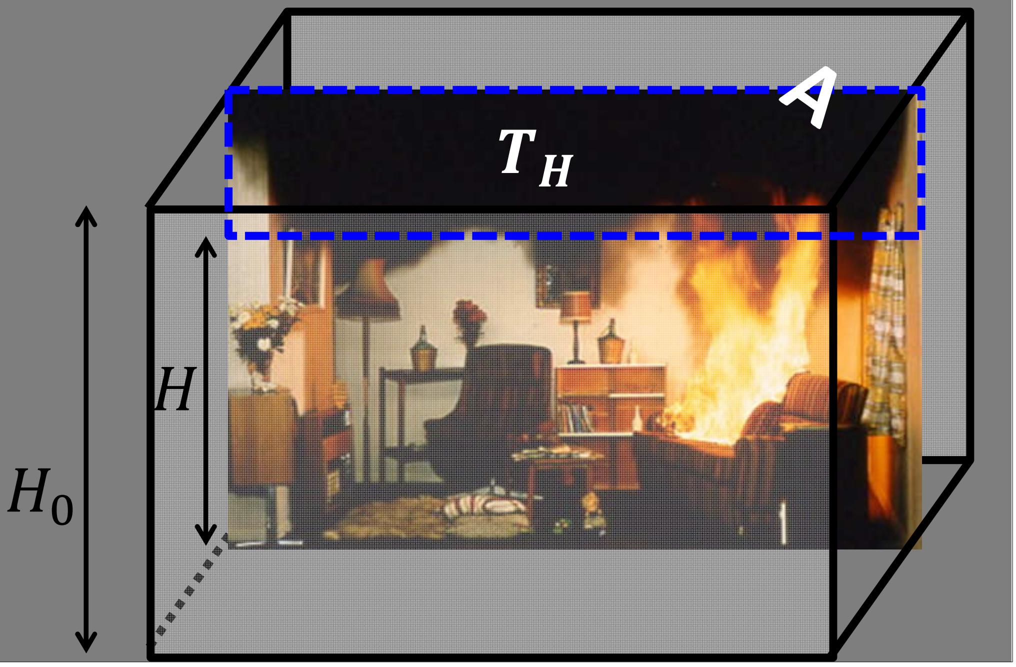


Can be solved using an Excel Spreadsheet

- $P = \rho R^* T$ *or* $\rho_2 = \frac{T_1}{T_2}\rho_1$
- $\dot{Q} = \alpha t^2$
- $T_S = T_A + \frac{\dot{Q}}{\dot{m}_A C_p}$
- $\dot{m}_A = E\left(\frac{g\rho_A^2}{C_p T_A}\right)^{1/3} \dot{Q}^{1/3} H^{5/3}$
- $\frac{dm_{CV}}{dt} = \dot{m}_A$ $m_{CV} = \rho_H A(H_0 - H) \rightarrow \Delta H_t = \frac{m_{CV,t+1}}{A\rho_2}$
- $\frac{d(m_{CV}C_pT_H)}{dt} = \dot{m}_A C_p T_S \rightarrow T_{H,t+1} = \frac{m_{CV,t}T_{H,t} + \dot{m}_A \Delta t T_S}{m_{CV,t+1}}$

Example: Slow Growing Fire

$$H_0 = 2.75\ m, X_0 = 4.75\ m, Y_0 = 3.5\ m$$

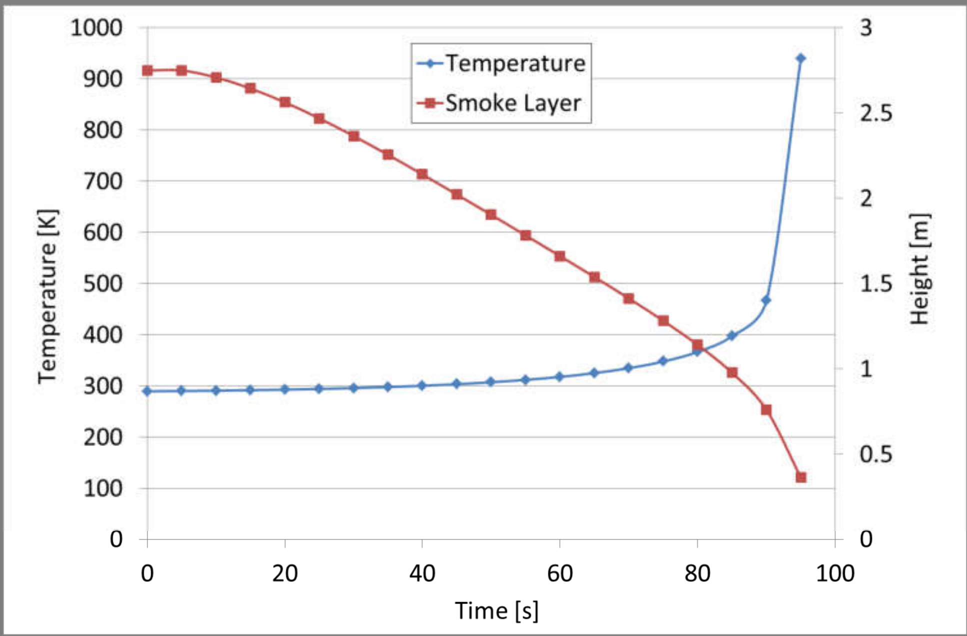


Implementation

α(slow)	0.0029	W/s2	H0	2.75	m	$E\left(\frac{g\rho_A^2}{C_pT_A}\right)^{1/3}$	0.073042309
E	0.2		X0	4.75	m		
g	9.81	m/s2	Y0	3.5	m		
ρA	1.2	kg/m3	A	16.625			
Cp	1	J/kg/K					
TA	290	K					
Δt	5	s					

$t_{t+1} = t_t + \Delta t$	$\dot{Q} = \alpha t^2$	$H_{t+1} = H_0 - \Delta H_t$	$\dot{m}_A = E\left(\frac{g\rho_A^2}{C_pT_A}\right)^{1/3}\dot{Q}^{1/3}H^{5/3}$	$T_S = T_A + \frac{\dot{Q}}{\dot{m}_A C_p}$	$m_{CV,t+1} = m_{CV,t} + \dot{m}_A \Delta t$	$T_{H,t+1} = \frac{m_{CV,t}T_{H,t} + \dot{m}_A \Delta t T_S}{m_{CV,t+1}}$	$\rho_2 = \frac{T_1}{T_2}\rho_1$	$\Delta H_t = \frac{m_{CV,t+1}}{A\rho_2}$
0	0	2.75	0	290	0	290	1.2	0
5	0.0725	2.75	0.164402464	290.440991	0.822012318	290.440991	1.19817798	0.041266282
10	0.29	2.708733718	0.254478455	291.1395857	2.094404591	290.8654011	1.195302931	0.105395227
15	0.6525	2.644604773	0.320407468	292.0364694	3.696441933	291.3729419	1.191631993	0.18658644
20	1.16	2.56341356	0.368489362	293.1479878	5.538888744	291.9633902	1.187113726	0.280652336
25	1.8125	2.469347664	0.40176389	294.5113562	7.547708193	292.6415303	1.181618273	0.38421671
30	2.61	2.36578329	0.422421744	296.1786592	9.659816913	293.4149198	1.174966491	0.494517608
35	3.5525	2.255482392	0.432332874	298.217048	11.82148128	294.2930322	1.166935299	0.609345303
40	4.64	2.140654697	0.433169816	300.7117344	13.98733036	295.2869274	1.157254474	0.727016571
45	5.8725	2.022983429	0.426418509	303.7716818	16.11942291	296.4091935	1.145597239	0.846361456
50	7.25	1.903638544	0.413359555	307.5392099	18.18622068	297.6740793	1.131563029	0.966723004
55	8.7725	1.783276996	0.395045362	312.2063106	20.16144749	299.0978091	1.114647553	1.087983949
60	10.44	1.662016051	0.372277411	318.0436032	22.02283455	300.6991223	1.094189591	1.21065105
65	12.2525	1.53934895	0.345576763	325.4552195	23.75071836	302.5001482	1.069271528	1.336063479
70	14.21	1.413936521	0.315129487	335.0925749	25.3263658	304.5278443	1.038518983	1.466887413
75	16.3125	1.283112587	0.280665661	348.1207547	26.7296941	306.8165037	0.999653124	1.60835905
80	18.56	1.14164095	0.241166169	366.9593849	27.93552494	309.4125581	0.948333833	1.771878498
85	20.9525	0.978121502	0.194077172	397.9596314	28.90591081	312.3851275	0.874460555	1.988313129
90	23.49	0.761686871	0.132891219	466.7611149	29.5703669	315.8540079	0.745563392	2.385670629
95	26.1725	0.364329371	0.04030385	939.3796419	29.77188615	320.0745138	0.370457251	4.833999439

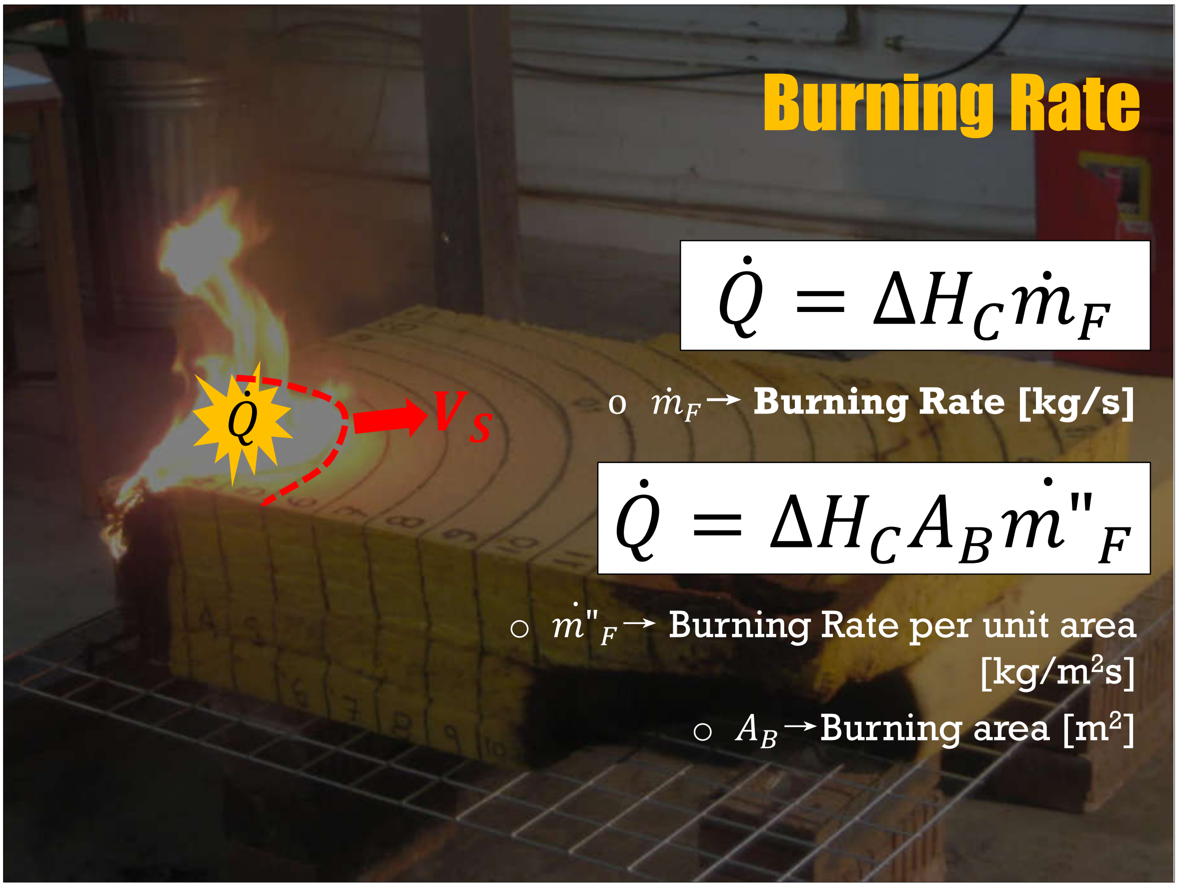
Compartment Evolution



Summary

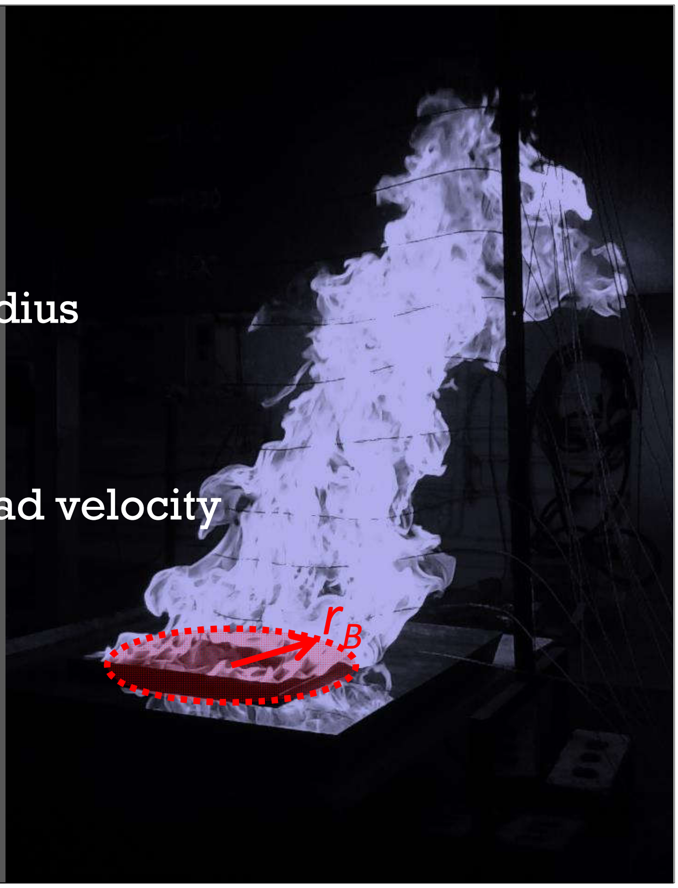
- Zone Model – Divides the room into two well defined zones
  - Upper Layer – Hot combustion products
  - Lower Layer – Cold air
- Provides the evolution of the height and temperature of the hot layer
  - It depends on an entrainment correlation
  - Results form a simple mass and energy balance between two control volumes
  - Breaks down when the smoke layer gets close to the floor, when the two control volumes become one and the entrainment correlation is no longer valid


Material Flammability
José L. Torero
University College London
United Kingdom
Lecture-4


Burning Rate
$\dot{Q}$
V_s
$\dot{Q} = \Delta H_C \dot{m}_F$
o $\dot{m}_F$ → **Burning Rate [kg/s]**
$\dot{Q} = \Delta H_C A_B \dot{m}''_F$
○ $\dot{m}''_F$ → Burning Rate per unit area [kg/m^{2}s]
○ A_B → Burning area [m^2]

Design Fire

- $A_B = \pi r_B^2$
  - $r_B \rightarrow$ burning radius
- $r_B = V_S t$
  - $V_S \rightarrow$ Flame spread velocity
  - $t \rightarrow$ time
- $\boxed{A_B = (\pi V_S^2)t^2}$



$$\boxed{\dot{Q} = \Delta H_C A_B \dot{m}''_F}$$

$$\boxed{A_B = (\pi V_S^2)t^2}$$

$$\boxed{\dot{Q} = \left[\pi \Delta H_C V_S^2 \dot{m}''_F\right] t^2}$$

Material Properties

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

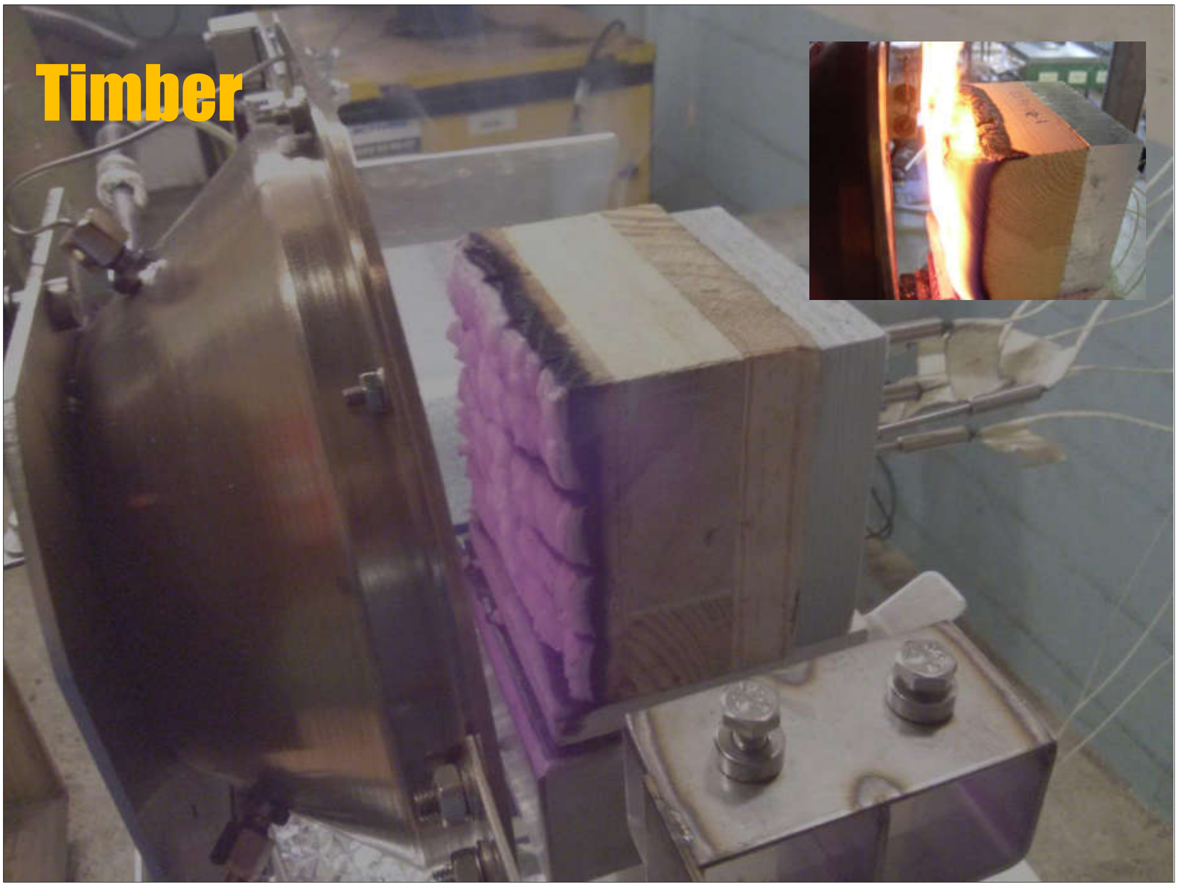
Need

$$\dot{Q} = \left[\pi \Delta H_C V_S^2 \dot{m}''_F\right] t^2$$

- Material properties to be introduced in the "Design Fire" Equation
- Small scale tests used to gather the information about material – we can not afford burning every building!
- Information is extrapolated to predict behaviour at all stages of a real fire ($\dot{Q} = \alpha t^2$)

Library

- Audacious architectural design
- Use of "formed polyurethane" to cover all surfaces leading to the atrium
- Test reports indicated that the material passed local standards


Timber

Timber Building Fire

Combustion

- **Heat of Combustion (ΔH_C): Energy released per kg of fuel burnt – Complete Combustion**

Fuel	ΔH_C [MJ/kg$_{FUEL}$]
Hydrogen	141.80
Propane	50.35
Gasoline	47.30
Paraffin	46.00
Kerosene	46.20
Coal (Lignite)	15.00
Wood	15.00
Peat (dry)	15.00
PVC (Poly-Vinyl-Chloride)	17.50
PE (Poly-Ethylene)	44.60

$$\dot{Q} = \Delta H_C A_B \dot{m}''_F$$

$$A_B = (\pi V_S^2)t^2$$

$$\dot{Q} = [\pi \Delta H_C V_S^2 \dot{m}''_F]t^2$$

Material Properties

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

Flame Spread Velocity (V_S)

$$\dot{Q} = [\pi \Delta H_C V_S^2 \dot{m}''_F]t^2$$

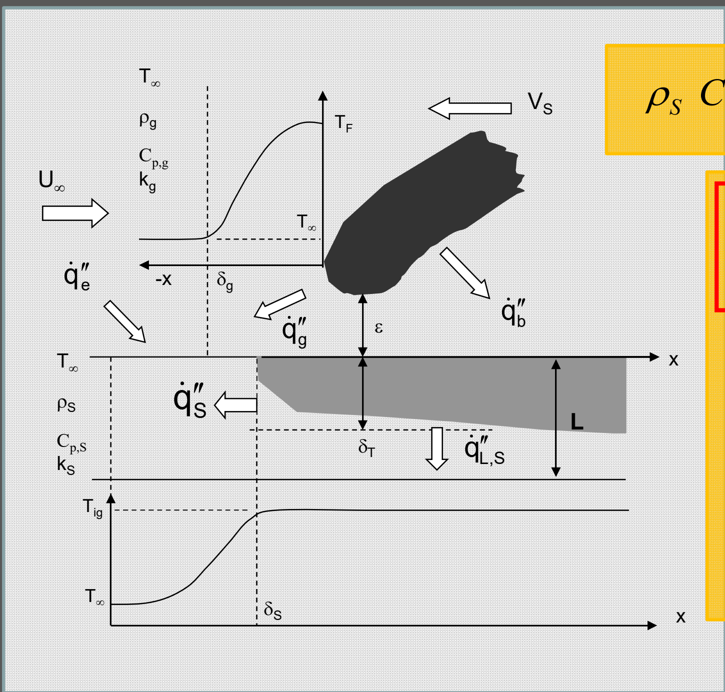
- **What do we need to determine the flame spread velocity *(V_S)*?**

Burning Rate ($\dot{m}''_F$)

$$\dot{Q} = \left[\pi \Delta H_C V_S^2 \dot{m}''_F\right] t^2$$

- What do we need to determine the Burning Rate ($\dot{m}''_F$)?

Flame Spread



$$\rho_S\ C_{P,S} V_S (T_{ig} - T_\infty)\ \delta_T = \dot{q}''_g\ \delta_S$$

$$\boxed{V_S = \frac{\dot{q}''_g\ \delta_S}{\rho_S\ C_{P,S}(T_{ig} - T_\infty)\ \delta_T}}$$

Thermally Thick

$$\delta_T = \frac{k_S (T_{ig} - T_\infty)}{\dot{q}''_g}$$

Thermally Thin

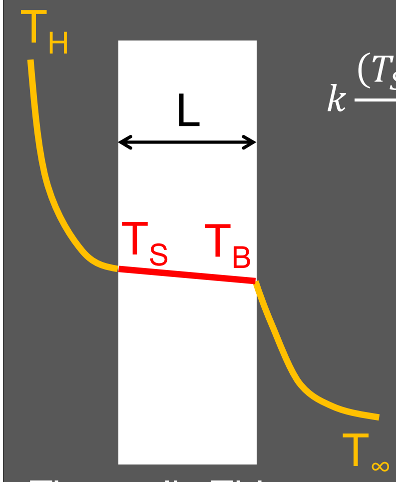
$$\delta_T = L$$

Thermally Thick vs. Thermally Thin

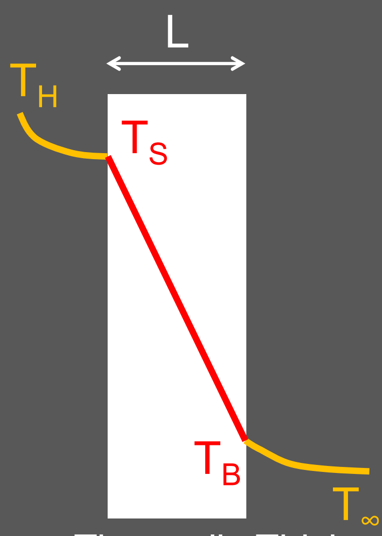
$$-k\frac{\partial T}{\partial x} = h_T(T_H - T_S)$$

$$k\frac{(T_S - T_B)}{L} = h_T(T_H - T_S)$$

$$\frac{Lh_T}{k} = \frac{(T_S - T_B)}{(T_H - T_S)}$$



Thermally Thin



Thermally Thick

<u>Biot Number</u>

$$Bi = \frac{Lh_T}{k}$$

$Bi<<1$ (Thermally Thin)

$Bi\geq 1$ (Thermally Thick)

Thermally Thick

- Most materials behave as thermally thick
- $V_S = \dfrac{\dot{q}''_g \delta_S}{\rho_S c_{P,S}(T_{ig} - T_\infty)\delta_T}$ $\qquad \delta_T = \dfrac{k_S(T_{ig} - T_\infty)}{\dot{q}''_g}$

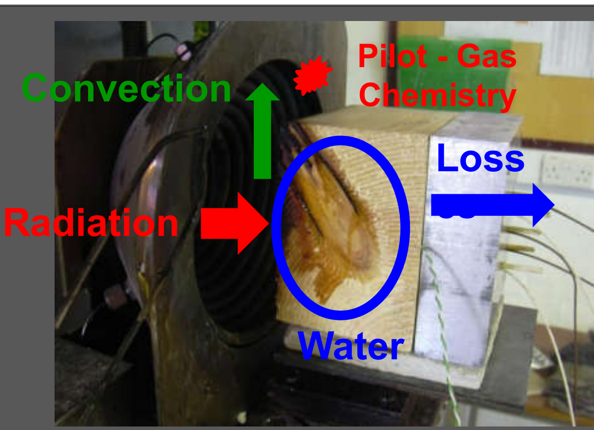
$$V_S = \frac{\dot{q}''^2_g \delta_S}{k_S \rho_S C_{P,S}(T_{ig} - T_\infty)^2}$$

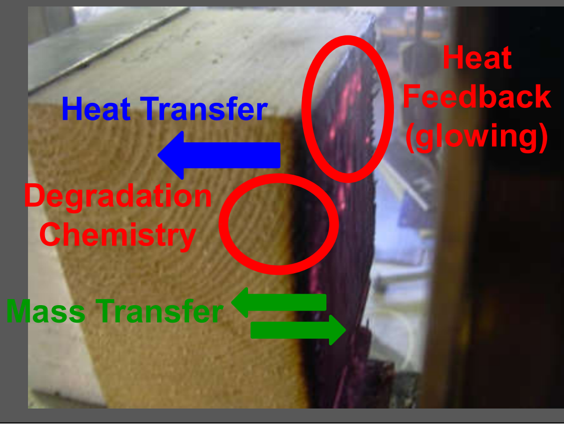
$$\phi = \dot{q}''^2_g \delta_S$$

Material Properties

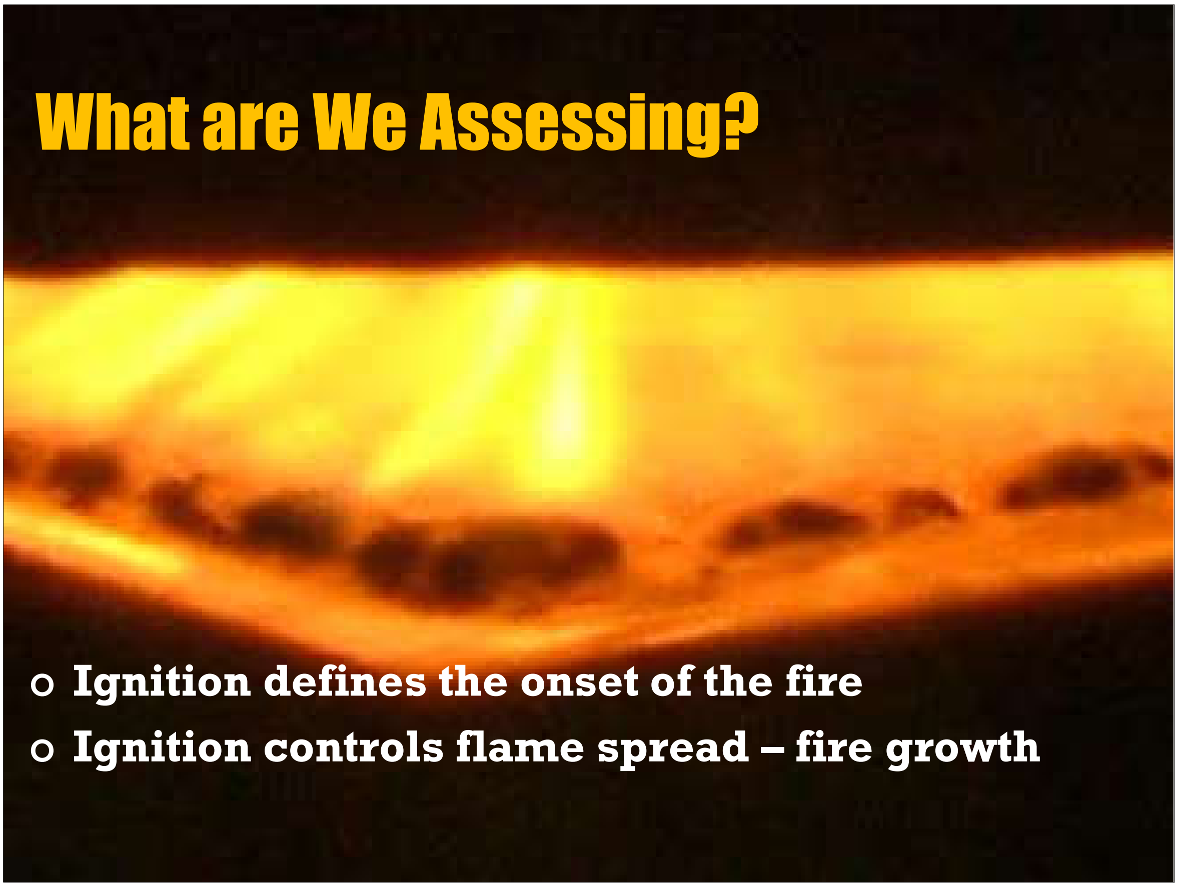
Ignition

- **Simplest**
  - No-combustion
  - No heat feedback from the flame
- **Complexity**
  - Implies models of the gas and solid phase





What are We Assessing?

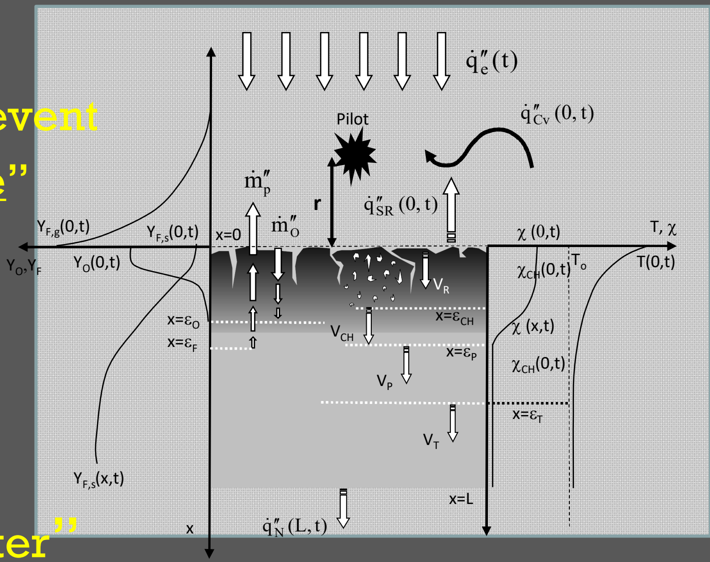


- **Ignition defines the onset of the fire**
- **Ignition controls flame spread – fire growth**

Processes

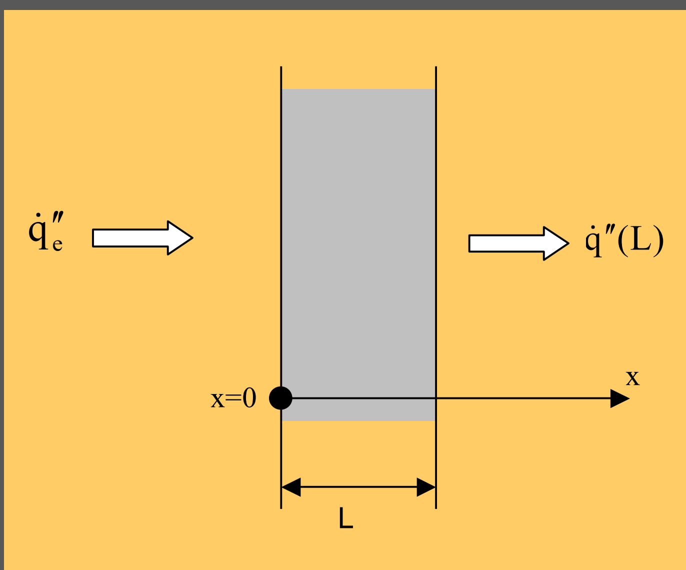
- $t_{ig} \rightarrow$ observable event

"Ignition delay time"



- "Integral Parameter"
  - Heat transfer equation through the material
  - Boundary conditions (front, back, side)
    - Radiative, convective, conductive
  - Material degradation
    - Chemistry & transport

Ignition



- **Simplest case**
  - 1-D
  - Constant heat flux

Ignition – The Solid Phase

$$\frac{\partial}{\partial x}\left(k_S \frac{\partial T}{\partial x}\right) = \frac{\partial(\rho_S C_S T)}{\partial t} + \sum \rho_S \Delta H_i A_i e^{-E_i/RT} + \dot{q}'''_R$$

Energy Conducted — Energy Accumulated — Energy Generation — In-depth Radiation

Boundary Conditions →

$t = 0$	$T = T_i$	
$x = 0$	$-k_S \left.\frac{\partial T}{\partial x}\right\|_{x=0^+}$	$= \alpha \dot{q}''_e - k_g \left.\frac{\partial T}{\partial x}\right\|_{x=0^-} - \dot{q}''_{S,R}$
$x = L$	$-k_S \left.\frac{\partial T}{\partial x}\right\|_{x=L^-}$	$= \dot{q}''(L)$

Fuel Generation

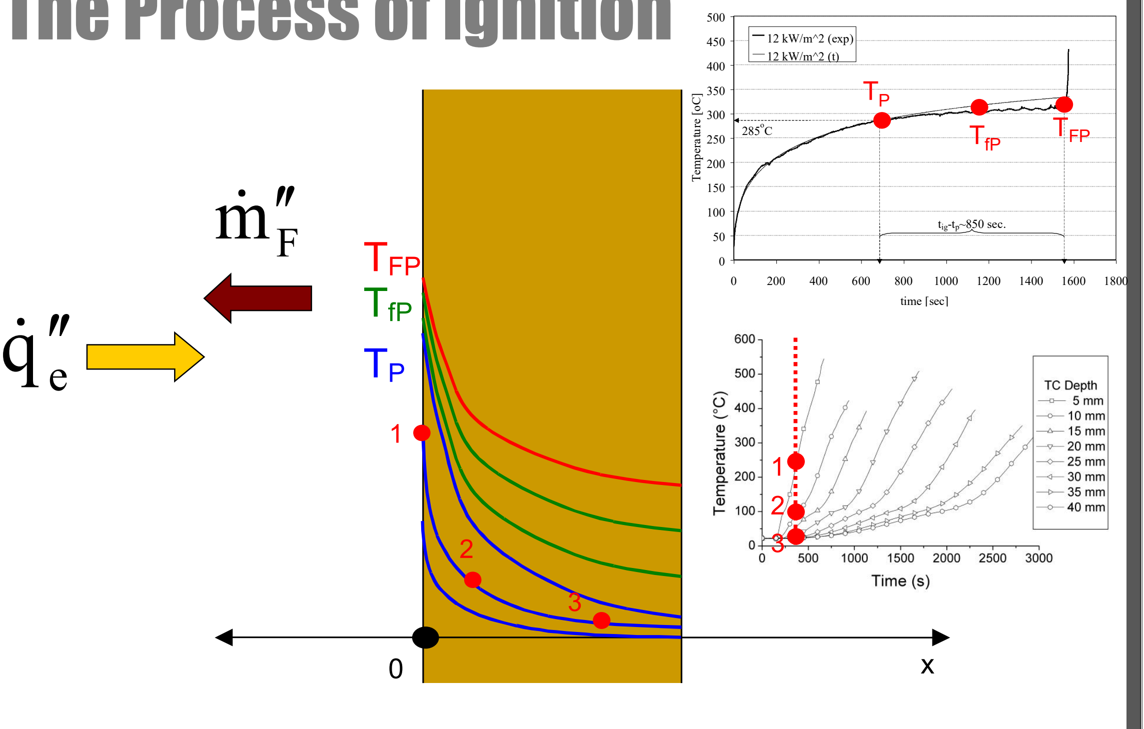
$$\dot{m}''_F = \int_0^L \chi(x) Y_F(x) \sum \rho_S A_i e^{-E_i/RT} dx$$

- **The Boundary condition for the gas phase**
  - $\chi(x)$ is function that defines the fuel permeability
  - $Y_F(x)$ is the mass fraction of "fuel"
  - L=thickness of the fuel

The Gas Phase

- **With the appropriate boundary conditions energy, species and momentum equations can be solved**
  - The combustion process is described by the appropriate reaction rate expressions
  - Ignition can be established by means of a critical concentration in the gas phase – Lean Flammability Limit-Flash Point
  - Flame establishes at a critical mass transfer number Minimum burning rate that sustains a flame -Fire Point

The Process of Ignition



Complete Solutions

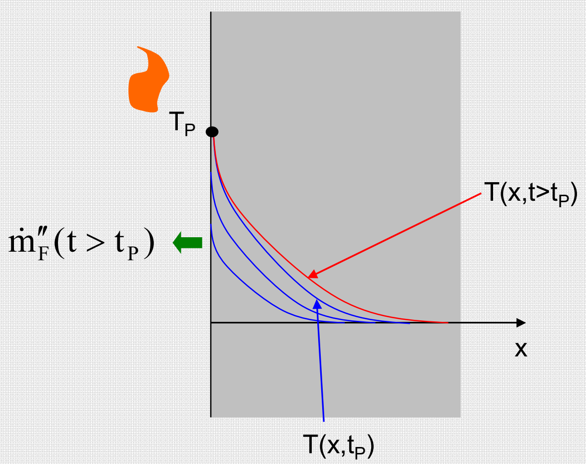
- **Numerical solutions to this problem abound!**
- **None of them reproduces ignition adequately**
  - Thermal properties vary with temperature
  - $\chi(x)$ is unknown
  - $Y_F(x)$ depends on surface oxidation thus is uncertain
  - Kinetic constants are unknown
  - Radiative properties are uncertain
- **A simplified solution is necessary**

Piloted Ignition

$$\boxed{t_{ig} = t_p + t_m + t_i}$$

$$t_{ig} = t_p > t_m > t_i$$

$$\boxed{t_{ig} \approx t_p}$$



$$\boxed{T_{ig} \approx T_p}$$

Simplifications

Inert until Ignition

Opaque

$$\frac{\partial}{\partial x}\left(k_S \frac{\partial T}{\partial x}\right) = \frac{\partial(\rho_S C_S T)}{\partial t} + \sum \rho_S \Delta H_i A_i e^{-E_i/RT} + \dot{q}''_R$$

Global properties: $k_S \frac{\partial^2 T}{\partial x^2} = \rho_S C_S \frac{\partial T}{\partial t}$

Energy Conducted — Energy Accumulated — Energy Generation — In-depth Radiation

Linearized

$x = 0 \rightarrow -k_S \frac{\partial T}{\partial x} = h_T(T_S - T_\infty)$

Boundary Conditions

$t = 0$	$T = T_i$	
$x = 0$	$-k_S \left.\frac{\partial T}{\partial x}\right\|_{x=0^+}$	$= \alpha \dot{q}''_e - k_g \left.\frac{\partial T}{\partial x}\right\|_{x=0^-} - \dot{q}''_{S,R}$
$x = L$	$-k_S \left.\frac{\partial T}{\partial x}\right\|_{x=L^-}$	$= \dot{q}''(L)$

Semi-Infinite

$x \rightarrow \infty, T = T_\infty$

Simplified Problem

- $k_S \frac{\partial^2 T}{\partial x^2} = \rho_S C_{P,S} \frac{\partial T}{\partial t}$

  - $t = 0 \rightarrow T = T_\infty$
  - $x = 0 \rightarrow -k_S \frac{\partial T}{\partial x} = \dot{q}''_e - h_T(T_S - T_\infty)$
  - $x \rightarrow \infty, T = T_\infty$

Material Properties

$$\boxed{t_{ig} = \frac{\pi}{4} k_S \rho_S C_{P,S} \left(\frac{T_{ig} - T_\infty}{\dot{q}''_e}\right)^2}$$

$$\dot{Q} = \Delta H_C A_B \dot{m}''_F$$

$$A_B = (\pi V_S^2) t^2$$

$$\dot{Q} = [\pi \Delta H_C V_S^2 \dot{m}''_F] t^2$$

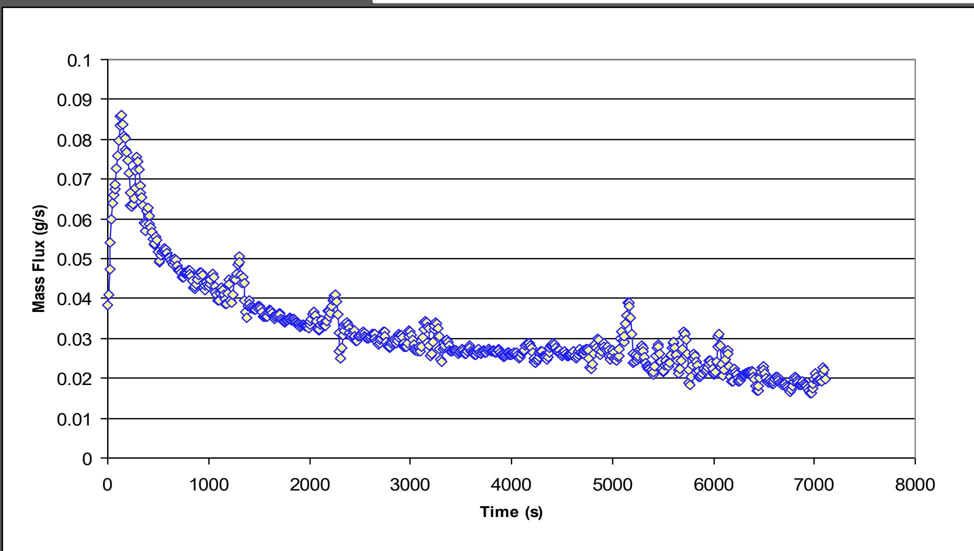
Material Properties

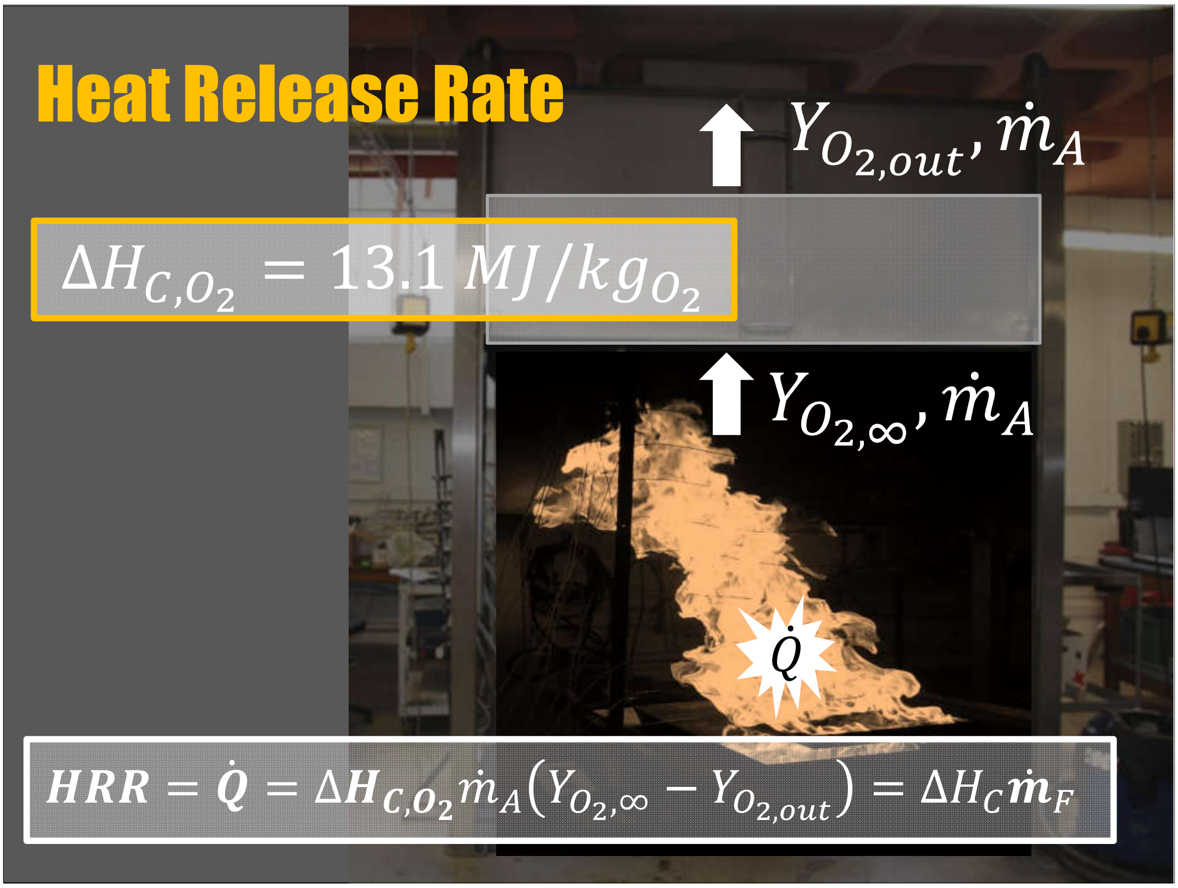
$$\dot{Q} = \alpha t^2$$

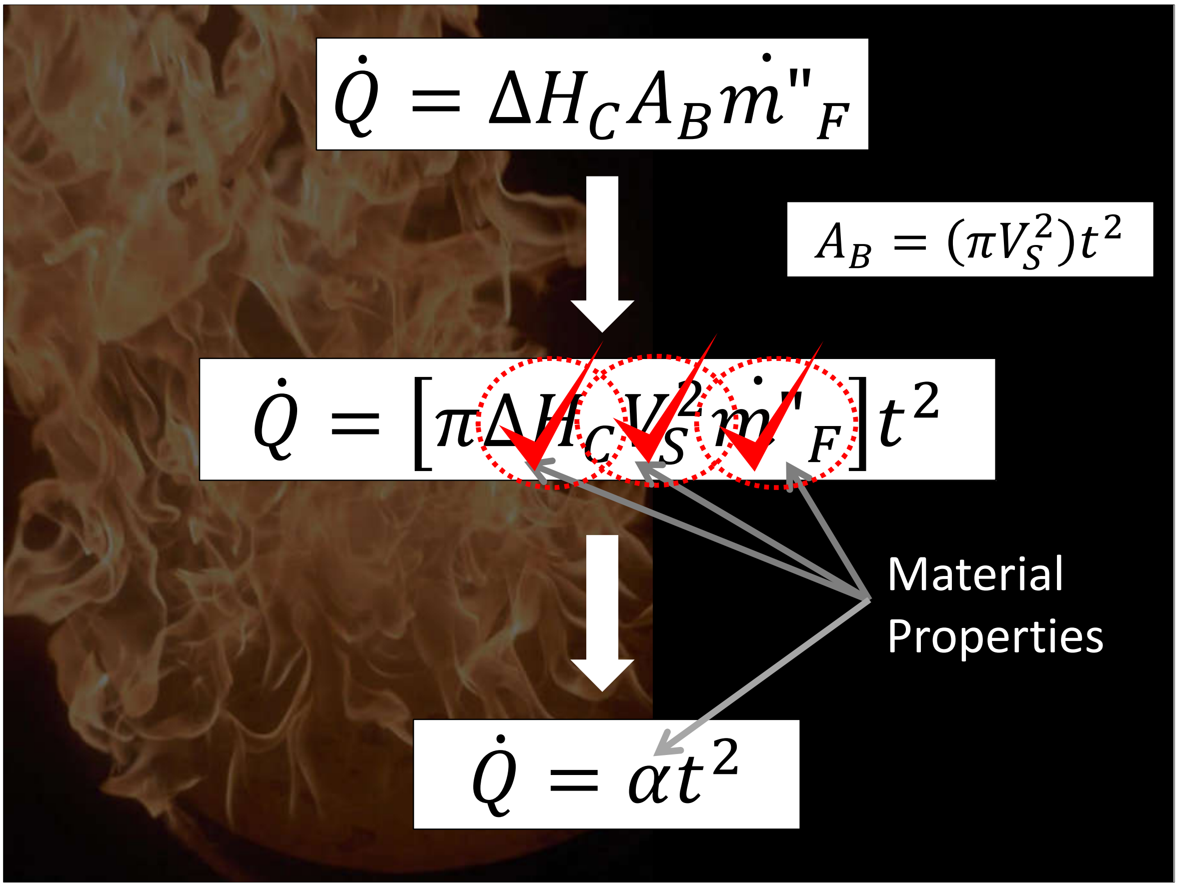
Burning Rate

- Temporal

$$\dot{m}_F'' = \sum_{i=0}^{i=n} \dot{m}_F''' \Delta c_i$$




Heat Release Rate
$Y_{O_{2,out}}, \dot{m}_A$
$\Delta H_{C,O_2} = 13.1\ MJ/kg_{O_2}$
$Y_{O_{2,\infty}}, \dot{m}_A$
$\dot{Q}$
$\boldsymbol{HRR = \dot{Q} = \Delta H_{C,O_2}} \dot{m}_A \left(Y_{O_{2,\infty}} - Y_{O_{2,out}}\right) = \Delta H_C \boldsymbol{\dot{m}_F}$


$\dot{Q} = \Delta H_C A_B \dot{m}''_F$
$A_B = (\pi V_S^2) t^2$
$\dot{Q} = [\pi \Delta H_C V_S^2 \dot{m}''_F] t^2$
Material Properties
$\dot{Q} = \alpha t^2$

Need

$$\dot{Q} = \left[\pi \Delta H_C V_S^2 \dot{m}''_F\right] t^2$$

- Material properties to be introduced in the "Design Fire" Equation
- Small scale tests used to gather the information about material – we can not afford burning every building!
- Information is extrapolated to predict behaviour at all stages of a real fire ($\dot{Q} = \alpha t^2$)

Material Flammability Properties

$$V_S = \frac{\dot{q}''^2_g \delta_S}{k_S \rho_S C_{P,S} (T_{ig} - T_\infty)^2} \qquad t_{ig} = \frac{\pi}{4} k_S \rho_S C_{P,S} \left(\frac{T_{ig} - T_\infty}{\dot{q}''_e}\right)^2$$

$$\left.\begin{matrix} \phi = \dot{q}''^2_g \delta_S \\ k_S \rho_S C_{P,S} \\ T_{ig} \end{matrix}\right\} \text{Material Properties}$$

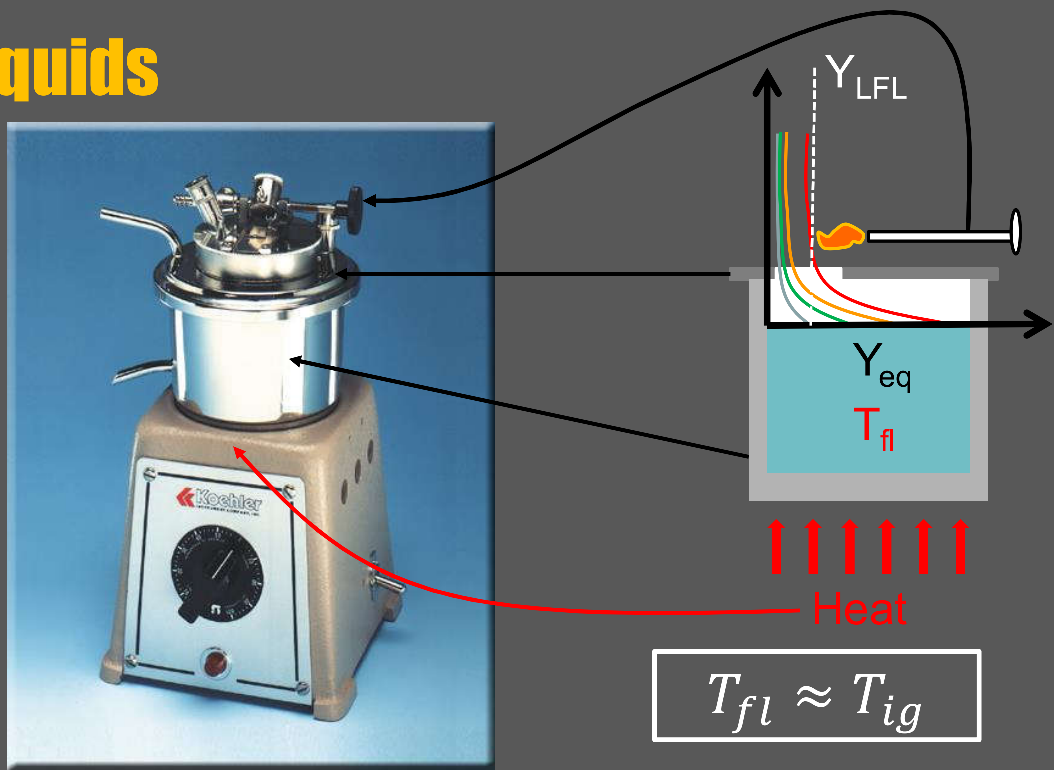
$$\boldsymbol{HRR} = \dot{\boldsymbol{Q}} = \Delta \boldsymbol{H}_{C,O_2} \dot{m}_A \left(Y_{O_{2,\infty}} - Y_{O_{2,out}}\right) = \Delta H_C \dot{\boldsymbol{m}}_F$$

$$\dot{Q} \quad \} \text{ Material Property}$$

Ignition

- **Liquids** – evaporation dominated by thermodynamic equilibrium
- **Solids** – pyrolysis dominated by thermal degradation
- In both cases simplified to T_{ig}

Liquids



$$T_{fl} \approx T_{ig}$$

Pensky-Martens Closed Cup Test – ISO 2719

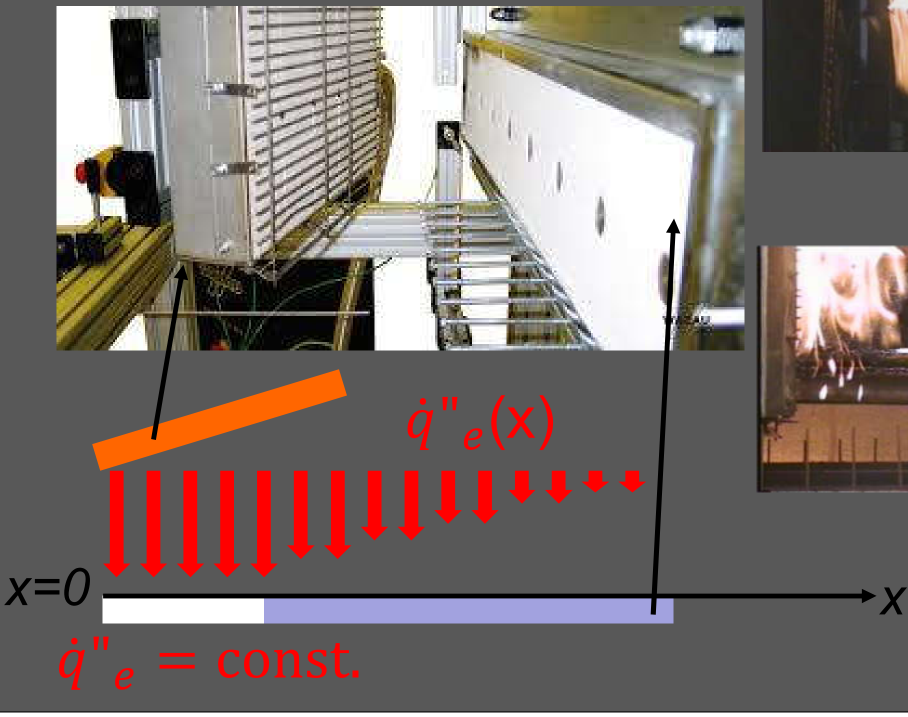
Classifications

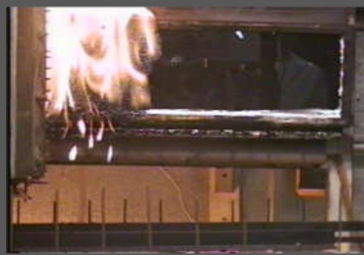
- Flammable Liquids: Any liquid having a flash point below 38°C and having a vapor pressure exceeding 2068.6 mm Hg (40 psia) at 38°C.
  - Class IA — flash point below 23°C and Boiling Point (B.P). at or below 38°C
  - Class IB — flash point below 23°C and B.P. above 38°C
  - Class IC — flash point at or above 23°C, but below 38°C
- Combustible Liquids: Any liquid having a flash point at or above 38°C
  - Class II — flash point at or above 38°C, but below 60°C
  - Class IIIA — flash point at or above 60°C, but below 100°C
  - Class IIIB — flash point at or above 100°C.

Typical Data

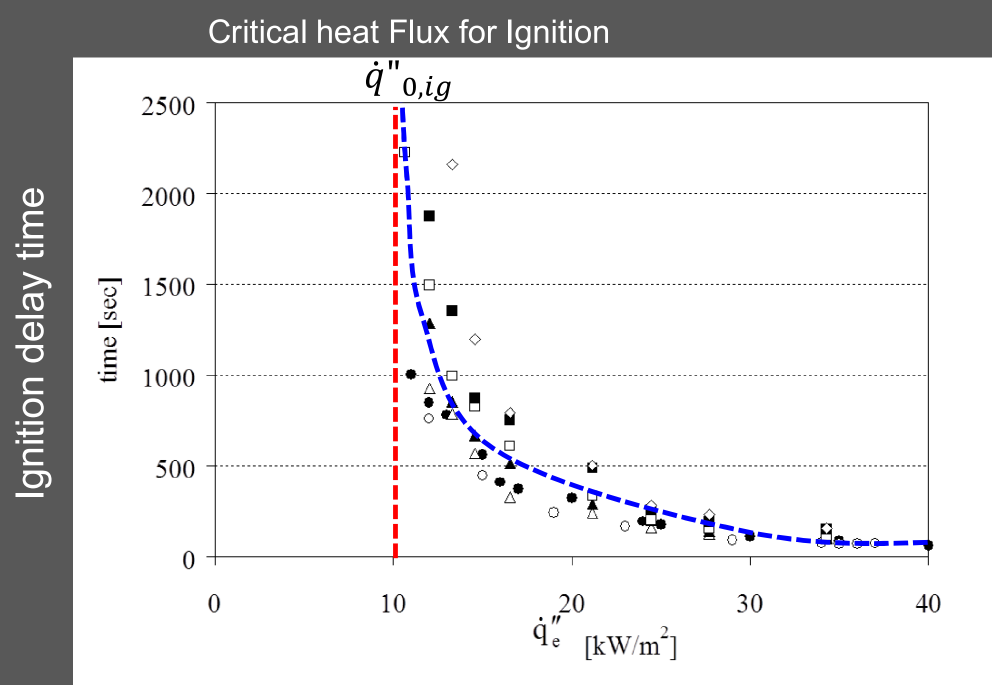
	NFPA Rating	Flash Point (°C)	Boiling Point (°C)
Acetaldehyde	4	-37.8	21.1
Acetic Acid (glacial)	2	39	118
Acetone	3	-18	5607
Acetonitrile	3	6	82
Carbon disulfide	3	-30.0	46.1
Cyclohexane	3	-20.0	81.7
Diethylamine	3	-23	57
Diethyl ether	4	-45.0	35.0
Dimethyl sulfoxide	1	95	189
Ethyl alcohol	3	12.8	78.3
Heptane	3	-3.9	98.3
Hexane	3	-21.7	68.9
Hydrogen	4	---	-252
Isopropyl alcohol	3	11.7	82.8
Methyl alcohol	3	11.1	64.9
Methyl ethyl ketone	3	-6.1	80
Pentane	4	-40.0	36.1
Styrene	3	32.2	146.1
Tetrahydrofuran	3	-14	66
Toluene	3	4.4	110
p-Xylene	3	27.2	138.3

Solids – Lateral Ignition and Flame Spread Test (ISO 9705)





Ignition



Critical Heat Flux for Ignition ($\dot{q}''_{0,ig}$)

$$k_S \frac{\partial^2 T}{\partial x^2} = \rho_S C_{P,S} \frac{\partial T}{\partial t}$$

$$0 = -k_S \frac{\partial T}{\partial x} = \dot{q}''_{0,ig} - h_T(T_{ig} - T_\infty)$$

$t = 0 \rightarrow T = T_\infty \qquad x \rightarrow \infty, T = T_\infty$

$$x = 0 \rightarrow -k_S \frac{\partial T}{\partial x} = \dot{q}''_e - h_T(T_S - T_\infty)$$

$$\boxed{T_{ig} = T_\infty + \frac{\dot{q}''_{0,ig}}{h_T}}$$

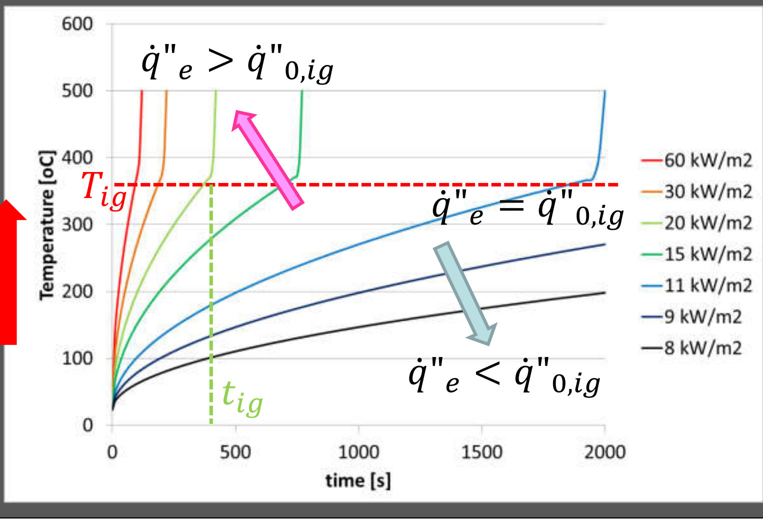
Test Value

$h_T \approx 45\ W/m^2K$

$$\dot{q}''_{Loss} = h_T(T_{ig} - T_\infty)$$

$$\dot{q}''_{Loss} = h_T(T_S - T_\infty)$$

$$\dot{q}''_{Loss} = 0$$



Thermal Inertia

$$t_{ig} = \frac{\pi}{4} k_S \rho_S C_{P,S} \left(\frac{T_{ig} - T_\infty}{\dot{q}''_e} \right)^2$$

$$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{k_S \rho_S C_{P,S}}} \frac{1}{(T_{ig} - T_\infty)} \dot{q}''_e$$

$$\boxed{y = Ax + B}$$

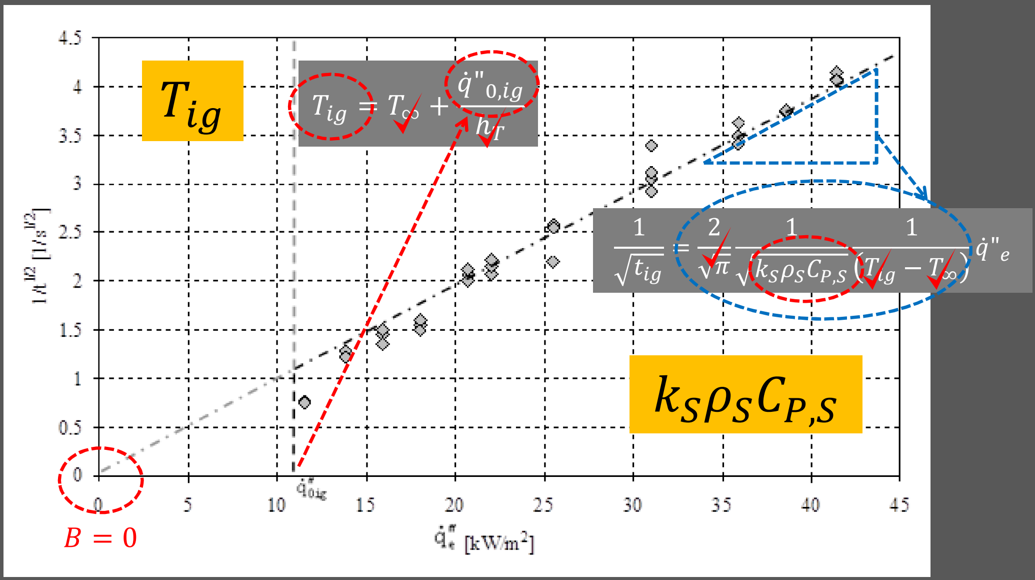
$y = \frac{1}{\sqrt{t_{ig}}}$

$x = \dot{q}''_e$

$A = \frac{2}{\sqrt{\pi}} \frac{1}{\sqrt{k_S \rho_S C_{P,S}}} \frac{1}{(T_{ig} - T_\infty)}$ Slope

$B = 0$ Intercept

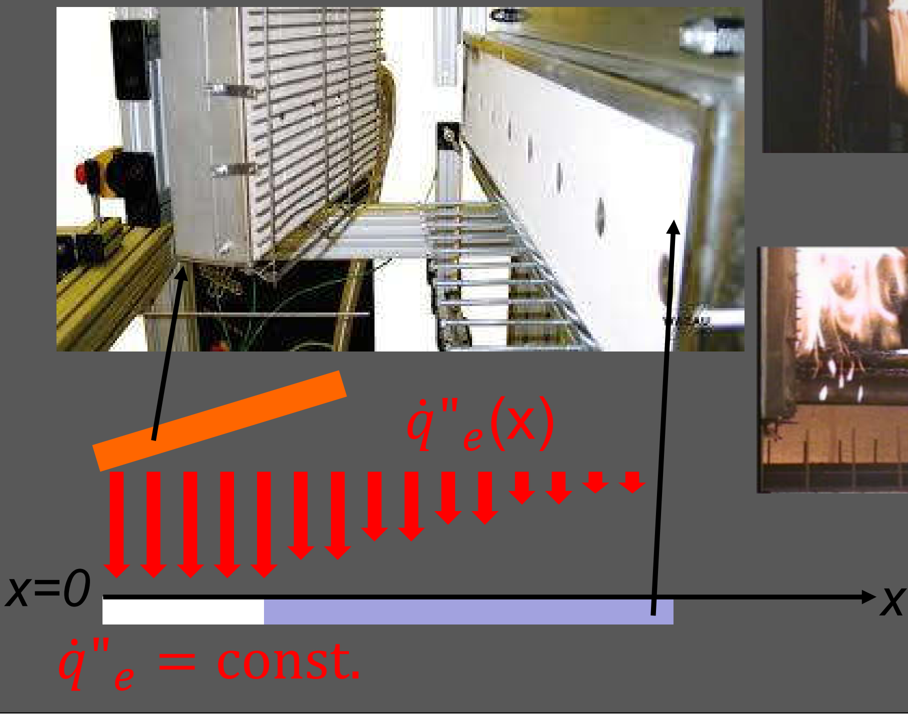
Material Properties

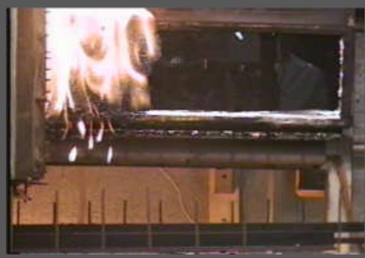


Data

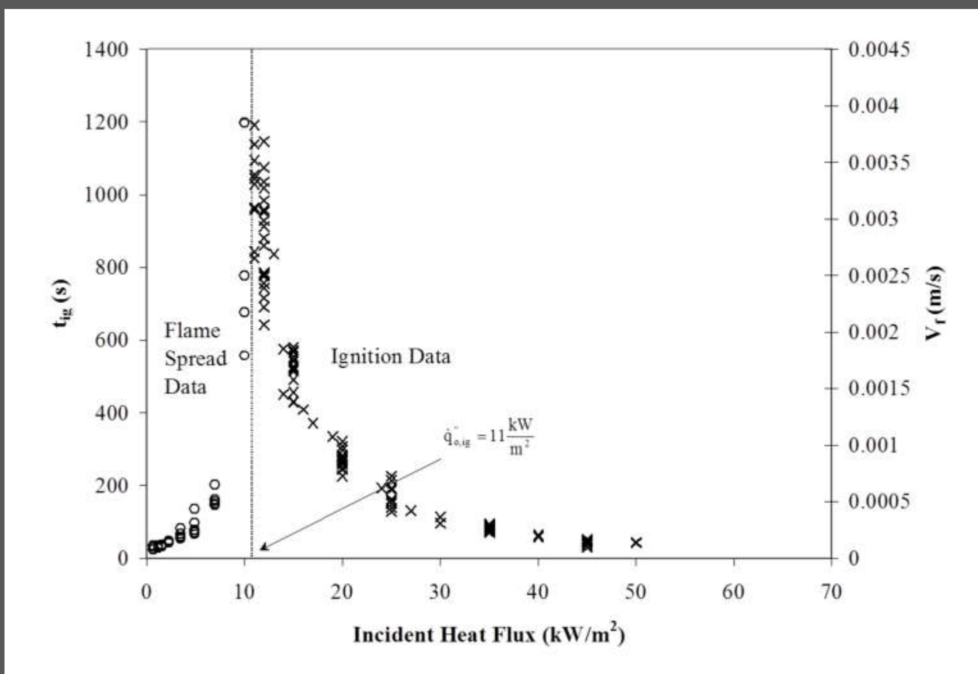
Material	T_{ig} [°C]	$\overline{k_S \rho_S C_S}$ [(kW/m^{2}K)^2.s]
Wood fiber board	355	0.46
Wood hardboard	365	0.88
Plywood	390	0.54
PMMA	380	1.00
Flexible Foam Plastic	390	0.32
Rigid Foam Plastic	435	0.03
Acrylic Carpet	300	0.42
Wallpaper on Plasterboard	412	0.57
Asphalt Shingle	378	0.70
Glass Reinforced plastic	390	0.32

Solids – Lateral Ignition and Flame Spread Test (ISO 9705)





Flammability Diagram



Surface Temperature (T_S)

$$k_S \frac{\partial^2 T}{\partial x^2} = \rho_S C_{P,S} \frac{\partial T}{\partial t}$$

$t = 0 \rightarrow T = T_\infty \qquad x \rightarrow \infty, T = T_\infty$

$x = 0 \rightarrow -k_S \frac{\partial T}{\partial x} = \dot{q}''_e - h_T(T_S - T_\infty)$

$$0 = -k_S \frac{\partial T}{\partial x} = \dot{q}''_e - h_T(T_S - T_\infty)$$

$$\boxed{\dot{q}''_e(x) = h_T(T_S - T_\infty)}$$

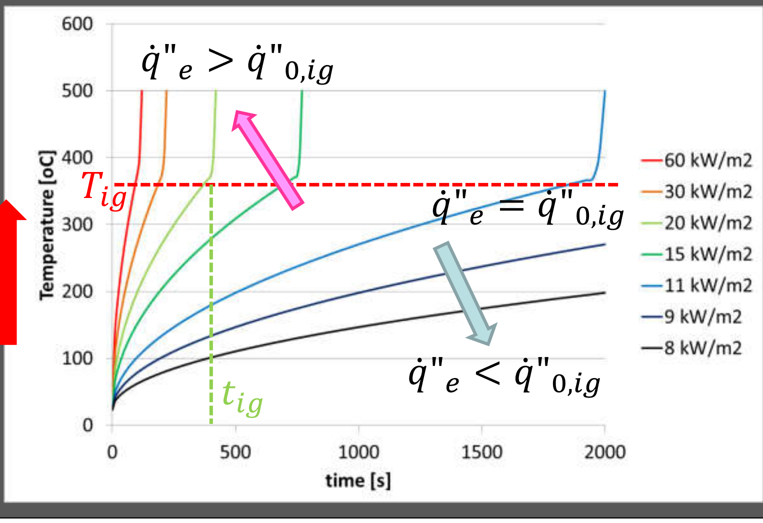
Test Value

$h_T \approx 45\ W/m^2K$

$\dot{q}''_{Loss} = h_T(T_{ig} - T_\infty)$

$\dot{q}''_{Loss} = h_T(T_S - T_\infty)$

$\dot{q}''_{Loss} = 0$



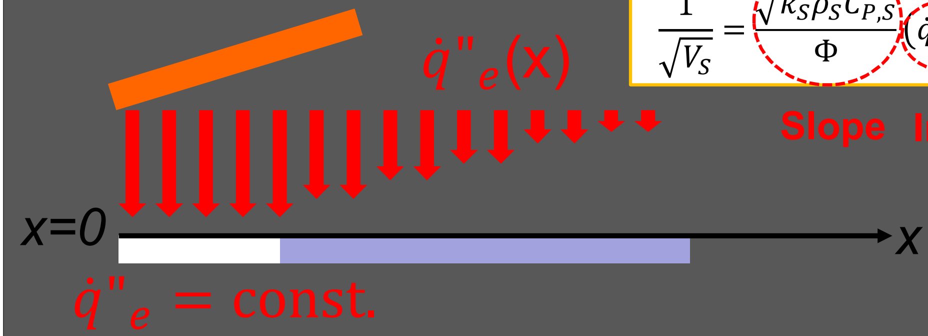
o $V_S = \frac{\dot{q}''^2_g \delta_S}{k_S \rho_S C_{P,S} (T_{ig} - T_S)^2}$

$\dot{q}''_{0,ig} = h_T(T_{ig} - T_\infty)$

o $V_S = \frac{\dot{q}''^2_g \delta_S}{k_S \rho_S C_{P,S} (T_{ig} - T_\infty + T_\infty - T_S)^2}$

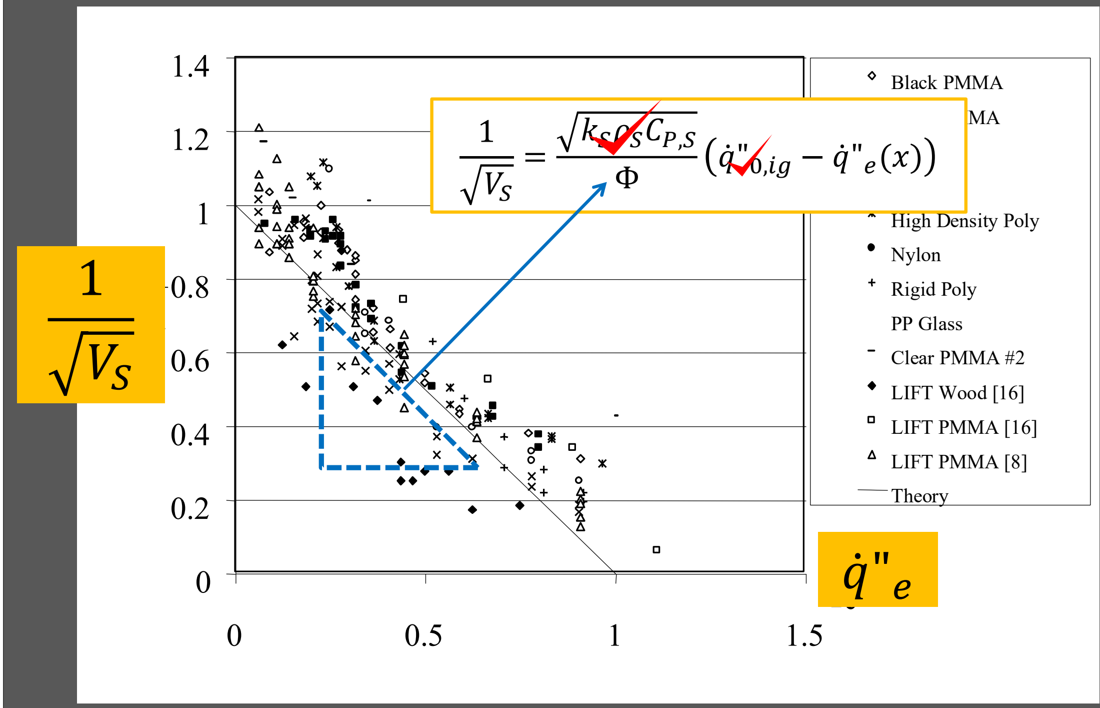
$\dot{q}''_e(x) = h_T(T_S - T_\infty)$

o $V_S = \frac{\dot{q}''^2_g \delta_S h_T^2}{k_S \rho_S C_{P,S} (\dot{q}''_{0,ig} - \dot{q}''_e(x))^2} = \frac{\Phi^2}{k_S \rho_S C_{P,S} (\dot{q}''_{0,ig} - \dot{q}''_e(x))^2}$



$$\boxed{\frac{1}{\sqrt{V_S}} = \frac{\sqrt{k_S \rho_S C_{P,S}}}{\Phi} (\dot{q}''_{0,ig} - \dot{q}''_e(x))}$$

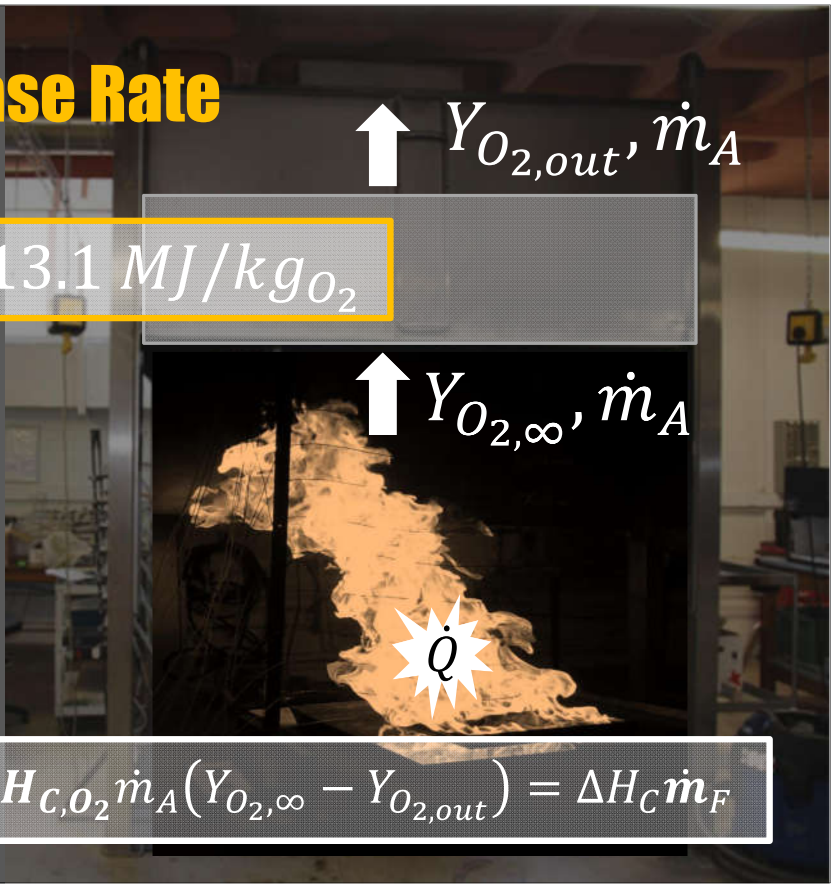
Slope Intercept



Data

Material	$(\Phi_{O,S})$ (kW^2/m^{3}s)
LIFT Wood	0.04
FIST Wood	0.04
LIFT black PMMA	0.01
LIFT black PMMA	0.01
FIST black PMMA	0.01
Clear PMMA	0.01
Delrin	0.02
High Density Polyetylene	0.01
Nylon	0.32
Rigid Polyetylene	0.02
PP/Glass Composite	0.01
Clear PMMA #2	0.01
Westinghouse Glass/Epoxy Laminate	No Spread

Heat Release Rate



$Y_{O_{2,out}}, \dot{m}_A$

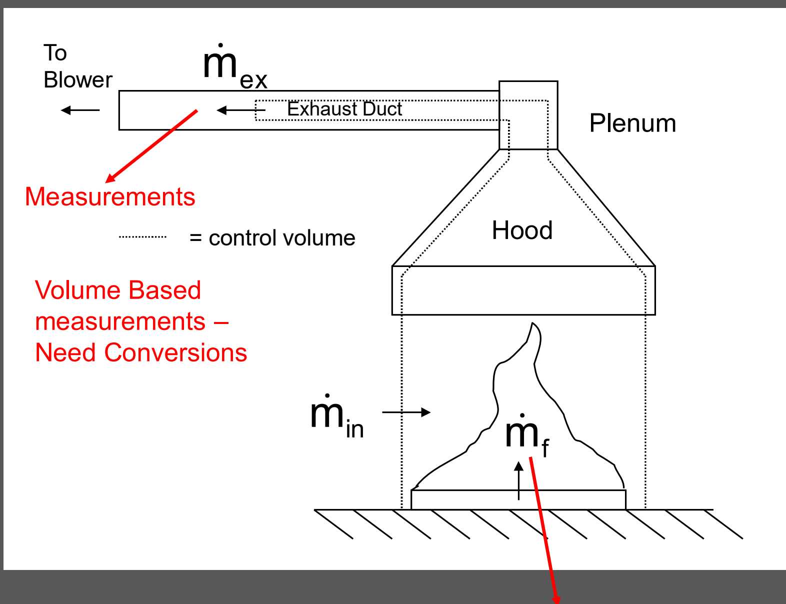
$$\Delta H_{C,O_2} = 13.1\ MJ/kg_{O_2}$$

$Y_{O_{2,\infty}}, \dot{m}_A$

$\dot{Q}$

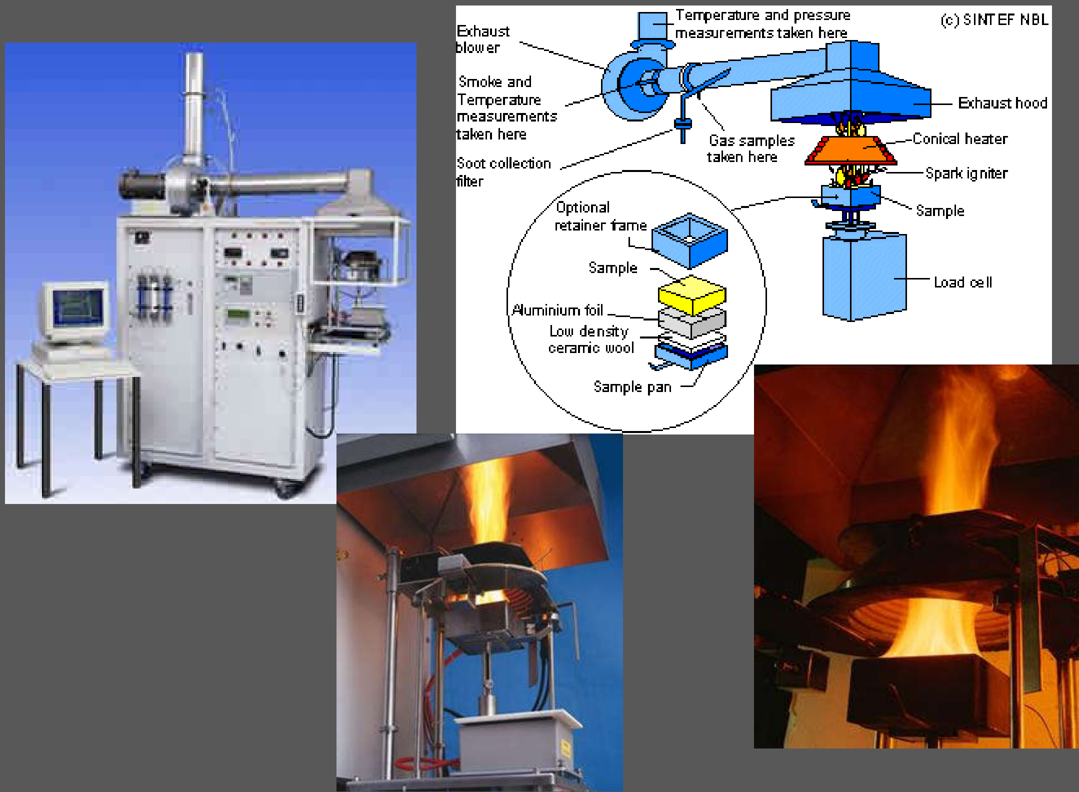
$$\boldsymbol{HRR = \dot{Q} = \Delta H_{C,O_2}} \dot{m}_A \left(Y_{O_{2,\infty}} - Y_{O_{2,out}}\right) = \Delta H_C \boldsymbol{\dot{m}_F}$$

O_2 Consumption



Measurements

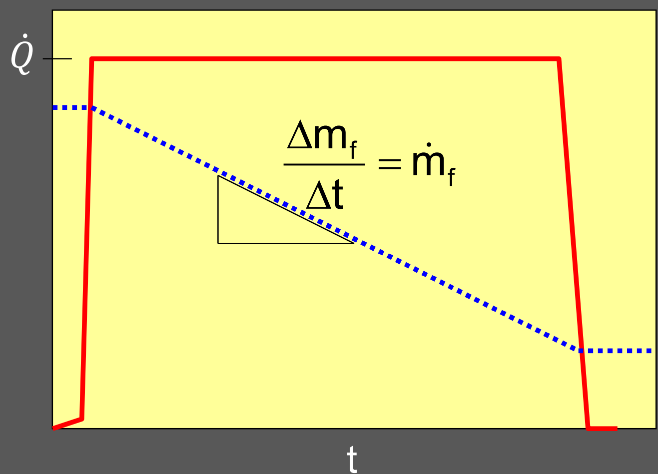
- Oxygen Concentration:
- $Y_{O_2} = \frac{m_{O_2}}{m_{Total}}$
- Air:
- $Y_{O_{2,\infty}} = 0.23$
- Measurements:
- $Y_{O_{2,out}} = ?$
- $\dot{m}_f = ?$



Experimental Results

- **Ideal Scenario:**

$$HRR = \dot{Q} = \Delta H_{C,O_2}\dot{m}_A\left(Y_{O_2,\infty} - Y_{O_2,out}\right) = \Delta H_C \dot{m}_F$$

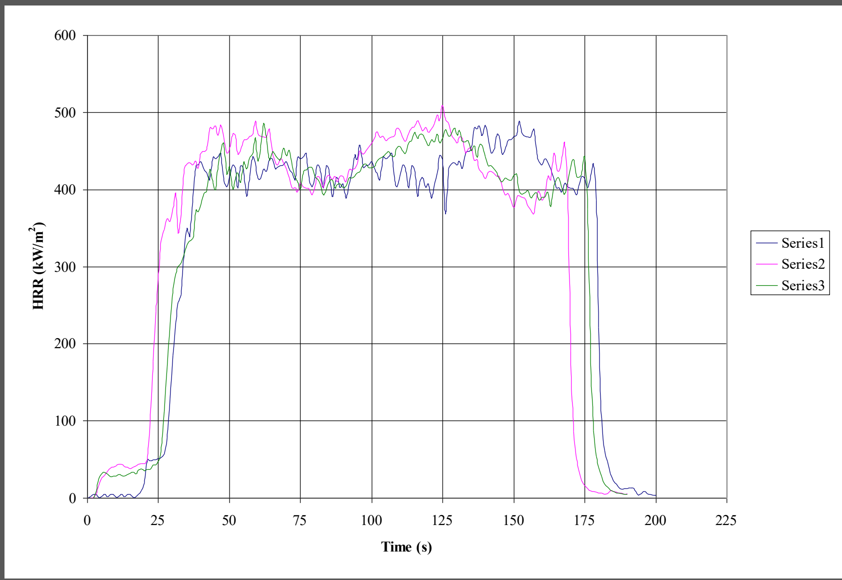


$$\Delta H_C = \frac{\dot{Q}}{\dot{m}_f}$$

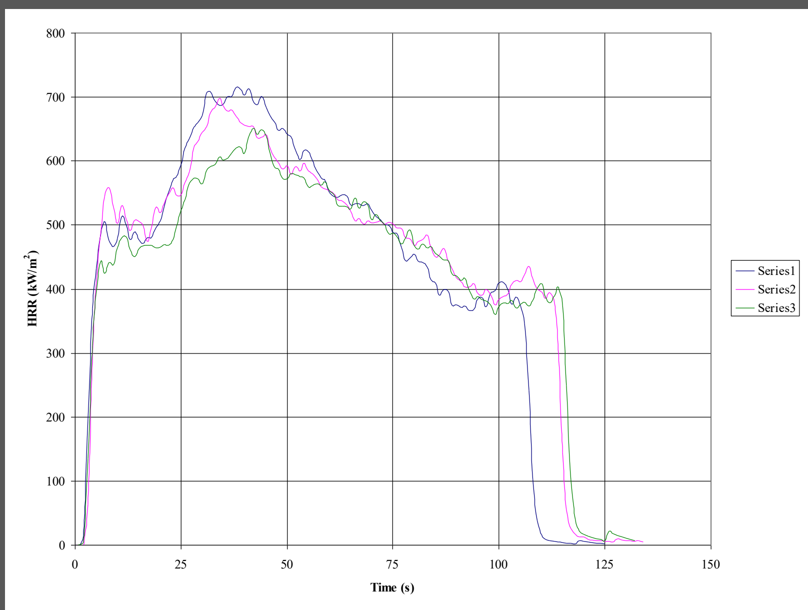
$$HRRPUA = \dot{Q}'' = \frac{\dot{Q}}{A_S}$$

$$A_S = 100\ cm^2$$

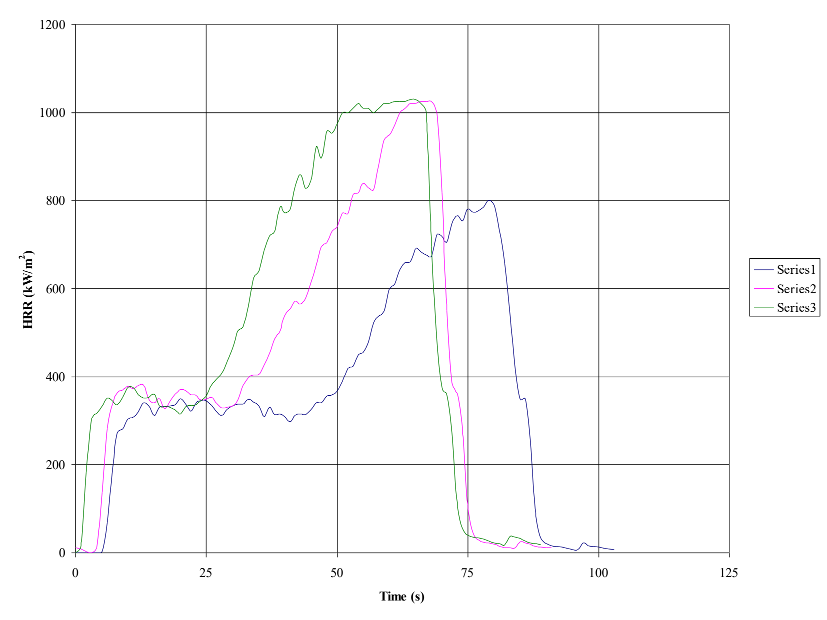
Kerosene



Gasoline



Naphthalene (I)

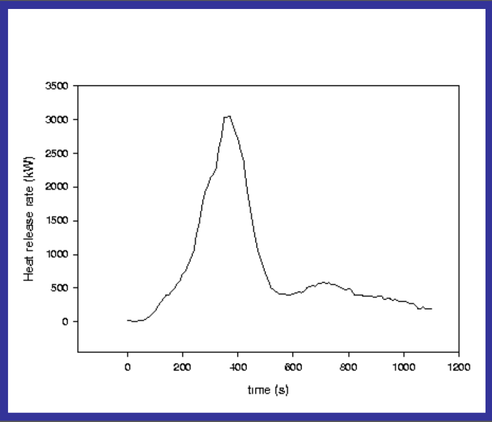


The Real Scale Application

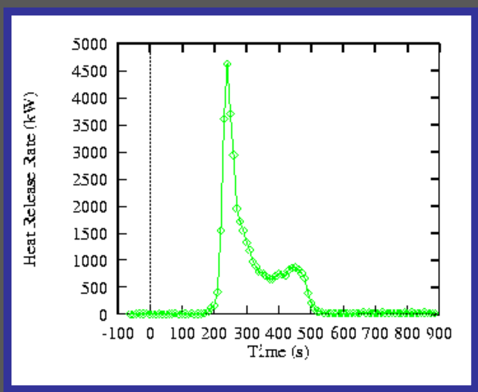
- **Large Scale Calorimeters**
  - Factory Mutual
  - Underwriters Laboratories
  - BRE

Loveseat

Loveseat

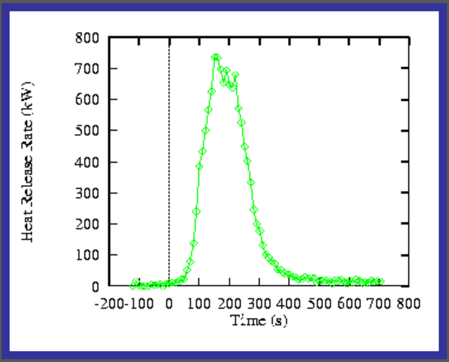


Bunk bed



- Corner ignition of lower bunk
- Data from "Fire on the Web" (www.bfrl.nist.gov)

Mattress



HRR data resources

- BFRL / NIST - Fire on the Web
  - www.bfrl.nist.gov
- Lund University - Report on initial fires
  - www.brand.lth.se
- Many other scattered reports
- Some data included in fire model suites
  - CFAST; FPETool


Post-Flashover compartment Fire
José L. Torero
University College London
United Kingdom
Lecture - 5

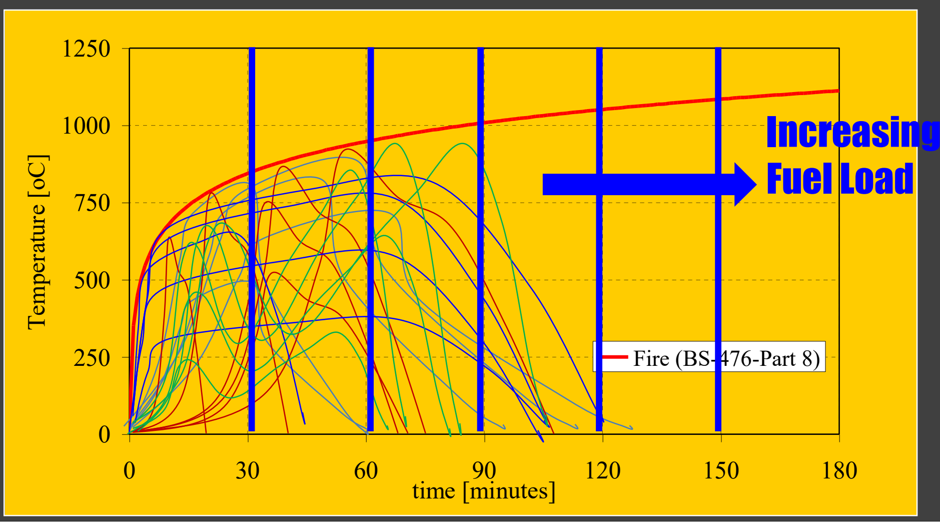

Assessing Structural Behavior

Fire Resistance

- Current approach is “Fire Resistance” (Ingberg S.H., “Fire loads: Guide to the application of fire safety engineering principles,” *Quarterly Journal of the National Fire Protection Association*, **1**, 1928.)

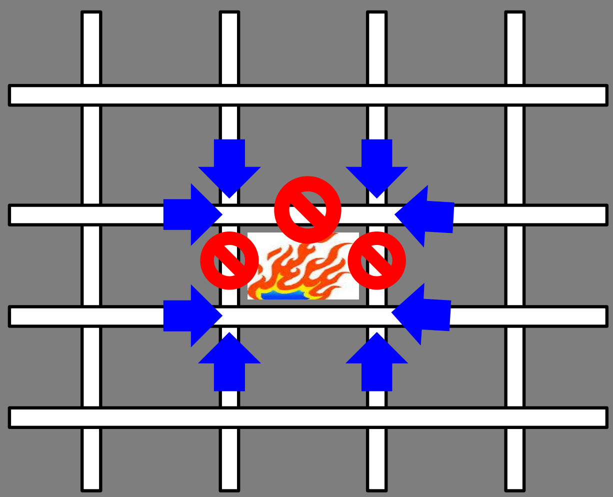
Origins

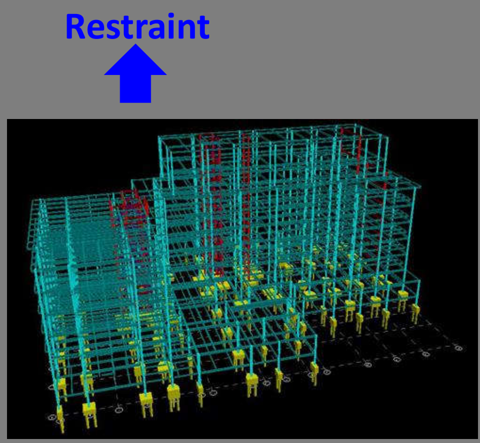
- Worst Case Scenario
- Curve defined by envelope to all fires
- Required Rating defined by total fuel consumption



Restraint

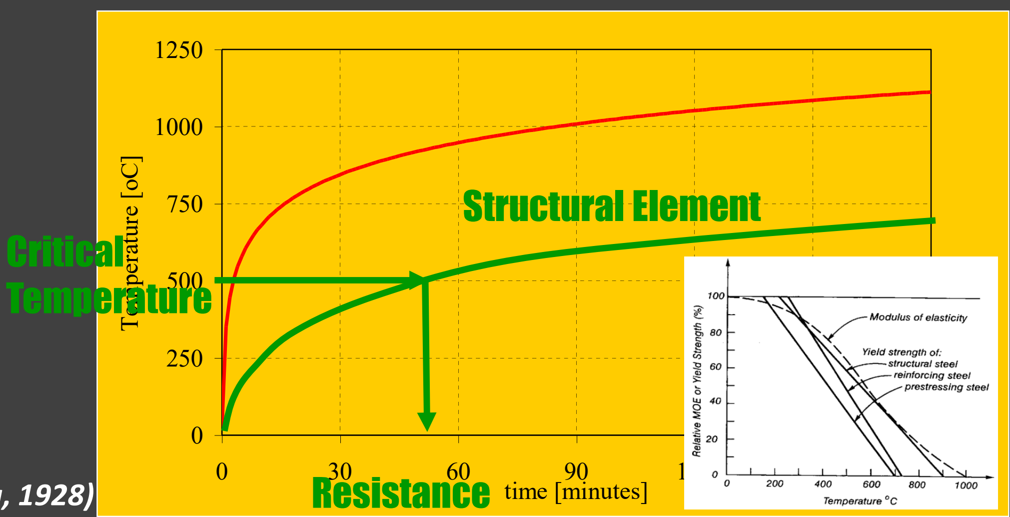
- Compartment allows to approximate global structural behaviour to single element – Restraint enables effective load transfer





Standard Fire

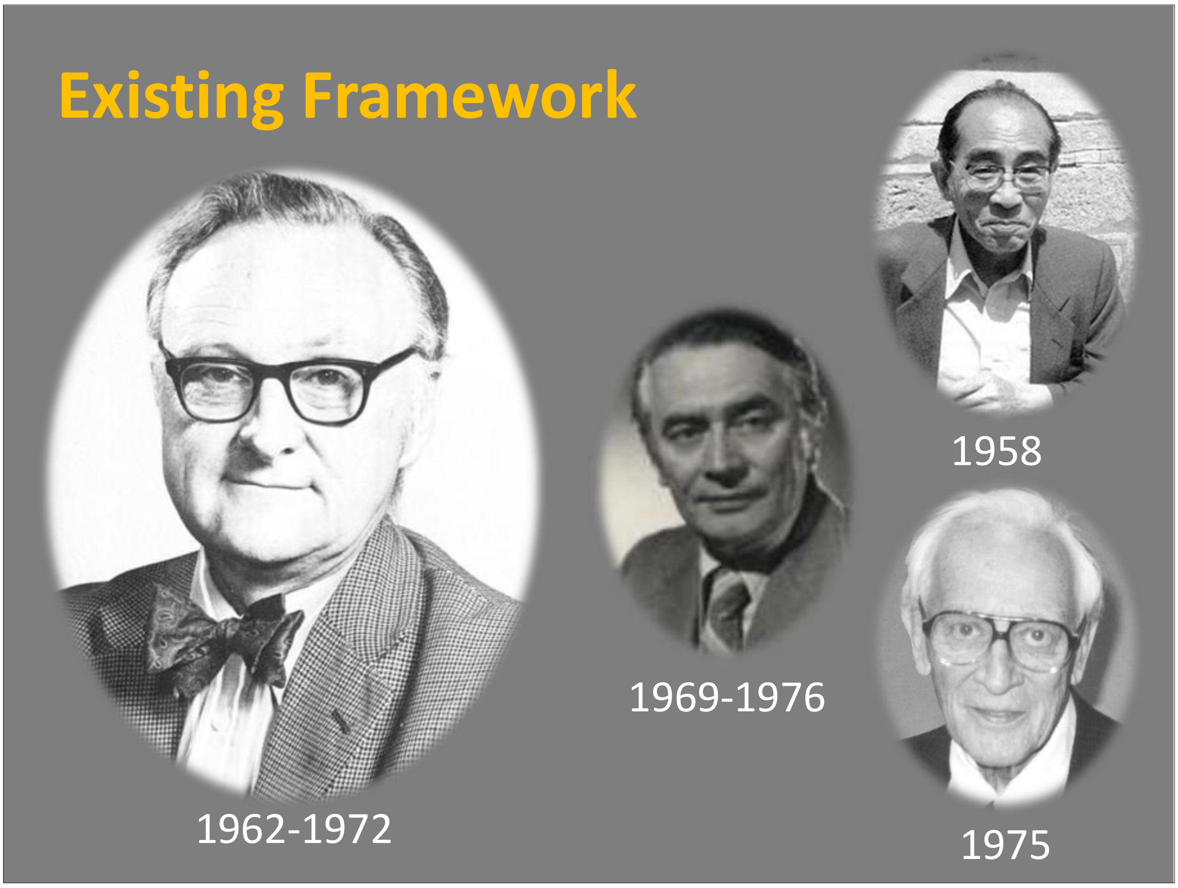
- Furnace to reproduce compartment
- Single element tested

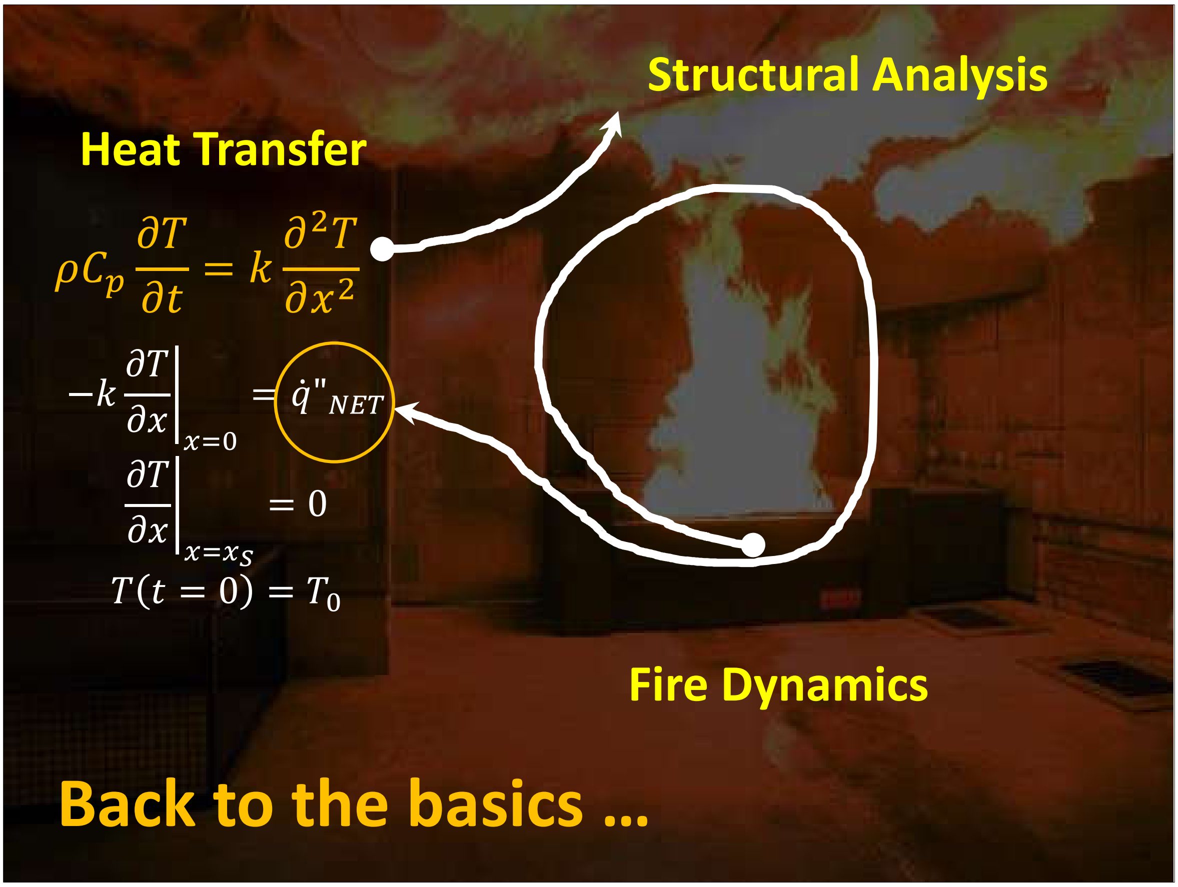


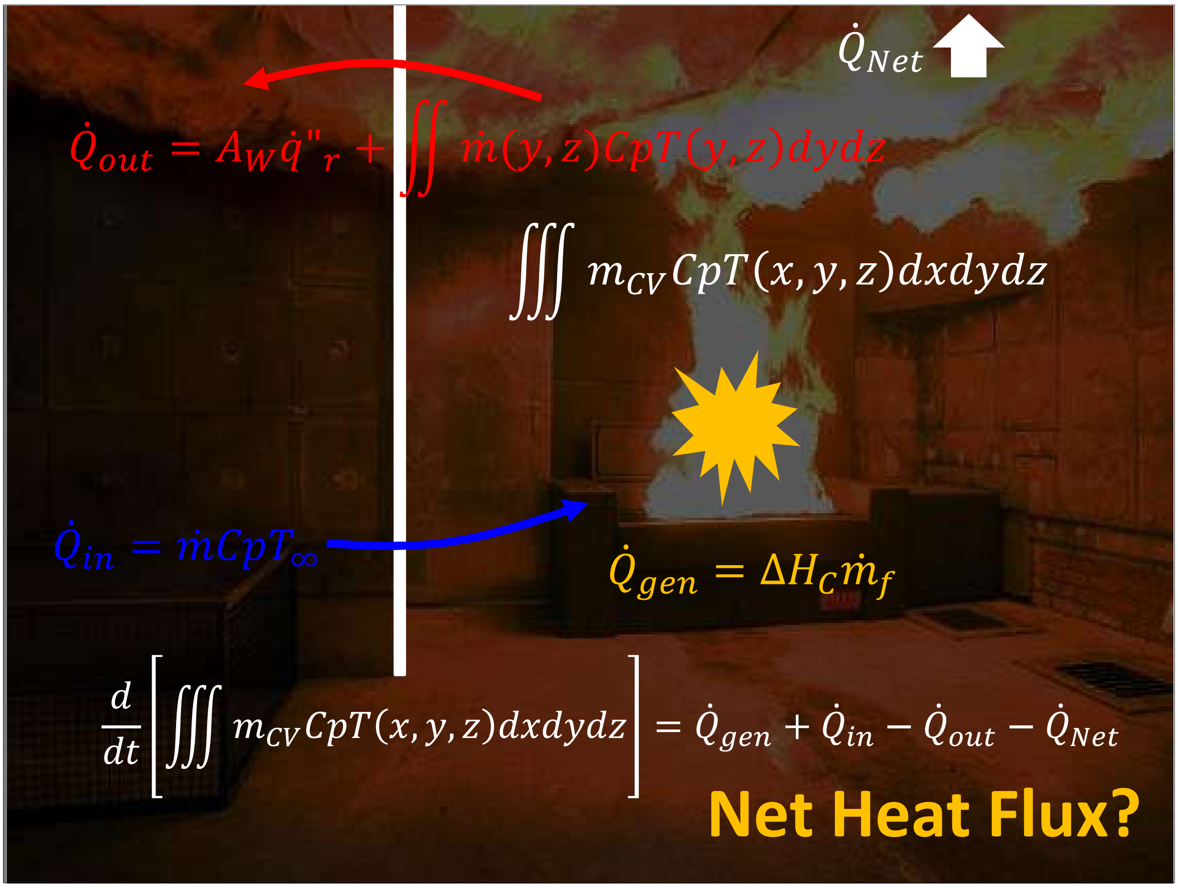
(Ingberg, 1928)


Large Safety Factor?
o Poor understanding of material behaviour at high temperatures
o Poor understanding of fire dynamics
o Fire Resistance embedded into Codes & Standards which represent societies responsibility to guarantee safety – i.e. Large Safety Factors!


The collapse of the WTC towers emphasizes the need for a detailed structural analysis of optimized buildings – ie. Tall Buildings


Existing Framework
1958
1969-1976
1962-1972
1975


Structural Analysis
Heat Transfer
$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$
$-k \frac{\partial T}{\partial x}\Big|_{x=0} = \dot{q}"_{NET}$
$\frac{\partial T}{\partial x}\Big|_{x=x_S} = 0$
$T(t=0) = T_0$
Fire Dynamics
Back to the basics …



The Compartment Fire

- It was understood that solving the full energy equation was not possible
- The different characteristic time scales of structure and fire do not require such precision
- Looked for a simplified formulation: The Compartment Fire

Typical Compartment

Thomas & Heselden (1972)

- Realistic scale compartment fires (~4 m x 4 m x 4 m) aimed at delivering average temperatures
- Simple instrumentation: Single/Two thermocouples

Regime I

Regime II

Thomas, P.H., and Heselden, A.J.M., "Fully developed fires in single compartments", CIB Report No 20. Fire Research Note 923, Fire Research Station, Borehamwood, England, UK, 1972.

Assumptions – Regime I

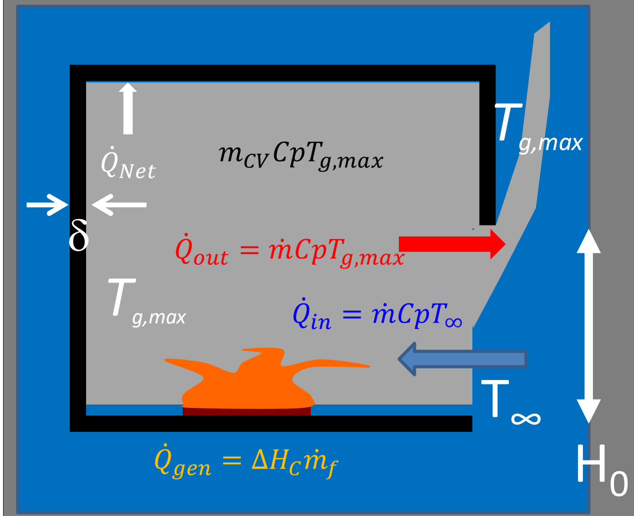
- The heat release rate is defined by the complete consumption of all oxygen entering the compartment and its subsequent transformation into energy, $\dot{Q} = \dot{m} Y_{O_2,\infty} \Delta H c_{O_2}$.
  - Eliminates the need to define the oxygen concentration in the outgoing combustion products
  - Eliminates the need to resolve the oxygen transport equation within the compartment.
  - Limits the analysis to scenarios where there is excess fuel availability
  - Chemistry is fast enough to consume all oxygen transported to the reaction zone
  - The control volume acts as a perfectly stirred reactor.
  - The heat of combustion is assumed to be an invariant/ the completeness of combustion is independent of the compartment.
- Radiative losses through the openings are assumed to be negligible therefore $\dot{Q}_{out}$ is treated as an advection term (3% of the total energy released (Harmathy)).
- There are no gas or solid phase temperature spatial distributions within the compartment.
- Mass transfer through the openings is governed by static pressure differences ($\dot{m} = C A_O \sqrt{H_O}$)
  - all velocities within the compartment to be negligible
  - Different values of the constant were derived by Harmathy and calculated by Thomas for different experimental conditions.

Maximum Compartment Temperature

$$\frac{d}{dt}[m_{CV}CpT_S] = \dot{Q}_{gen} + \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{Net}$$

S.S.

$\dot{Q}_{in} \ll \dot{Q}_{out}$



$$\dot{m}_{in} = \dot{m}_{out} = \dot{m} = CA_O\sqrt{H_O}$$

$$\dot{Q}_{gen} = \dot{m}Y_{O_2,\infty}\Delta Hc_{O_2}$$

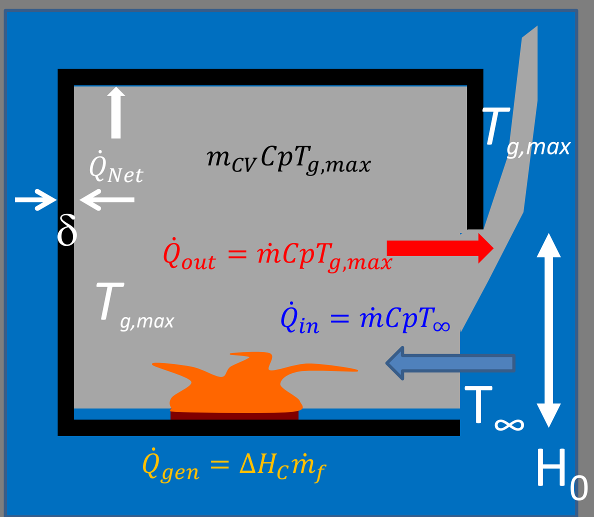
$$\dot{Q}_{out} = \dot{m}C_pT_{g,max}$$

$$\dot{Q}_{Net} = Ak\frac{(T_{g,max} - T_\infty)}{\delta}$$

Maximum Compartment Temperature

$$\boxed{0 = \dot{Q}_{gen} - \dot{Q}_{out} - \dot{Q}_{Net}}$$

Substituting and solving for $T_{g,max}$

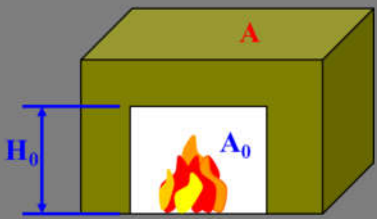


$$\boxed{T_{g,max} = \left(\frac{1 + \frac{T_\infty}{T_{CD}}}{1 + \frac{T_F}{T_{CD}}}\right)T_F}$$

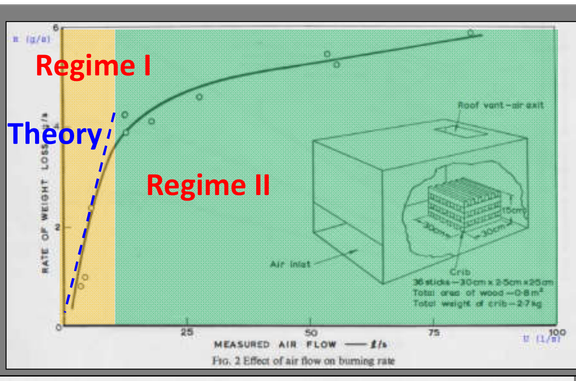
$$T_F = Y_{O_{2,\infty}}\Delta Hc_{O_2}/C_p$$

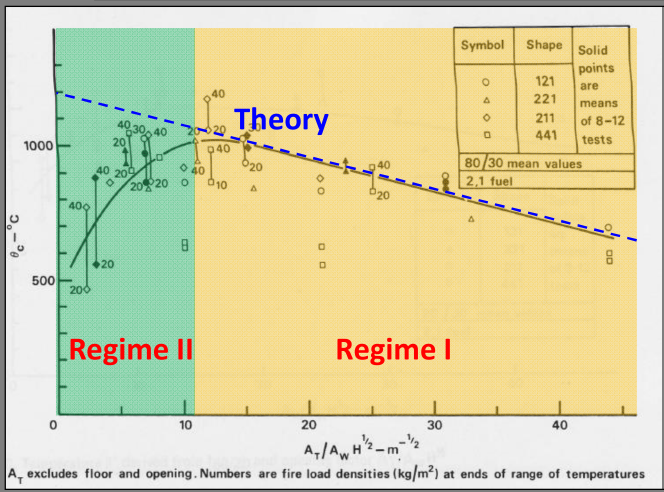
$$T_{CD} = \frac{CY_{O_{2,\infty}}\Delta Hc_{O_2}}{(k/\delta)}\left(\frac{A_O\sqrt{H_O}}{A}\right)$$

The Data



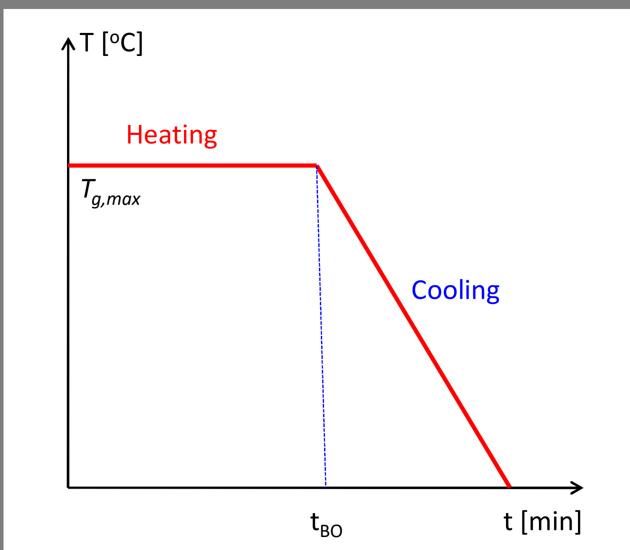
$$A/A_0\sqrt{H_0}$$

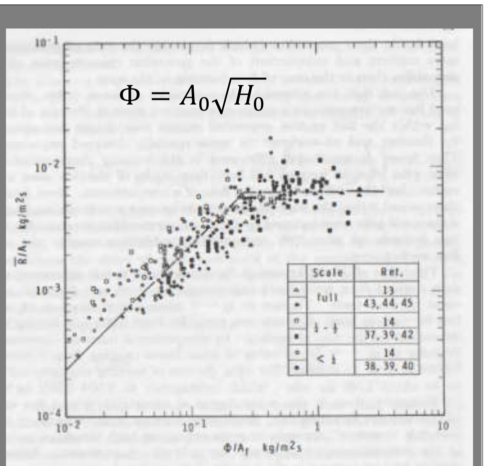




Design Method

(Law, M., "A Basis for The Design of Fire Protection of Building Structures," Struct. Eng., no. February, pp. 25–33, 1983.)





$R = 0.1\ A_0H_0^{1/2}$ (kg/s)

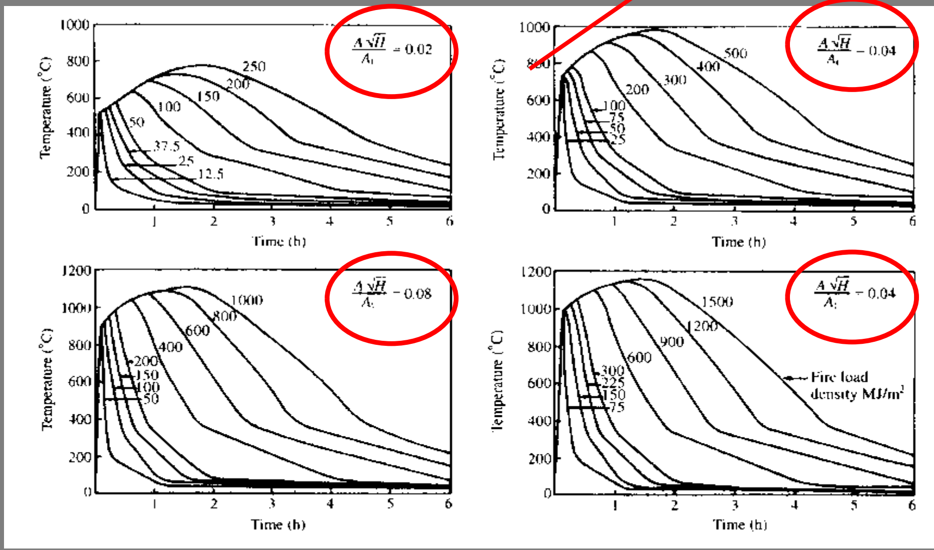
Kawagoe (1958)
Thomas & Heselden (1972)

$$t_{BO} = \frac{M_f}{R}$$

Parametric Fires

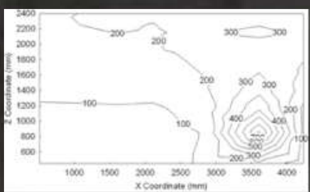
(Pettersson, O. Magnusson, S. E. and Thor, J. "Fire Engineering Design of Steel Structures," Stockholm, Jun. 1976.)

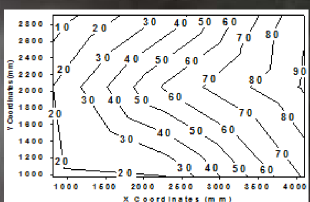
$\dot{Q}_{Net} \downarrow$

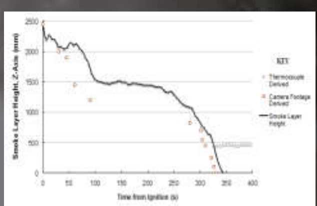


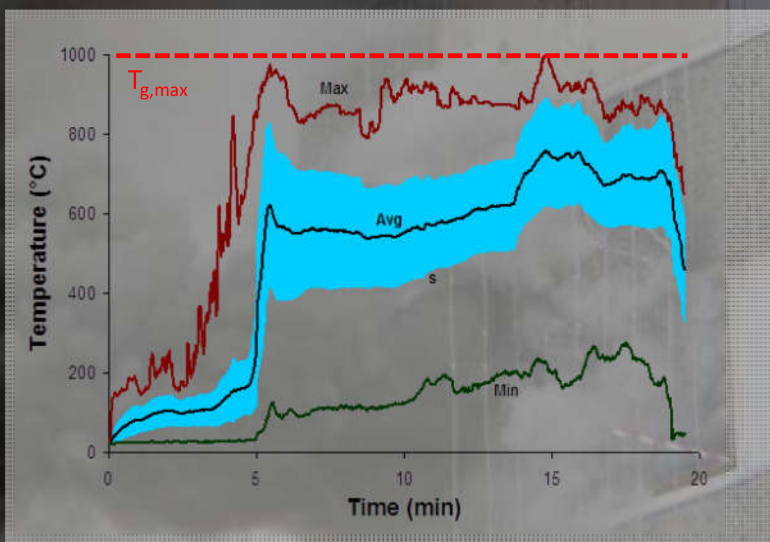
- Recorded temperature evolution – effect of structural heating
- Average temperature – single thermocouple rack (6 – TC)

Realistic Fire



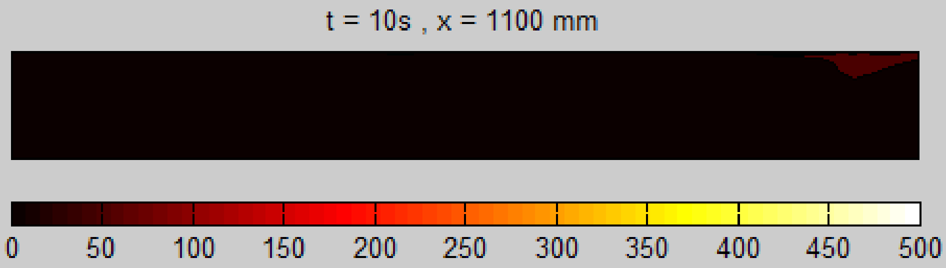




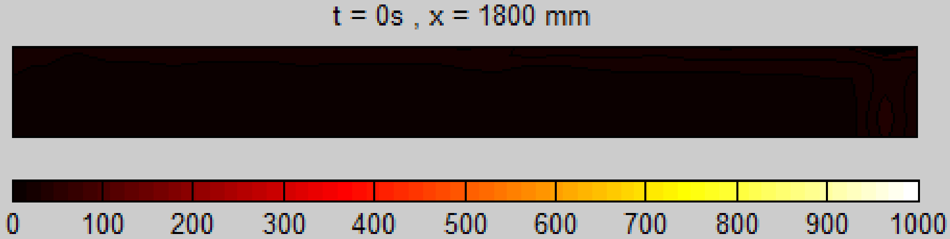


Regime II?

- Data scatter is very large
- Factors such as aspect ratio, nature of the fuel and scale were shown by Thomas & Heselden to have a significant effect on the resulting temperatures
- The relationships between $T_{g,max}$ and R with $A/A_0\sqrt{H_0}$ and $A_0\sqrt{H_0}$ are no longer valid



Travelling Fires (Regime II)



Growing Fires
(Regime II or Regime I?)

Executive Summary

(SFPE Engineering Guide – Fire Exposures to structural Elements – May 2004)

$$\frac{A}{A_0\sqrt{H_0}}$$

Designing fire resistance on a performance basis requires three steps:

1. Estimating the fire boundary conditions
2. Determining the thermal response of the structure
3. Determining the structural response

This guide provides information relevant to estimating the fire boundary conditions resulting from a fully developed fire. Methods are provided for fully developed enclosure fires and for fire plumes. Fully developed enclosure fires can be expected in compartments with fuel uniformly distributed over their interiors. For situations where a fire would not be enclosed or for enclosures with sparse distributions or concentrated fuel packets, the methods identified in the fire plumes section should be used.

Several methods are evaluated for fully developed enclosure fires. Law's method is recommended for all roughly cubic compartments and in long, narrow compartments where $\frac{A}{A_o\sqrt{H_o}}$ does not exceed $\approx 18\ m^{-1/2}$. To ensure that predictions are sufficiently conservative in design situations, the predicted burning rate should be reduced by a factor of 1.4 and the temperature adjustment should not be reduced by Law's Ψ factor.

Law's method does not predict temperatures during the decay stage. For cases where a prediction of temperatures during the decay stage is desired, a decay rate of 7°C/min can be used for fires with a predicted duration of 60 minutes or more, and a decay rate of 10°C/min can be used for fires with a predicted duration of less than 60 minutes.

For long, narrow spaces in which $\frac{A}{A_o\sqrt{H_o}}$ is in the range of 45 to 85 $m^{-1/2}$, Magnusson and Thelandersson provide reasonable predictions of temperature and duration. For long, narrow spaces in which $\frac{A}{A_o\sqrt{H_o}}$ is approximately 345 $m^{-1/2}$, Lie's method is recommended.

For ranges of $\frac{A}{A_o\sqrt{H_o}}$ that fall outside the ranges identified above, the calculations should be performed using the methods identified for the ranges of $\frac{A}{A_o\sqrt{H_o}}$ that bound the situation of interest, and the most conservative results should be used.

For fire plumes, methods are presented for conducting a bounding analysis and for specific geometries. These geometries include flat vertical walls, corners with a ceiling, unbounded flat ceilings, and an I-beam mounted below a ceiling. Additionally, correlations are provided for axisymmetric plumes for those wishing to conduct a heat transfer analysis from first principles.

- Quintiere
- McCaffrey
- Pettersson
- Rockett
- Tanaka, etc.

Summary

- An elegant framework was established that provided an *"answer"* to a *"fundamental question"*
  - Assumptions were clearly established
  - Limitations were clearly established
- A simple design methodology was developed that provided a *"worst case: $T_{g,max}$ vs t"* curve for the purposes of structural analysis.

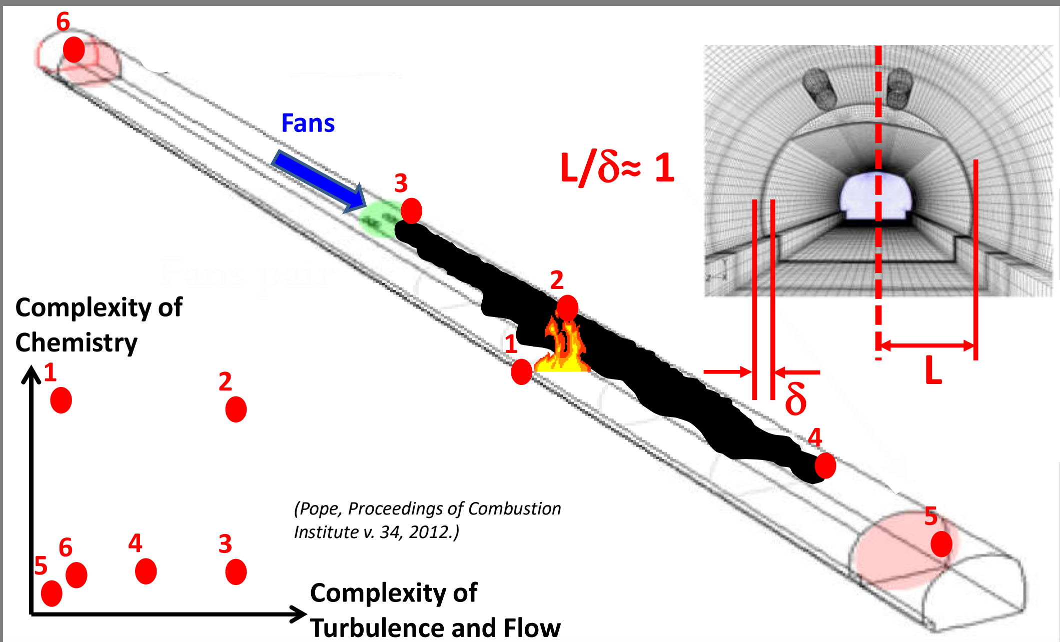
Complex problems require detailed solutions

- Only CFD provides temporal and spatial resolution required
- Precision, robustness and uncertainty need to be consistent with the requirements of the problem
- Validation & Verification need to be consistent with the complexity of the model

Coupling

Fuel Degradation
↓
Gas Phase Chemistry
↓
Soot Production
↓
Radiative Losses
↓
Flame Temperature
↓ Heat Transfer
↓ Air Entrainment

Complexity



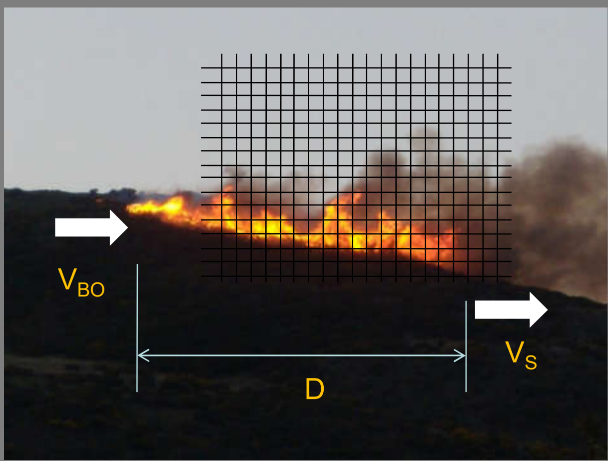
Incompatibility of Scales

Type	Time Scale (s)	Vertical Scale (m)	Horizontal scale (m)
Combustion	0.0001 – 0.01	0.0001 – 0.01	0.0001 – 0.01
Fuel particles	-	0.001 – 0.01	0.001 – 0.01
Fuel complex	-	1 – 20	1 – 100
Flames	0.1 – 30	0.1 – 10	0.1 – 2
Radiation	0.1 – 30	0.1 – 10	0.1 – 50
Conduction	0.01 – 10	0.01 – 100	0.01 – 0.1
Convection	1 – 100	0.1 – 100	0.1 – 10
Turbulence	0.1 – 1,000	1 – 1,000	1 – 1,000
Spotting	1 – 100	1 – 3,000	1 – 10,000
Plume	1 – 10,000	1 – 10,000	1 – 100

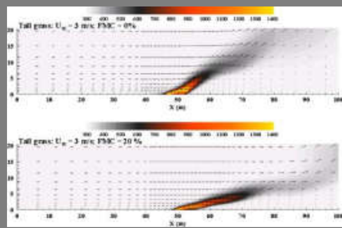
Sullivan, A., "A Review of Wildland Fire Spread Modelling, 1990-Present, 1: Physical and Quasi-Physical Models", arXiv:0706.3074v1[physics.geo-ph] (2007).

Classic Scaling-Up

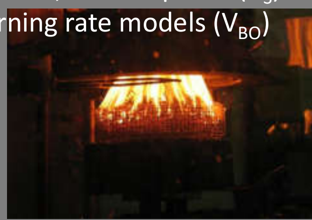
- Uncouple processes
- Develop simplified models
- Feed Models with experimental data



Gas Phase Combustion/Transport Models ($\dot{Q}, D$) (Morvan *et al.* 2009)



Ignition, Flame Spread (V_S) & Burning rate models (V_{BO})



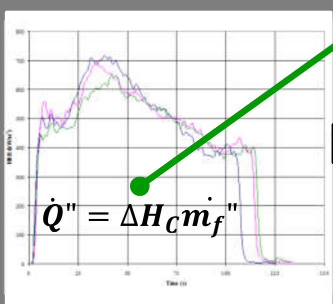
$\dot{Q}, D$

Compartment Fire

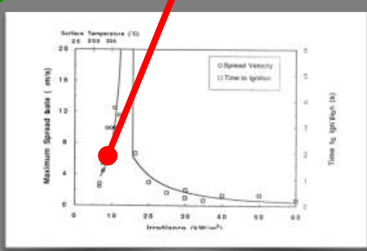
$$\dot{Q} = \Delta H_C \dot{m}_f = \Delta H_C A_B \dot{m}''_f$$

$$A_B = \pi r^2 = \pi (V_f t)^2 = (\pi V_f^2) t^2$$

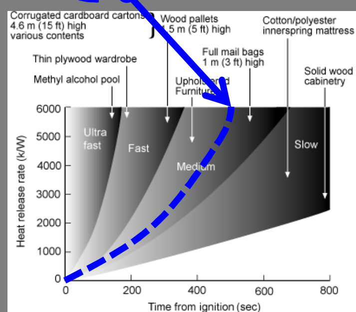
$$\dot{Q} = \Delta H_C A_B \dot{m}''_f = \left[\Delta H_C (\pi V_f^2) \dot{m}''_f\right] t^2 = \alpha t^2$$



$\dot{Q}'' = \Delta H_C \dot{m}_f''$

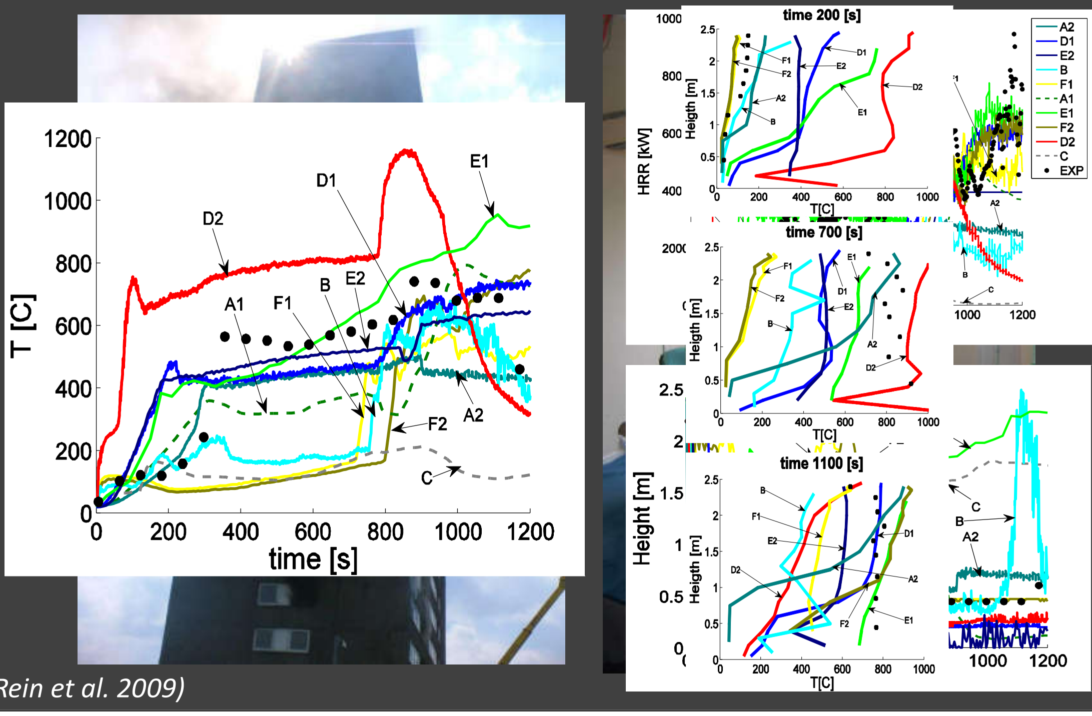


(Quintiere, 1998)



(SFPE, 2009)

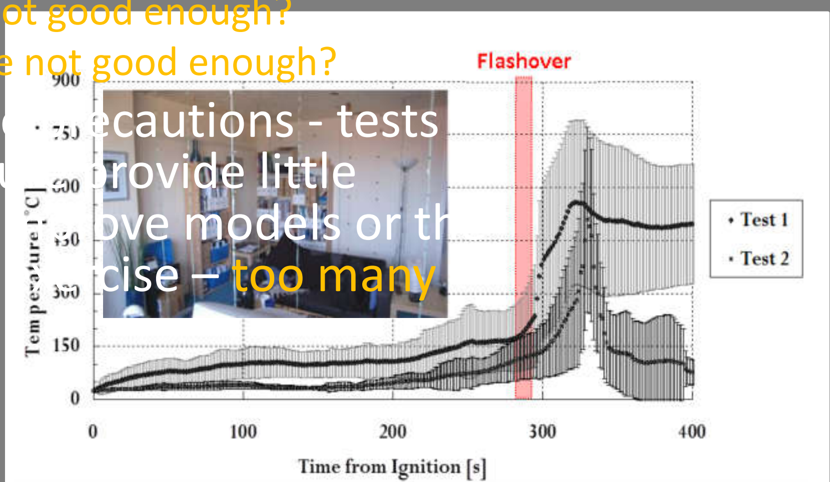
- Can Models Predict this Detail?
- Can Modellers Use Available Tools for this Purpose?



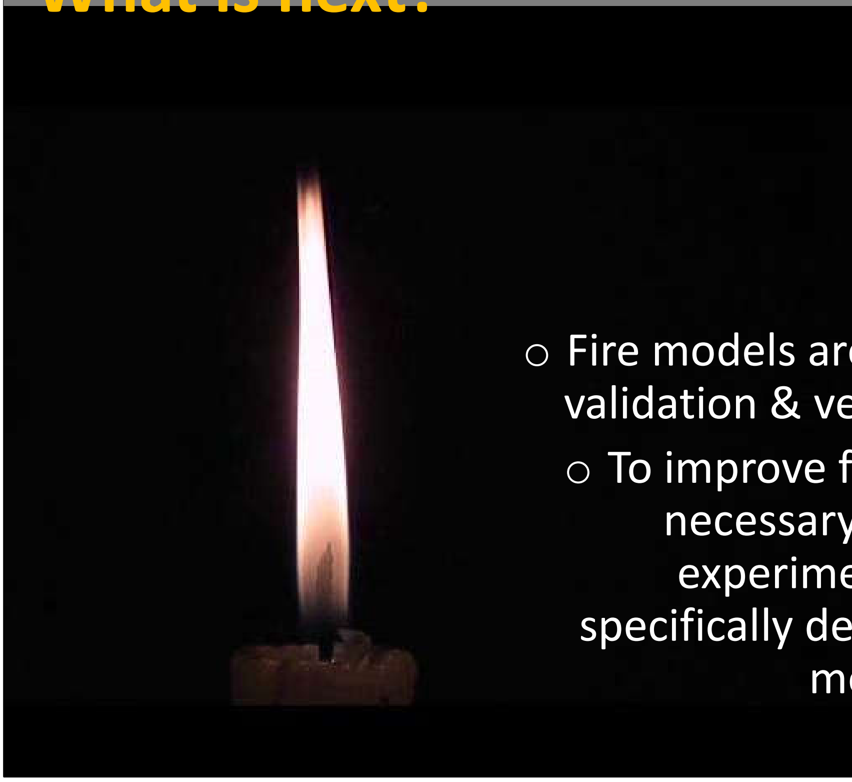
(Rein et al. 2009)

What went wrong?

- Experimental uncertainty?
  - Repeatability
  - Nature of the tests over emphasized secondary ignition
- Models are not good enough?
- Modellers are not good enough?
- Despite the ecautions - tests of this natu provide little insight to i ve models or th modelling cise – too many variables!



What is next?



- Fire models are not ready for validation & verification tests
  - To improve fire models it is necessary to develop an experimental data base specifically designed for CFD model validation

What is next?

- Comprehensive Fire Models will not be a viable solution for a very long time
- Fundamental understanding of the different processes involved and their couplings can enable formulations consistent with the modelling domain
- The simplified formulations need to be specifically designed for the purpose of CFD based scaling-up of the fire